STUDY ON THE NATURAL VENTILATION STRATEGIES FOR HOSPITAL WARDS IN THE TROPICS

by

Farhan E Shafrin

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Department of Architecture
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
Dhaka 1000, Bangladesh

The thesis titled "STUDY ON THE NATURAL VENTILATION STRATEGIES FOR HOSPITAL WARDS IN THE TROPICS" submitted by **Farhan E Shafrin**, Roll No.: **0418012017**, Session: **April 2018**, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Architecture** on 23 February 2022

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DEDICATION

TO MY CHILDREN.
You have strengthened, enriched, and fulfilled me in ways I could never have imagined.

Samien Shaheed
Juwayen Shaheed
&
Nuwaira Shaheed

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ABSTRACT

Owing to the growing concern for energy in developing countries, including Bangladesh, natural ventilation strategies remain the main alternative to expensive mechanical ventilation strategies, especially in primary health care facilities. Further, when writing this report, the World Health Organization (WHO) had declared the novel coronavirus-2 (nCoV-2) outbreak a pandemic and an international public health emergency. Besides, current evidence suggests that the COVID-19 virus spread in poorly ventilated and crowded indoor settings adds complexity. Thus, this study aims to articulate a relationship between ward design, ventilation, and airborne infection. It defines architectural and ventilation variables related to each other in a way that promotes or hinders patients' safety. The study begins with a comprehensive literature review to evaluate trends and practices in hospital ward design in the tropics, emphasizing existing strategies and guidelines. Furthermore, a questionnaire survey, tracer gas test, and CFD model are used to evaluate potential ventilation strategies in the context of the location.

The study tries to establish a strong connection between architectural design, ventilation, and infection, which can enhance and promote the effectiveness of ventilation in reducing airborne infection. The simulation results indicate that using each indicator independently can lead to paradoxical results. Using the whole set of indicators can provide a more holistic and comprehensive assessment inside the ward. The study inferred the probability of infection through ventilation performance.

One of the challenges healthcare designers faces is the difficulty of quantifying design efficiency and predicting their ability to prevent infections. Thus, the study recommends some guidelines to perform a more holistic and complete evaluation inside a naturally ventilated ward to reduce the risk of airborne infection while maintaining thermal comfort.

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LIST OF ABBREVIATIONS

Acronym	**Description**
ABL	Atmospheric Boundary Layer
ach_1	Air Change Per Hour
ACR	Air Change Rate
AIA	American Institute of Architects
AIVC	Air Infiltration and Ventilation Centre
ANSI	American National Standard Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineering
ASTM	American Society for Testing and Materials
BERC	Bangladesh Energy Regulatory Commission
BHFS	Bangladesh Health Facility Survey
BMD	Bangladesh Meteorological Department
BNBC	Bangladesh National Building Code
CC	Community Clinics
CDC	Centres For Disease Control and Prevention
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Service Engineers
CRI	Centre For Research and Information
DBT	Dry Bulb Temperature
DGHS	Directorate General of Health Services
EE&C	Energy Efficiency & Conservation
EIA	Energy Information Administration

EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Global Greenhouse Gas
HAI	Healthcare Associated Infections
HCW	Health Care Workers
HTM	Health Technical Memorandum
HVAC	Heating Ventilating and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEDCR	Institute Of Epidemiology, Disease Control and Research
IMC	International Mechanical Code
IPCC	Intergovernmental Panel on Climate Change
ISIAQ	International Society of Indoor Air Quality and Climate
ISO	International Standard Organization
JICA	Japan International Cooperation Agency
kgoe	Kilogram(S) of Oil Equivalent
LCC	Life Cycle Cost
MIS	Management Information System
MOHPW	Ministry of Housing and Public Works
MPEMR	Ministry of Power, Energy and Mineral Resources
MRT	Mean Radiant Temperature
NGO	Non-Governmental Organization
OOP(e)	Out-Of-Pocket (expense)
PD	Percentage Dissatisfied

PM	Particulate Matters
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPM	Parts Per Million
RANS	Reynolds-Averaged Navier-Stokes
RD	Rural Dispensary
REB	Rural Electrification Board
SAARC	South Asian Association for Regional Cooperation
SARS	Severe Acute Respiratory Syndrome
SREDA	Sustainable And Renewable Energy Development Authority
THE	Total health expenditure
UHC	Upazilla Health Complexes
UHFWC	Union Health And Family Welfare Centres
VOC	Volatile Organic Compounds
USC	Union Sub Centre
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

Chapter Structure

1 CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The study "Study on the Natural Ventilation Strategies for Hospital Wards in the Tropics" was initiated to provide adequate ventilation in hospital wards of the research area to minimize the risk of infection while maintaining the occupants' thermal comfort. Ventilation is a key concern in hospitals. Providing acceptable indoor air quality requires an effective ventilation system that can remove indoor contaminants (Mohammed, 2015) while reducing transmission of the infection in the hospital wards.

At the time of writing this report, the Globe Health Organization (WHO) had declared the novel coronavirus-2 (nCoV-2) outbreak a pandemic and an international public health emergency, and the entire world is working to address it. It is a rapidly evolving and emerging situation. In less than five months after the first emergence of the virus in December 2019, nearly two million people in 185 countries around the globe have been identified as confirmed cases of coronavirus disease 2019 (COVID-19)(Agarwal et al., 2020). As the coronavirus outbreak spreads rapidly throughout the world, numerous governments have implemented non-therapeutic preventive measures such as travel bans, remote office activities, country lockdown, and, most significantly, social isolation. However, in Bangladesh, a lower-middle-income economy with one of the world's densest populations, these efforts meet obstacles. Social distancing is difficult in many areas of the country, and with the country's low resources, implementing mitigating measures would be extremely difficult, particularly in resource-constrained healthcare settings (Anwar et al., 2020).

Indoor air quality in the context of this study stands for the ability of the natural ventilation system to provide the acceptable ventilation rates of at least 6-ach-1 recommended by ASHRAE while eliminating or reducing the risk of infection transmission. However, this has received less attention in multi-bed hospital wards than operating theaters or isolation rooms, which have a high risk of infections. Therefore, the challenge of ventilation in multi-bed rooms is a major concern in many countries worldwide, including Bangladesh, where private rooms are not yet the standard (JICA, 2018).

In addition, most indoor air-related infections in hospitals result from poor architectural design, material selection, ventilation system design, and ambient climatic situations (Megahed & Ghoneim, 2020). Current evidence suggests that the COVID-19 virus spread in poorly ventilated and crowded indoor settings adds complexity. There is strong and sufficient evidence to show an association between ventilation and air circulation in buildings and the transmission and spreading of infectious diseases such as measles, mycobacterium tuberculosis, varicella, influenza, smallpox, and severe acute respiratory syndrome (SARS) (Yu et al., 2017). However, the primary concern of this study was the ventilation design of multi-bed hospital wards, which, due to the nature of its complex and mixed patient environment, happens to be one of the most critical spaces in the hospital. As a result, proper ventilation in the wards will help to reduce the prevalence of infection issues that can affect hospital patients.

On the other hand, energy consumption in buildings is a key issue that directly affects a building's indoor air quality and thermal comfort (Adamu et al., 2012). According to International Energy Agency IEA, the world's energy consumption has increased by more than 50% over the last few decades (S. Omrani et al., 2017) due mainly to economic and population growth. Therefore, due to increasing energy issues in developing countries, including Bangladesh, natural ventilation strategies continue to be the key alternative to costly mechanical ventilation strategies, especially in health care facilities.

Further, designers cannot modify and control uncontrollable variables, e.g., wind, weather conditions, and the surrounding environment. Design-related parameters, such as building height, orientation, openings, and internal layout, play an essential role in determining natural ventilation performance (Hegazy et al., 2019). Besides, design elements can enhance and promote the effectiveness of ventilation in reducing airborne infection. For successful natural ventilation design, a detailed consideration of uncontrolled variables and design-related parameters must be undertaken.

Moreover, thermal comfort is a significant factor for creating a comfortable indoor environment for the hospital occupants. It reduces the stress upon the patient's health to achieve psychological stabilization. It may reduce a patient's duration of stay in the hospital by facilitating their recovery process (Appah-Dankyi & Koranteng, 2012).

Therefore, the primary concern is to provide sustainable and clean indoor air through adequate ventilation in hospital wards to reduce the airborne infection risk with less energy without compromising occupants' thermal comfort. However, a lack of knowledge about infection prevention is one of the reasons for inadequate natural ventilation in most healthcare buildings in Bangladesh (M. T. Islam et al., 2020).

Hence this research aims to provide acceptable indoor air quality using natural ventilation in hospital wards of the study area. The selected case study has been investigated to ascertain the actual situation in the context of the tropical climate of Dhaka to provide strategies for clean indoor air quality to reduce the infection risk in hospital wards. Based on the existing hospital wards' ventilation outcome, Computational Fluid Dynamics (CFD) simulations of various natural ventilation strategies have been conducted.

1.2 Statement of Problem

The study was informed by the problems of the infection risk associated with ventilation in the multi-bed hospital wards in the tropics. Due to the nature of the multi-bed hospital wards, which accommodate the most vulnerable group of people, often weak in the immune system due to certain illnesses, there is a high opportunity for infectious pathogens and other healthcare-acquired illnesses to spread rapidly. Furthermore, these infectious pathogens were spread often due to poor ventilation and contaminant sources within and around the hospital wards.

Besides, overcrowding, inadequate facilities, lack of adequate infection control measures, and ineffective ventilation methods are reported as the primary cause of infection in hospital wards of Bangladesh (Begum et al., 2017). Despite these findings, very few studies have been carried out on natural ventilation strategies in hospital wards in Bangladesh; hardly any research focuses on the effect of architectural design on hospital wards' infection control. Further, in the primary healthcare hospitals of Bangladesh, the electricity demand exceeds the supply, and even the supply remains unreliable. Generation capacity is about 60 percent, and per capita, annual generation is less than 400 kWh, one of the lowest levels in the world (Pargal, 2017). Thus, energy-intensive ventilation systems are not applicable to the study area.

Further, most available building codes, including BNBC, are developed based on mechanically ventilated buildings. No specific guidelines were found related to natural ventilation in hospital multi-bed wards. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers or ASHRAE requires that air changes occur to keep fresh air continuously entering spaces. However, this guideline does not suggest how to effectively remove contaminated air that may be caught in dead zones or poorly circulated areas, depending on the room configuration.

Furthermore, Bangladesh lies in a tropical region with a high air temperature and relatively high humidity, making indoor air quality and ventilation more difficult. Bangladesh has also shown deviations from international standards such as ASHRAE and CIBSE in thermal comfort criteria. Little research was found on hospital buildings and their thermal comfort conditions in the context of Bangladesh. Therefore, the challenges faced by the healthcare designers are the difficulty of quantifying the design performance and predicting its ability to hinder infection transmission while ensuring the thermal comfort of the occupants. This study tried to fill these knowledge gaps. Thus, a holistic approach is needed to investigate natural ventilation strategies for the multi-bed hospital wards that may be appropriate to the situation in the tropical climates of Bangladesh

1.3 Aims and Objectives

1.3.1 Aims

The study aims to investigate the possibility of natural ventilation strategies to reduce the risk of airborne infection in hospital wards in the tropical climate while maintaining the occupants' thermal comfort.

1.3.2 Objectives

The objectives of this study are as follows:

Objectives 1: To investigate the nature of existing ventilation systems used in hospital wards in Dhaka. (Chapter 4 & 5)

Objectives 2: To articulate a relationship between ventilation, openings, and thermal comfort. (Chapter 7)

Objectives 3: To explore the potential of using natural ventilation strategies to reduce the risk of infection in the wards. (Chapter 8)

1.4 Research Questions

It is necessary to define key study objectives and ask some research questions based on these objectives before conducting any ventilation investigation in hospital wards. Below presents some of the questions which will be answered during this research:

a. What are natural ventilation methods available in hospital wards in Dhaka?

b. How can different parameters be designed to deliver effective natural ventilation and thermal comfort in hospital wards?

c. What are the natural ventilation strategies that can be used to minimize infection risk in hospital wards?

1.5 Importance of the Study

The study investigated natural ventilation strategies to reduce airborne infection risk and maintain thermal comfort in multi-bed hospital wards in the tropics. Current evidence suggests that the COVID-19 virus spreads in poorly ventilated and crowded indoor settings, where people spend longer periods of time (WHO, 2021).

The outcome of this study would help to provide multi-bed hospital wards in Dhaka with adequate ventilation, which is essential for patient safety. Moreover, the adoption and implementation of natural ventilation strategies in hospital wards will conserve energy and consequently reduce the running cost of hospitals. Reducing the airborne infection risk will prevent hospital ward occupants from related diseases such as COVID-19, influenza, and respiratory illnesses. Furthermore, improving the ventilation rate will help remove indoor air contaminants and provide the required fresh air.

Therefore, the research is necessary to determine whether the existing standard is appropriate for multi-bed patient room configurations and sizes and ventilation configurations. It also addresses the causal effect of airborne means inpatient rooms on the transmission of COVID-19 virus and influenza A pathogens.

1.6 Context of the Study

The study explored existing multi-bed hospital wards in Dhaka and other parts of Bangladesh to determine the exact nature of indoor thermal condition and ventilation rate and its effects on airborne infection risk management. Collected data was then used to refine the issue of research. It was then used as an input for simulation with CFD to provide efficient natural ventilation strategies in the tropics' multi-bed hospital wards.

1.7 Overview of the Research Methodology

This section provides an overview of the thesis research methodology. The flow diagram in Figure 1-1 represents the various stages of the research process.

The first stage of the research was identifying the problem, which was initiated through a literature review of previous studies. The literature review facilitated identifying the knowledge gap in ventilation and infection control studies in multi-bed hospital wards in tropical climates. Various design factors affecting natural ventilation design concerning infection control and indoor thermal comfort have been identified.

The selection of a case study hospital ward was the second stage of this investigation. Essential factors such as a case that is aligned with the research topic, an accurate representation of a primary hospital ward in Dhaka, and easy to assess for data collection were all taken into account when selecting this. The first and second stages could be considered as the ***proposal stage***.

The third stage of this research was investigating the hospital wards' psychosocial perception about indoor air quality and other indoor environmental factors that affect indoor thermal comfort and ventilation in buildings. The inquiry about psychosocial perception was conducted by administering a questionnaire survey to medical doctors, nurses, and other healthcare workers who are the most frequent users of the hospital wards.

The fourth stage of the analysis was the validation using a full-scale assessment of the findings obtained through the psychosocial experience. This is because the result of the survey questionnaire was a mere social perception of the occupants, which was not sufficient to determine the existence of problems and therefore needed confirmation using experimental methods. The CO_2-based tracer gas decay method has been used to assess the indoor air quality of an existing hospital ward in the study area. Together the third and the fourth stages could be viewed as the ***problem exploration stage***.

The fifth stage of this research was selecting building performance prediction software (CFD) to enable an in-depth investigation of different ventilation strategies and validate the simulation models. State-of-the-art CFD simulation software Fluent 18.1 was used to validate the hospital ward models using the results obtained from the full-scale measurement. This stage could be viewed as the ***CFD validation stage***.

This study's sixth and seventh stages evaluated different ventilation strategies to provide acceptable indoor air distribution and thermal comfort. They estimated the risk of infection using the infection model with Wells-Riley, respectively. The case study wards indicated a quantifiable reduction in the transmission of viruses via airborne methods. Together the sixth and the seventh stages could be viewed as the ***design alternation stage***.

Finally, several recommendations and strategies for designing hospital wards in Dhaka were suggested to minimize the risk of infection while maintaining the occupants' thermal comfort. This stage could be viewed as the ***recommendation stage.*** The schematic diagram of the research methodology of this study is as follows Figure 1-1.

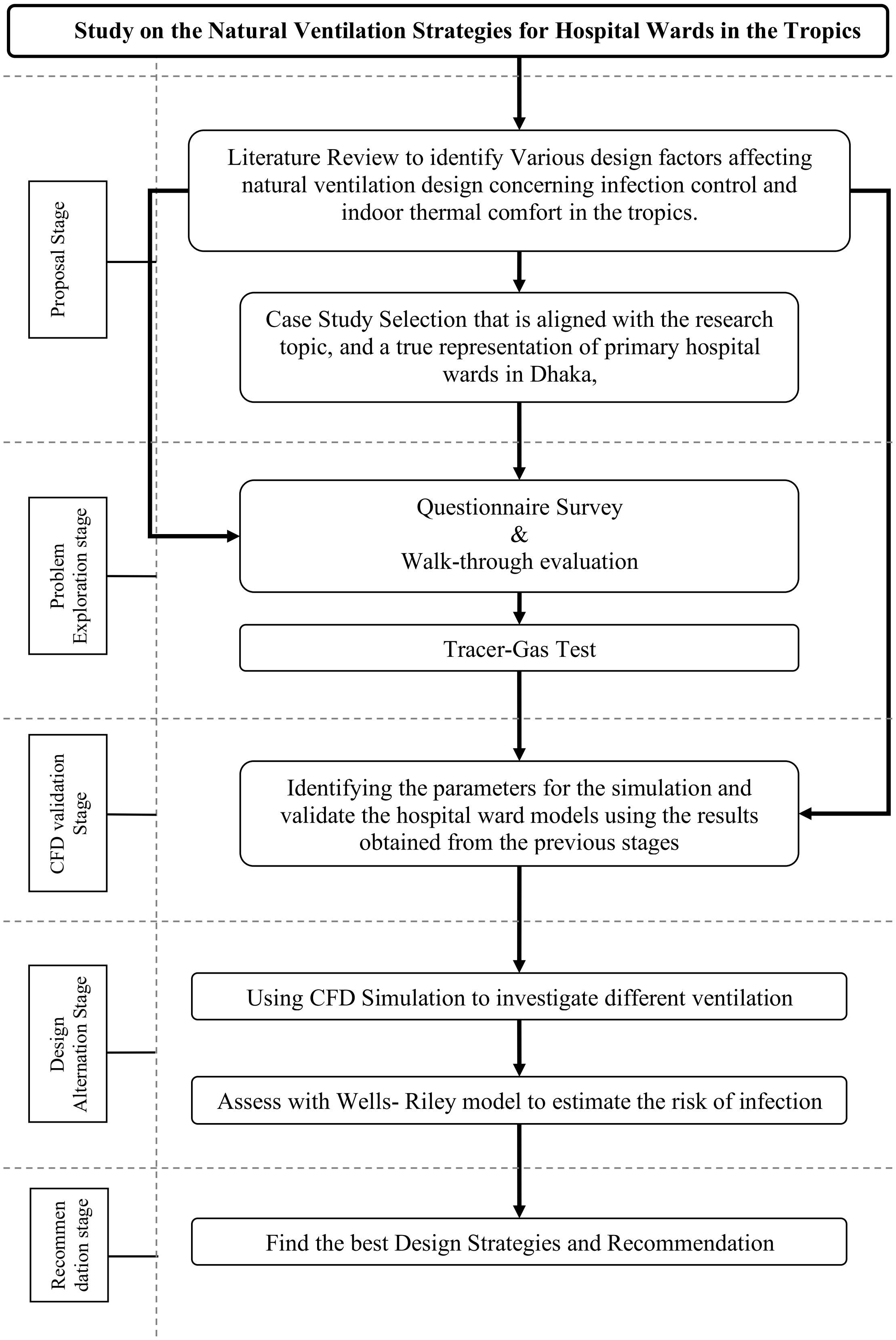


Figure 1-1: Diagram of Research Methodology

1.8 Thesis Structure

Chapter one (1) introduces the entire study, providing a general overview. It provides context to the research problem, aims, and objectives.

Chapter two (2) introduces the characteristics of the study area.

Chapter three (3) is the literature review, in which the previous related works are critically reviewed, and the gaps in the knowledge are identified.

Chapter four (4) presents the results of the physical, environmental, and social assessment of the existing hospital wards.

Chapter five (5) discusses and presents the methods and results of the ventilation rate measurements using tracer gas decay methods.

Chapter six (6) describes the methods used in conducting the CFD simulation and the results of the CFD validation.

Chapter seven (7) presents the CFD simulation results on the effects of opening positions, outdoor wind speed, and building orientation on ventilation rates.

Chapter eight (8) assesses the risk of infection associated with ventilation

Chapter nine (9) is a conclusion, limitations, and recommendations for future research.

CHAPTER TWO

CLIMATE

Chapter Structure

2 CHAPTER TWO: CLIMATE

2.1 Introduction

The introduction of the study area (Warm- humid tropical climate of Dhaka) is necessary to provide the required information about the various factors to be considered while designing the ventilation system in the study area. The geographic location of the building is among the most critical considerations in the design of natural ventilation systems that will eventually determine the seasonal differences in the outdoor environmental factors, such as air temperature, solar radiation, wind, humidity, and outdoor air quality (Awbi, 1994). The previous chapter (Chapter 1) introduces the background of the entire thesis and describes the research problem and objectives. This chapter introduces the environmental characteristics of the study area Dhaka and various factors affecting natural ventilation and thermal comfort.

2.2 The Climate of Bangladesh: An Overview

The climate can be classified as a warm-humid climate, based on the widely used classification of tropical climate (Wilson, 1975). According to the tropical climate classification by Atkinson (1953), Bangladesh is located in a composite or monsoon climate zone dependent on landmass between the Cancer and Capricorn Tropics. This climate character can be taken from Bangladesh’s position on the world map (Figure 2-1).

Figure 2-1: Location of Dhaka (World Atlas Travel, 2017)

According to the ecological area identified by UNESCO (Green, 1977), Bangladesh lies between 20^0 34' N to 26^0 33' N and 88^0 01'E to 92^0 41'E in the Indo-Malay region.

Bangladesh is bounded by landmass and south by the Bay of Bengal on three sides. The climate of the country is hot and humid for a major part of the year and is generally representative of tropical climates (Mallick, 1994). Except for the hilly southeast, most of the country is a low-lying plain land.

2.3 Climatic Context of Dhaka Region

There are some differences within the patterns of climatic factors among various parts of the country (Mallick, 1994), where Dhaka, the capital of Bangladesh, is centrally located. Dhaka and its surrounding region lie between longitudes 90^0 20' E and 90^0 30' E and between latitudes 23^0 40' N and 23^0 55' N at the southern extremity of the Pleistocene Terrace of the Madhupur Tract. The climate of this region is tropical and greatly influenced by the Himalayan Mountain range and Tibet plateau in the north and the Bay of Bengal in the south (Mridha, 2005).

There are significant differences between the urban built-up areas and their surrounding rural areas (Givoni, 1976). Similarly, the climatic conditions of the surrounding rural areas vary from those of Dhaka city. This variation is largely responsible for physical development, variation in surface quality, density, height (three-dimensional objects), and other related factors.

2.4 Climatic Regions

Meteorologically the climate of Bangladesh is categorized into four distinct seasons (Table 2-1): Pre-monsoon, Monsoon, Post-Monsoon, and Winter, where winter is cool and dry, the pre-monsoon is hot and dry, monsoon and post-monsoon periods are hot and wet (Mridha, 2005).

Table 2-1: Climatic seasons of Bangladesh (Mridha, 2005)

March-May	June - September	October - November	December - February
Pre-monsoon	Monsoon	Post-monsoon	Winter
Hot-Dry	Hot-Wet		Cold-Dry

There are significant differences in climate in different parts of the country defined by seven sub-zones (Rashid, 2019). These are the South-Eastern Zone, North-Eastern Zone, Northern Part of Northern region, North-Western Zone, Western Zone, and South-Central Zone (Figure 2-2). One of the most important contributing factors to this variability is its nature and surrounding topography. Among all the climatic sub-zone characteristics (Figure 2-2), the Dhaka region and other areas such as Mymensingh, Tangail, and Manikganj are located in the south-central zone. This is a transitory boundary between the South-East, North-West, and South-West regions, sharing similar features of all three zones.

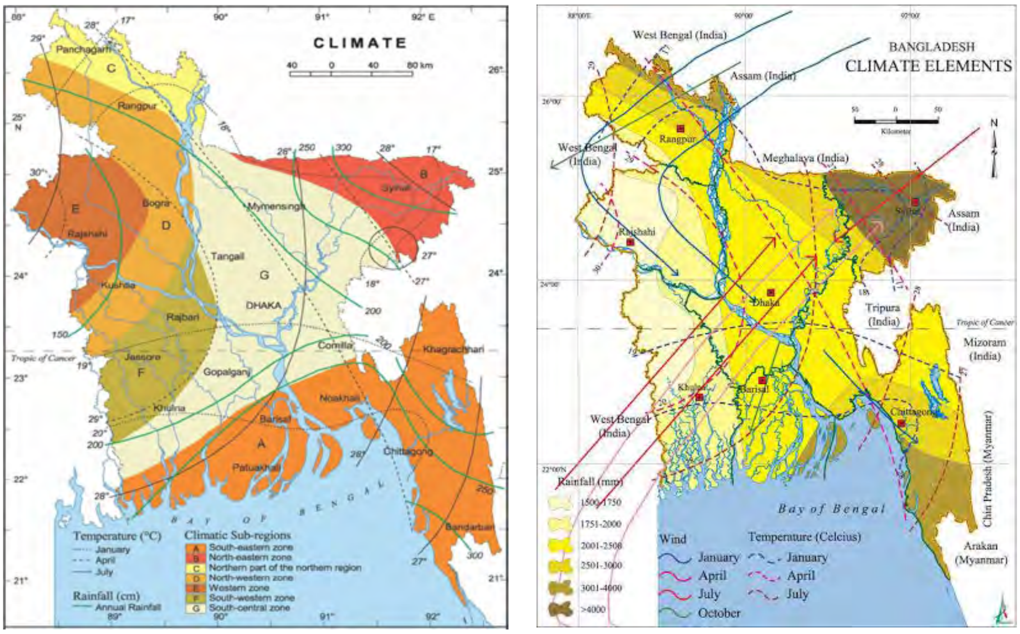


Figure 2-2: The climatic subzones of Dhaka

2.5 Climatic Components of Dhaka Region

Climate is the combined effect of several factors (Sarma, 2002). The climate components are solar radiation, long-wave radiation to the atmosphere, air temperature, humidity, wind, and precipitation, according to the climatologist Givoni (1995). While Markus, T.A., and Morris (1979) listed three main climate driving components: temperature, moisture, and air movement.

According to the generic typologies, comprehensive information on local air temperature, humidity, and wind patterns is required to describe the local climate precisely (Gonzalo & Habermann, 2006). These climatic factors also affect the indoor conditions of the built environment. The following review of climatic factors is based on meteorological sources (2016-2020) of the Dhaka region.

2.5.1 Temperature

The summer or pre-Monsoon season consists of March, April, and May; this is the hot-dry period with an average rainfall of 17% and an average monthly temperature of 18.9-34.4°C (BMD 2020). Based on measurements provided by the Bangladesh

Meteorological Office, Agargaon, the temperature profile of Dhaka is in ways consistent with the regional trend. During the wet season, the monthly mean maximum temperature fluctuates between 35.1-36.2°C, and the average monthly mean temperature remains steady at 29.9°C. The monthly mean maximum temperature in winter gradually decreases, and the temperature drops to an average of 29.1°C, while the mean minimum is 11.7°C. According to the profile, the maximum temperatures are observed during the pre-monsoon season (March, April, and May). The profile clearly reveals that the annual average maximum temperature has risen by 4.05ºC over the last 68 years. Table 2-2 and *Figure 2-3* show the increasing trend of the annual maximum temperature of Dhaka for the last 70 years.

Table 2-2: Annual maximum temperature of Dhaka (1950-2020)

Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Annual Avg. Temp. oC
Season	Hot-Dry(°C)			Hot-Wet(°C)						Cool-Dry(°C)			
	Pre-Monsoon			Monsoon			Post-Monsoon			Winter			
1950-1980	32.6	34.5	33.0	31.4	31	31.1	31.4	30.8	28.7	26.0	25.5	28.5	30.38
1981-1990	32.4	33.5	33.1	32.4	31.5	31.9	31.9	31.8	29.9	26.7	25.8	28.4	30.78
1991-2000	32.6	34	33.2	32.7	31.8	31.9	32.4	32.0	29.8	26.6	25.0	28.0	30.83
2001-2010	32.5	34.6	33.2	32.5	31.8	32.2	32.0	31.6	28.6	26.0	24.0	28.5	30.63
2011-2020	35.5	37.5	36.9	36.2	35.9	35.2	35.7	36.0	33.4	29.8	28.6	32.4	34.43

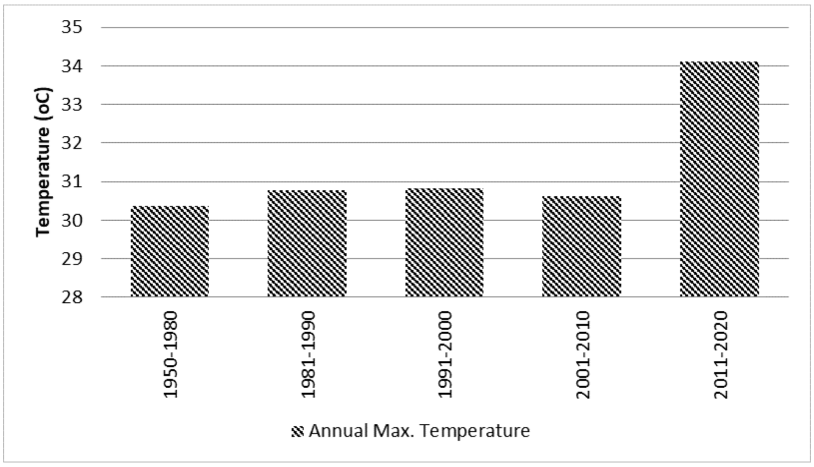


Figure 2-3: Annual maximum temperature of Dhaka

Moreover, studies revealed a clear temperature difference between the city center and rural areas at the fringes (Table 2-3). Besides, a recent study by analyzing the 2000-

2020 climate data also showed significant positive temperature changes (Khatun et al., 2020).

Table 2-3: Comparison of Air Temperature Between Dhaka City and Its Suburbs

	Mean Minimum Temperature (°C)		Mean Maximum Temperature (°C)		Mean Annual Temperature (°C)	
	Temperature	Difference	Temperature	Difference	Temperature	Difference
Dhaka (Urban)	21.4	+0.5	30.6	+0.4	25.8	+0.4
Tangail (Rural)	20.9		30.2		25.4	

2.5.2 Relative Humidity

Dhaka's relative humidity is lower than neighboring rural areas, and it usually declines when one gets closer to the city center (Khatun et al., 2020). Furthermore, relative humidity is inversely proportional to the current temperature. As a result, the increasing temperature reduces relative humidity levels in any given case while other conditions remain constant.

According to data provided by Dhaka's meteorological office, Dhaka's climate (2016-2020) has the highest relative humidity during September & October and the lowest during April & May (Figure 2-4). According to the Bangladesh Meteorological Office, Agargaon, Dhaka's RH profile has remained consistent over the last 50 years, with values averaging about 70% over the year.

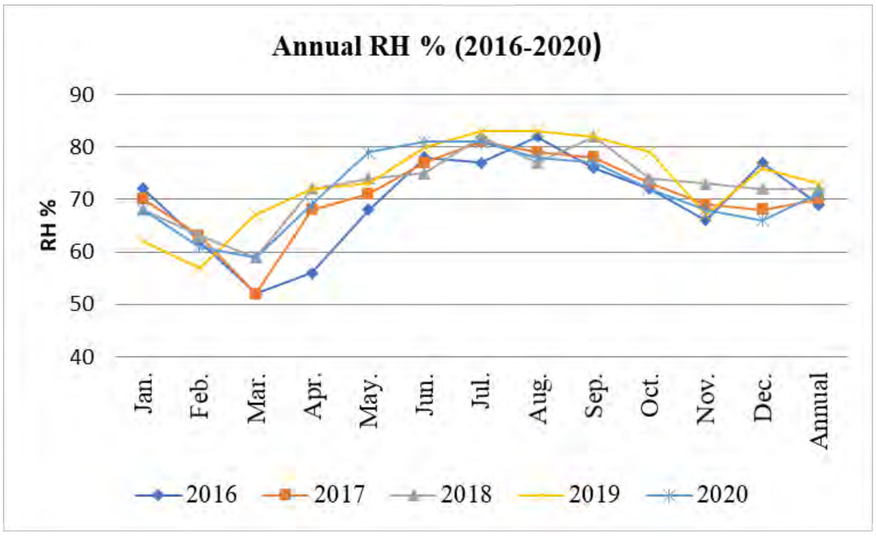


Figure 2-4: Annual relative humidity of Dhaka city

Table 2-4: Monthly average relative humidity with monthly Avg. means temperature in Dhaka city, (2016-2020)

	March-May	June - September	October - November	December - February
	Pre-monsoon	Monsoon	Post-monsoon	Winter
Temperature (ºC)	27.8	29.9	26.7	21.2
RH (%)	66	79.5	71.3	67

2.5.3 Wind Speed and Direction

Meteorological data are based on conditions measured in open locations and published as general conditions for the city as a whole (Mallick, 1994). The data (2016-2020) shows that the prevailing wind speed in Dhaka is comparatively high in the pre-monsoon period starting from March to May, where the average value is over 1.4 m/s, and the highest is in May (1.5 m/s). Table 2-5 shows the meteorological data from 2014 to 2018, measured in the open locations of Dhaka.

Table 2-5: Monthly mean wind speed and prevailing direction (BMD, 2020)

	March-May	June - September	October - November	December - February
	Pre-monsoon	Monsoon	Post-monsoon	Winter
Wind speed m/s	1.4	1.3	1.3	1.2
Direction	SW	SE	NE	NW

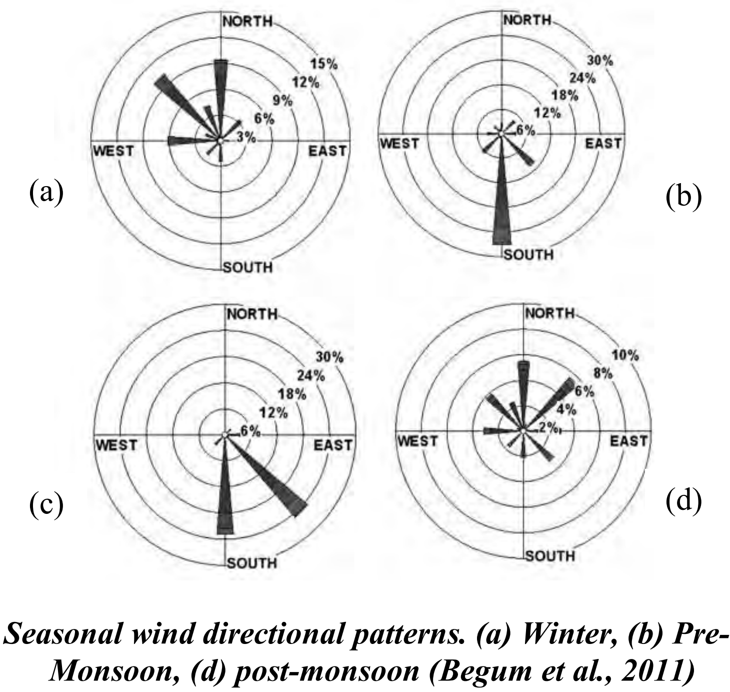


Figure 2-5: Seasonal wind directional patterns. (a) Winter, (b) Pre-monsoon, (c) Monsoon, (d) post-monsoon (Begum et al., 2011)

The prevailing wind direction is south and South-Easterly during the monsoon period (June-September) and north-westerly during winter. The most striking feature of Dhaka’s climate is the reversal of the wind circulation between summer and winter, which is an integral part of the circulation system of the South Asian subcontinent (Ahmed, K. S., 1995). Figure 2-5 shows the seasonal wind directional patterns of the Dhaka region. Wind speed and temperature are closely correlated (Thangprasert & Suwanarat, 2017). The wind speed is elevated, with the temperature increasing. *Figure 2-6* shows the relation between Dhaka's wind speed and temperature.

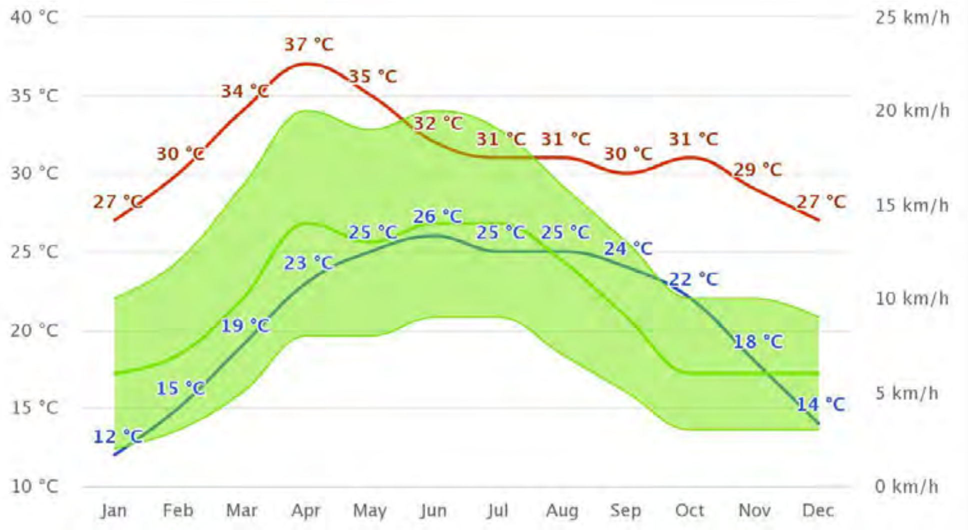
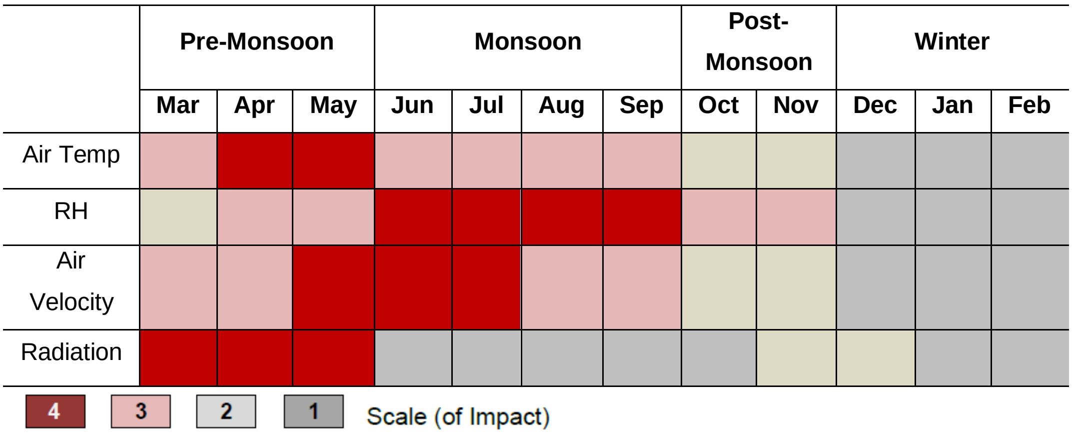


Figure 2-6: Monthly mean wind speed and temperature of Dhaka (CD, 2020)

2.6 Climate Variable Matrix

Thermal comfort requirements vary based on environmental factors for various seasons of the year. Table 2-6 contrasts the environmental factors for the year and describes their possible temperature effect (BMD, 2020). This table shows that the pre-monsoon season, i.e., March to May, is the most important part of the year because high temperatures in the air are associated with higher solar radiation levels. This phase of the year is also crucial to the potential effect on the indoor thermal comfort of the occupant.

Table 2-6: Environmental Matrix for Dhaka (2020)



	Pre-Monsoon			Monsoon				Post-Monsoon		Winter		
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Air Temp	▩	■	■	▩	▩	▩	▩	▢	▢	▒	▒	▒
RH	▢	▩	▩	■	■	■	■	▩	▩	▒	▒	▒
Air Velocity	▩	▩	■	■	■	▩	▩	▢	▢	▒	▒	▒
Radiation	■	■	■	▒	▒	▒	▒	▒	▢	▢	▒	▒

■ 4 ▩ 3 ▢ 2 ▒ 1 Scale (of Impact)

2.7 Chapter Conclusion

This chapter introduced the environmental characteristics of the study area, including climatic conditions and other climatic factors that distinguished the zone from other parts of the world. As Bangladesh is located in a humid tropical region, its climate is characterized by high temperatures, heavy rainfall, excessive humidity, and fairly marked seasonal variations. The most striking characteristic of its climate is the inversion of wind movement during summer and winter, which is an integral part of the circulation system of the South Asian subcontinent.

The chapter provides detailed information concerning the climatic condition of the study area, which is divided into four meteorological seasons, including pre-monsoon (hot-dry), monsoon (hot-wet), post-monsoon (hot-wet), and winter (cool-dry). Moreover, the individual climatic characteristics of the study area, including temperatures, humidity, and wind speeds, have been presented.

The mean monthly wind speed in the study area ranges from 1.2 m/s to 1.5 m/s. The dominant wind direction is North-East (7-8 months in the dry season) and South-West (4-5 months in the wet/rainy season). The study area's average monthly mean air temperature ranges from 18.9ºC to 34.4ºC and monthly average relative humidity 71.63%. The climatic data obtained, including air temperature, relative humidity, wind speed, wind direction, was used to input the full-scale measurement and the CFD simulation analysis.

CHAPTER THREE

LITERATURE REVIEW

Chapter Structure

3 CHAPTER THREE: LITERATURE REVIEW

3.1 Introduction

This study focuses mainly on natural ventilation design and strategies for hospital wards in the tropics. The preceding chapter (Chapter 2) discusses the characteristics of the study area with all the climate parameters. Therefore, this chapter explores and addresses the current literature on factors influencing the multi-bed hospital ward's ventilation, infection, and thermal comfort.

3.2 Healthcare Sector in Bangladesh

The healthcare sector can be described as one of the most significant sectors of the economy since treatment is considered a basic need for life and has a high and steady demand. However, Bangladesh's healthcare system is largely dependent on the government or public sector to finance and improve overall policy and service delivery systems. (A. Islam, 2014).

Bangladesh has a low per capita health expenditure and a low percentage of GDP spent on health. Public health allocation in 2020 was equal to 2.6 percent of gross domestic product compared to a global average of 6.3 percent (D. K. R. Islam, 2021). Government expenditure on health is only about 28% of the Total Health Expenditure (THE), The rest (72%) being out-of-pocket (OOP) expenses (Titumir, 2020). Bangladesh ranks 2nd from the bottom of THE as a percentage (%) of the Public Health Expenditure index for SAARC nations. Figure 3-1 shows the comparison.

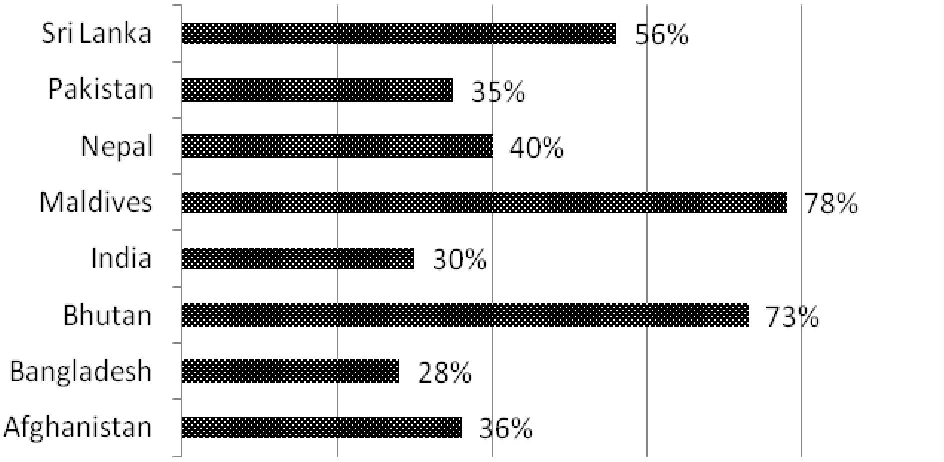


Figure 3-1: Public health expenditure as % of THE by SAARC nations, (WHO, 2018)

Bangladesh currently has a well-structured healthcare system comprising three main tiers of primary health care, such as sub-district level Upazilla Health Complexes (UHC), Union Health Centers (UHFWC) at Union level (collection of several villages), and village level Community Clinics (CC). These are backed by the District Hospitals providing secondary level care and tertiary hospitals in large urban centers (Hossain, 2016). Primary healthcare facilities in the Upazilla level and below are presented in Table 3-1. According to the Centre for Research and Information (CRI) in Dhaka, the country has over 600 hospitals, including 482 primary care hospitals at the sub-district level and below 65 secondary hospitals at the district level, 15 medical and dental college hospitals, and specialty facilities such as the chest, respiratory diseases, and leprosy hospitals. Furthermore, the government has established 16.438 Community Clinics and Health Centers and 30.000 Satellite Clinics. (Centre for Research and Information, CRI, 2018).

Table 3-1: Primary healthcare facilities in Upazilla level and below (Evans & Alam, 2017)

Level	Type of Hospitals	Type of service	No. of Hospitals	No. of Beds
Upazilla	Upazilla health complex (UHC) Mother and child welfare center (MCWC)	Hospital	425	17,645
Union	Union Level Hospital	Hospital	34	695
	Union health and family welfare center (UHFWC)		23	410
Wards	Community clinic (CC)	Outpatient Only	16,438	-

In addition to the public health service, 8,203 private hospitals, clinics, and diagnostic centers in Bangladesh have been licensed by the Directorate-General for Health Services (DGHS) since 2013. Two thousand nine hundred eighty-three licensed private hospitals and clinics and 5,220 licensed private diagnostic centers. The estimated number of beds for licensed private hospitals and clinics is 45,485 (University of South Carolina, 2012).

Despite rapid urbanization, in 2019, approximately 62.6 percent of the population in Bangladesh resided in rural areas. In comparison, 59.54 percent of the population in Bangladesh lived in rural areas in 2010 (Statista Research Department, 2021). Thus, this study focuses on Upazilla-level hospitals, representing Bangladesh's mass-level primary health care facilities.

3.3 Healthcare Sector and Energy Usage

Hospitals are the most energy-specific buildings. Hospital buildings require constant, uninterrupted functioning 24 hours a day, all year round, ranking them second-most in the building sector to use a significant amount of energy (Reddy et al., 2019). Furthermore, hospitals are large, energy, and water-intensive public buildings that produce significant amounts of waste. Hence, the level of concern for energy-efficient design is higher than other forms of facilities (Robert, 2011).

Moreover, HVAC system installation accounts for between 35 and 60 percent of the average healthcare facility's total energy costs, depending on the environment. Growing demand for spatial comfort and heavy internal loads has resulted in a major rise in energy requirements (Rycroft, 2018). As a result, traditional HVAC-based hospital heating and cooling systems are energy-intensive and costly. According to research, a hospital's conventional energy consumption spectrum (Figure 3 2) shows that heating and air conditioning (HVAC) consume large amounts of energy (more than 50%).

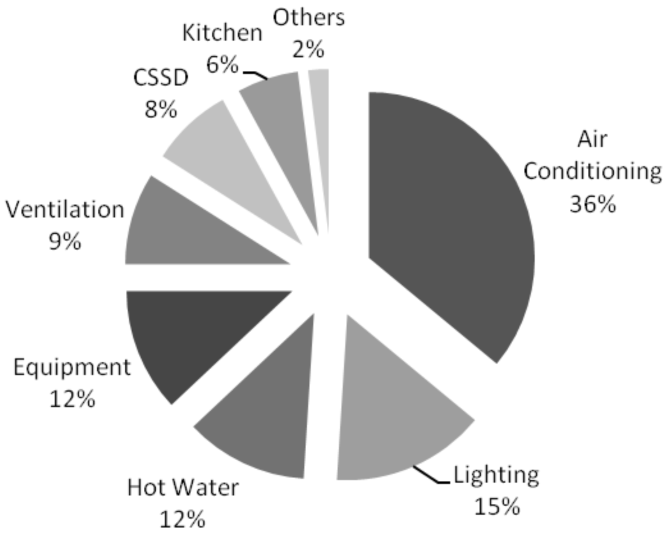


Figure 3-2: Typical energy use spectrum for a hospital, Rycroft (2018)

3.3.1 Energy Consumption in Bangladesh

Energy has been one of the most important factors in developing Bangladesh's economic growth and people's lives. However, Bangladesh is one of the lowest in the world in primary energy consumption per capita (S. Islam & Khan, 2017). In 2012, the total net installed electricity generation capacity in Bangladesh was 5719 MW, from which 4162 MW are considered usable, while the country’s power demand was 6066 MW (Table 3-2). The per capita electricity consumption was 136 kWh/year, which was considered the lowest consumption rate globally (EECMP, 2015).

Furthermore, during peak hours, of average power supply of 4,700 MW against a demand of approximately 5,300 MW (Ahsan, 2018) was obtained by the Rural Electrification Board (REB). Besides that, the rest of the country's power supply condition is more or less similar to power outages occurring 4-5 times a day in urban areas and 10-12 times a day in rural areas.

An average of 77.9% of the population had access to electricity in Bangladesh. Bangladesh will need an estimated 34,000 MW of power by 2030 to sustain its economic growth of over 7 percent. Therefore, the government must control energy consumption by introducing adequate Energy Efficiency & Conservation (EE&C) plans, schemes, and initiatives and promoting energy efficiency in the economy.

Table 3-2: Bangladesh's general indicators for the electricity situation ((Taheruzzaman & Janik, 2016)

Indicator	Power Demand	Production Capacity	Supply	Exports	Imports
Rate/Value	6066 MW	5719 MW	4162 MW	0	0

3.3.2 Energy and Healthcare Sector in Bangladesh

According to the Bangladesh Health Facility Survey (University of South Carolina, 2012), about 80% of all health services, except community clinics (CCs), are linked to the national power grid, and 45 percent of these facilities have regular electricity.

In comparison, 76% of district and upazilla public facilities, 81% of non-governmental organizations, and 98% of public hospitals have regular energy supplies. One-fifth of the CCs have an electrical link to the national electrical grid, but only 9 percent have regular electricity (Table 3-3). Regular power is considered available if the facility is connected to the central electricity grid or if, at daily operating periods, power deliveries in seven days were not disrupted for more than two hours at a time (BERC, 2018).

Table 3-3: The percentages with regular electricity service (NIPORT, 2017)

Primary Healthcare Sector	National electricity grid %	Regular electricity %
Upazilla Level		
UHC	97.1	72.5
MCWC	95.7	79.3
Union level		
UHFWC	66.1	28.0
USC/RD	76.0	24.8
Ward Level		
Community Clinic (CC)	21.2	9.1

However, due to climate change, Bangladesh is vulnerable to sea level and global temperature rise from global greenhouse gas (GHG) emissions from fossil fuels (Rashid, 2019). According to the IPCC(1996) forecast, Bangladesh will experience a temperature rise of 1.9° C by 2030. Studies indicate that climate change would significantly affect Bangladesh's public health. Rising temperature and power demand with the rise of temperature, increasing trends in several hot days, has also been observed in Bangladesh (Shahid, 2013). Increased temperature and hot days can increase energy usage for cooling spaces. It would increase overall energy usage and contribute to high electricity demand.

Kolokotsa et al. (2012) reported that it would be possible to save about 10% of primary energy consumption by introducing simple energy-saving techniques that include natural ventilation strategies in health care facilities. Considering the importance of energy efficiency in buildings, BNBC has been revised following MOHPW, where the building's heating insulation and ventilation performance are high on the priority list Energy Efficiency and Conservation Master Plan until 2030 (BERC, 2018).

3.4 The Hospital Multi-bed Wards

Hospitals remain the most complex buildings because of their wide range of functional units and services. Based on functionality, Robert (2011) classified the optimal essential types of hospitals as bed-related inpatient functions, outpatient-related functions, diagnosis and treatment functions, managerial functions, facilities functions, and research and teaching functions. “The multiple-bed hospital ward is a generic term used to describe the concept of a non-partitioned area that contains several beds for patients who need a similar kind of care at a healthcare facility” (Williams, 1966). The number of beds in a ward differs from one facility to another. The number of beds in a ward varies from facility to facility. As a result, in many areas, including Bangladesh, the layout of a multiple-bed hospital ward will vary from 2 to 30 patients per ward.

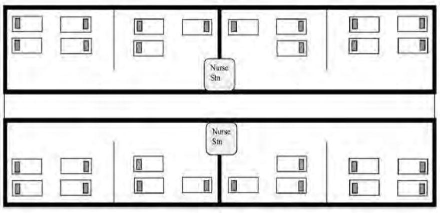
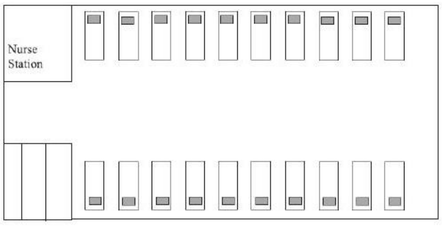
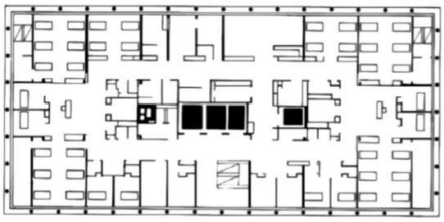
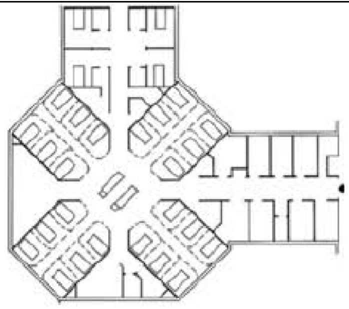
The planning of all open ward facilities is based on three standards: adequate patient access at all hours, cross ventilation, and building and maintenance savings. This allows the easy supervision of the sick patient (Williams, 1966). However, due to increased concern and awareness of the spread and transmission of disease in hospital wards in Bangladesh the control and management of infectious and infectious pathogens in hospital wards involves the design, equipment, and ventilation considerations (Rimi1 et al., 2014).

Moreover, around 50% of rooms in a general hospital of Bangladesh are wards spaces (S. Zaman, 2006). The application of open multi-bed wards in resource-limited developed countries dominates the hospital setting. However, the possibility of infection is higher in the open ward, and the spread of infectious organisms within the space occurs within a short period. The application of open multi-bed wards in resource-limited developed countries and regions dominates the hospital setting.

3.4.1 Multi-Bed Hospital Wards Type

Multi-bed wards in hospitals are classified into different types, depending on the shape and layout. The wards' layouts affect the time spent by nurses in performing different activities (Ampt et al., 2008). Various researchers have presented the classification of hospital wards. Recently, Yau et al. (2011) described four types of hospital ward designs that are frequently being utilized throughout the world, including; (1) bay wards, (2) nightingale wards, (3) racetrack wards, and (4) hub & spoke units. Hospital ward arrangements such as Bay and Nightingale are obtainable in the study area, but the rest are not commonly used in the study area. The four types of wards categorized by Yau et al. (2011) are described in Table 3-4.

Table 3-4: Classification of multi-bed wards in hospitals

Type	Description	Images
Bay Wards	In Bay wards, space is divided into various cubicle rooms, each housing beds with a central nurses' station and peripheral rooms accommodating small beds.	
Nightingale Wards	The nightingale wards are a form of multi-bed arrangement in which the beds are placed along the room's perimeter, with the nurses' station located at the middle or end from which visibility and hearing are maximized.	
Racetrack Wards	The nursing and other service areas are situated between two corridors in the racetrack ward arrangement, also known as the double corridor.	
Hub And Spoke Wards	The central nurses' station acted as the hub and spoke unit's central focus, with large rooms acting as radiating spokes.	

3.5 Ventilation in Buildings

Ventilation in an enclosed space can be described as a regulated movement or changing air. The primary function of ventilation is to provide appropriate indoor air quality and thermal comfort in buildings (J. Atkinson, 2009). Ventilation is also used for odor control, contaminant control, and climate control (temperature and relative humidity). The process of space ventilation can be viewed as two separate simultaneous processes. The first process is the airflow through openings in the external envelope and internal partitions, while the second is indoor airflow (Hensen & Lamberts, 2012).

An efficient ventilation system design in buildings dilutes indoor air pollutants and the concentration of carbon dioxide emitted by breathing. Three main components of building ventilation are (WHO, 2017): a) Ventilation rate, b) Airflow direction, and c) Air Distribution or Airflow Pattern In order to ventilate a building, it is possible to use three different methods: natural, mechanical, and hybrid (mixed-mode). Mechanical and hybrid (mixed-mode) ventilation is beyond the scope of this study. Therefore, the following sections discuss only natural ventilation.

3.5.1 Natural Ventilation in Buildings

Natural ventilation is usually driven by natural forces such as wind and thermal buoyancy force due to indoor and outdoor air density variation, forcing fresh air from outside through custom-made building envelope openings (Atkinson, 2009). It relies on pressure differences caused by either wind or buoyancy effect created by temperature or humidity to move fresh air through buildings. Natural ventilation in buildings is becoming an increasingly attractive means of reducing energy costs. However, most naturally ventilated buildings have narrow plans to increase daylight utilization, reducing electrical demand for electric lighting (Raji et al., 2020). The performance of different types of ventilation concerning different climatic conditions has been illustrated in Table 3-5.

Table 3-5: Potential applicability of natural ventilation solutions in ideal conditions (Atkinson, 2009)

Climate	Natural Ventilation					Hybrid/mixed ventilation	Mechanical ventilation
	Single-sided corridor	Stack (Atrium/ chimney)	Courtyard		Wind tower		
			Outer corridor	Inner corridor			
Hot and Humid	★★	★	★★	★★	★	★★★	★★★★
Hot and dry	★★★	★	★★★	★★★	★★★	★★★★	★★★★
Moderate	★★★	★★★	★★★	★★★	★★★	★★★★	★★★★
Cold	★	★★	★	★	★	★★	★★★★
Energy Requirement	Low					Medium	High

In addition, natural ventilation should not necessarily be seen as an alternative to air conditioning but is a more effective tool for enhancing indoor air quality in hospitals, safeguarding safety, increasing thermal comfort, and decreasing excessive energy use (Ghiaus & Allard, 2012).

Tantasavasdi et al. (2001) conducted a study to determine the comfort zones for various indoor air velocities of a naturally ventilated building in one of the tropical countries. The study found that the winter months are most suitable for natural ventilation. The tropical climate can be classified into five groups according to Tantasavasdi et al. (2001).

Table 3-6: Tropical climate classification

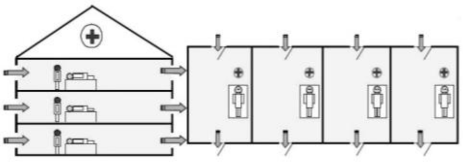
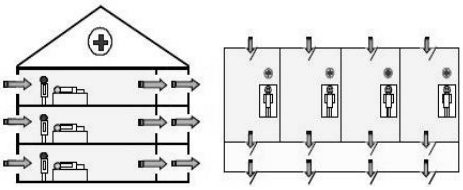
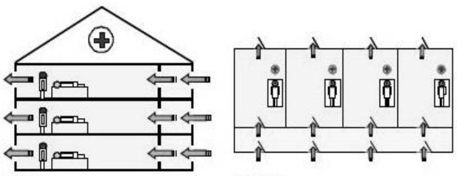
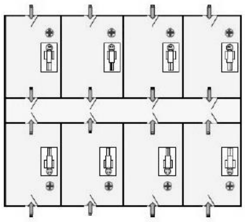
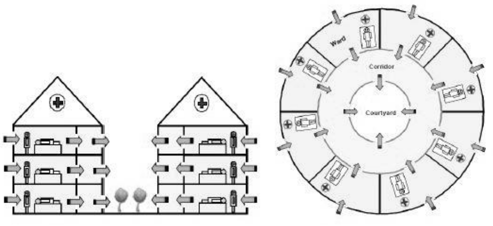
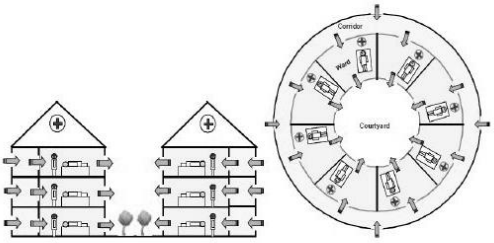
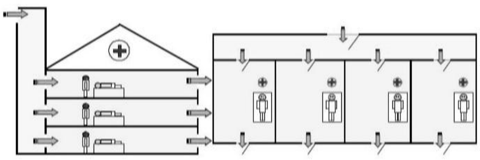
Type of Air	Climatic Parameter	Remarks
Hot air	33oC< - RH 55%	natural ventilation does not work
Warm air	30oC - RH 72%	high natural ventilation is needed
Comfortable air	25oC - RH 70%	moderate ventilation is appropriate
Humid air	27oC - RH 90%	natural ventilation is not appropriate
Cool, humid air	21oC - RH 85%	minimal ventilation will help

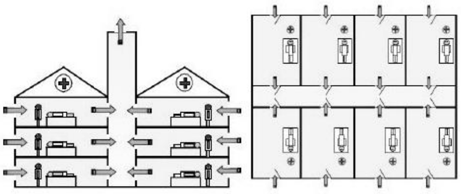
Besides, the design concern for natural ventilation includes climatic considerations, high air-change requirements, thermal comfort, infection risk control, indoor air quality, fire protection, and external noise (Mohammed, 2015). The consideration of these factors is essential for the designing of any building with natural ventilation. The scope of this study does not include fire safety or exterior noise.

3.5.2 Types of Natural Ventilation Systems in Hospital Wards

Natural ventilation systems are classified by their basic architectural design elements, i.e., corridors, courtyards, wind towers, and chimneys in hospital wards (J. Atkinson, 2009). These building elements define the routes of airflow and the primary natural ventilation strategy. Natural ventilations are classified based on their basic architectural design features as follows (Atkinson, 2009; CIBSE, 1997): (1) single-side corridor, (2) central corridor, (3) courtyard, (4) wind tower, and (5) atrium and chimney. These systems are listed in table form below (Table 3-7). Some of these systems can be combined to meet the needs of the local environment and the hospital.

Table 3-7: Types of natural ventilation systems in hospital wards

Types	Description	Images
Cross Ventilation	Cross-ventilated wards have ventilation openings on both sides of the room, allowing direct passage of air from one side of the building to the other through the inlet window(s) and exiting through another window(s) or door (s).	
Single-Side Corridor	The corridor is located on one side of the ward. The airflow depends on the wind direction from the ward to the corridor and from the corridor to the wards. This one-way flow would help in the prevention of cross-infection.	 
Central Corridor	A central corridor is a form of natural ventilation created by connecting an additional set of wards on the other side of the corridor to the single-side corridor system.	
Courtyard Ventilations	Courtyards are enclosed areas that allow the overall airflow to be channeled and directed. This natural ventilation system can be divided into two types: the relative arrangement of wards and corridors to the courtyard, namely the inner and outer corridor.	 
Wind Tower	The wind on the roof can be captured and guided down to the rest of the building by a wind tower type of natural ventilation system. The wind tower is typically made up of four quadrants that can span the structure's entire length and serve as air intakes or extractors.	

Types	Description	Images
Stack (Atrium and Chimney)	An atrium or chimney type of natural ventilation system can be a side-atrium or chimney type, or a central atrium or chimney type, depending on the wards' relative position and the atrium chimney. Outdoor air is sucked through the windows through a stack (or buoyancy) effect.	

3.5.3 Natural Ventilation Mechanism

Dynamic pressure and static pressure differences are natural ventilation driving forces. Higher pressure variations thus give rise to a higher ventilation rate. The difference in dynamic pressure is caused by the incident wind, while the difference in static pressure is due to the temperature variation known as the buoyancy or stack effect. A mixture of static and dynamic pressure differences can also contribute to natural ventilation. (Aynsley, 2014)

The wind that strikes a building surface creates a pressure difference by creating positive wind pressures and negative pressure on the windward and leeward sides (Figure 3-3). Therefore, having openings at the external walls directs the external air to flow through the internal spaces from the zone with positive pressure to the zone with negative pressure(Huppert, 1990). A greater difference in pressure results in a higher indoor airflow rate.

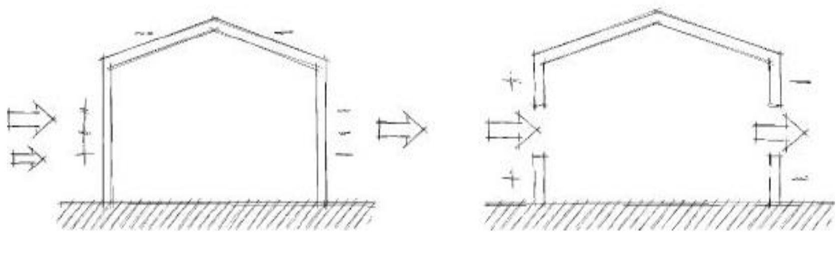


Figure 3-3: Positive and negative pressure zones due to wind force.

Buoyancy-driven ventilation can be divided into two major groups: mixing ventilation and displacement ventilation (S. Omrani et al., 2018). Mixing ventilation is generally characterized by one opening acting as supply and exhaust. Fresh air enters the enclosure from the lower part of the opening, and the warm air escapes from the upper part. Displacement ventilation, however, occurs from two openings situated at different heights. Cold air enters from the lower opening, and warm air escapes from the higher opening near the ceiling Figure 3-4.

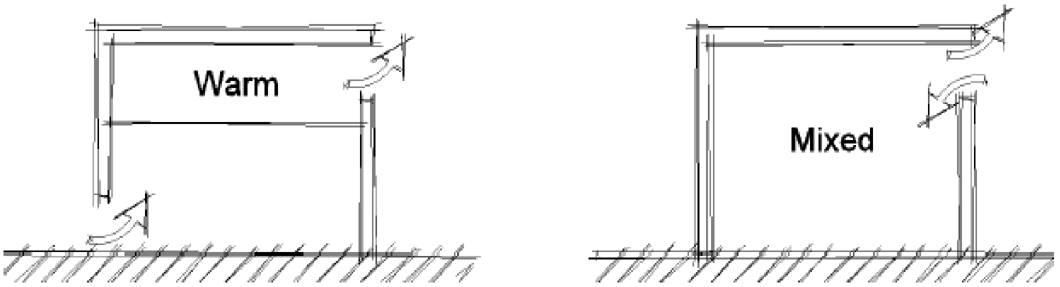


Figure 3-4: Buoyancy-driven ventilation: displacement ventilation (left) and mixing ventilation (right).

Natural ventilation can also be driven by a combination of wind force and stack effect. These forces may counteract or complement each other based on openings and the incident wind direction. Indoor and outdoor temperature differences in a room with openings at different heights produce buoyancy forces and the stack effect, as illustrated in Figure 3-5.

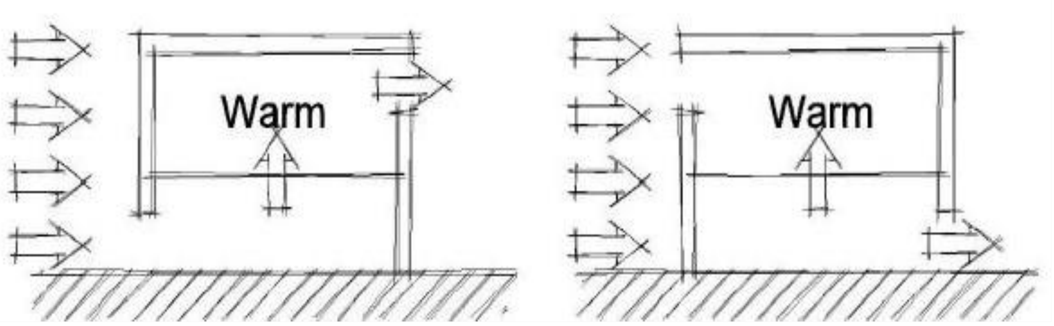


Figure 3-5: Combined wind and buoyancy forces when complementing each other (left) and opposing one another (right)

3.5.4 Advantages and Disadvantages

The main advantages of natural ventilation are reducing energy consumption and consequent pollutants, providing thermal comfort, improving indoor air quality, and low initial and operating costs.

Elevated air velocity can eliminate the excessive heat of the human body and provide it with a thermally comfortable environment. Uncomfortable indoor thermal conditions encourage air-conditioners' use, resulting in energy consumption (De Dear, 2004). Natural ventilation replaces the hot air inside a space with cooler air from the outside through natural processes. Thus, natural ventilation can reduce energy consumption and pollution emissions.

In addition, natural ventilation can enhance indoor air quality by replacing the aged air inside the space with fresh air from outside (Allard & Santamouris, 1998). In contrast to naturally ventilated buildings, mechanically conditioned buildings have often reported problems such as sick building syndrome. Besides, a study on the effect of using natural ventilation instead of mechanical ventilation on airborne infection transmission in hospitals suggests natural ventilation decreases the chance of airborne contagion by 6%-28% (Lipinski et al., 2020).

Despite the benefits described above, certain disadvantages are associated with natural ventilation in buildings, such as limited control, noise, and outdoor pollution. Natural ventilation is heavily dependent on natural factors such as wind speed and direction. Furthermore, the reliance on wind conditions on building ventilation efficiency requires proper building site analysis and design to promote natural ventilation, introducing additional challenges to the design process (Walker, 2010). In addition, open windows used for natural ventilation make the enclosure vulnerable to external noise and pollution (Kwon & Park, 2013), especially in high-traffic areas and regions close to sources of pollution.

Despite the limitations of applying natural ventilation in buildings, this passive cooling system remains an attractive solution for space cooling. This becomes even more feasible for tropical climates, where thermal comfort is most needed.

3.6 Indoor Air Quality (IAQ) and Ventilation

Indoor air quality (IAQ) refers to the air quality within and around buildings and structures. IAQ has been shown to impact building occupants' health, comfort, and well-being (Reddy et al., 2019). Poor indoor air quality has been linked to sick building syndrome, including allergies, eye irritations, decreased productivity, and respiratory issues (Yau et al., 2011). According to ASHRAE, *“an acceptable indoor air is one in which there are no known contaminants in harmful concentrations, as determined by the competent authorities and a substantial majority (80% or more) of occupants are not exposed to dissatisfaction”* (Orosa & Oliveira, 2012).

IAQ can be susceptible to being infected by gasses (including carbon monoxide, radon, and organic volatility), particles, temperature, and humidity variations. The fundamental approaches to improving indoor air quality in most buildings include source protection, filtering, and ventilation to dilute pollutants.

The level of air quality in the hospital environment has a significant effect on the concentration of pathogens in the air. Subsequently, it dictates the rate of airborne infectious diseases obtainable indoors (Ulrich, Roger S, et al., 2008). Providing acceptable indoor air quality in hospital wards is necessary to reduce the risk of infection and cross infection among patients, nurses, and other healthcare workers. Thus, it is essential to control indoor air pollutants of both indoor and outdoor sources.

3.6.1 Health Consequences of Indoor Air Pollution

Globally, there is rising awareness about the health consequences of indoor air quality in hospital buildings. 30 to 40 percent of the 760 million registered worldwide respiratory diseases are caused primarily by particulate air pollution (Santamouris & Wouters, 2006). The highest risk of infections is obtainable in healthcare facilities because it brings together communicable and susceptible individuals, causing frequent airborne nosocomial transmission (Yau et al., 2011). It can cause transient morbidity, disability, disease, and extreme circumstances resulting in death.

CIBSE specifies valuable regulations on reducing indoor contamination by understanding outdoor pollutants behavior and assessing their effect on indoor air quality. It is essential to eliminate pollutants at their origin and improve ventilation, such as local exhaust, displacement, or dilution. Because of the complicated relationships between ventilation rates, contaminant levels, and health complaints, ventilation as a control mechanism for air quality issues should be tempered with an appreciation of conditions that may restrict its efficacy.

3.6.2 Building-Related Illness (BRI) and Sick Building Syndrome

Building-related illness (BRI) is a term that refers to any illness caused by human exposure to building indoor air and characterized by signs of diagnosable illness. These illnesses can be traced back to environmental agents in the air. Legionnaire's disease and hypersensitivity pneumonitis are two severe, even life-threatening, instances (U.S. Environmental Protection Agency-EPA, 1991).

SarkinGobir et al. (2017) defined Sick Building Syndrome (SBS) as a situation in which at least 20 percent of building occupants experience symptoms of illness for two weeks or more, without determining the actual source of the symptom. Moreover, SBS is a condition where the inhabitants of the concerned buildings repeatedly express a complex range of unclear and often subjective health complaints, which are often linked with poor indoor air quality.

Many studies have shown reduced SBS symptoms with high ventilation rates. Workers in air-conditioned offices reported increased work-related sicknesses (Jones, 1999). Irritation of eyes, nose, throat, dry mucous membranes and skin, hoarseness of voice, wheezing, nausea, and dizziness are symptoms of SBS.

3.6.3 Nosocomial Infection (Hospital-Associated Infection)

The emergence of any infectious disease not presents and without evidence of incubation at the time of patient admission to a healthcare environment or receiving treatment for other conditions is referred to as Healthcare-Associated Infections (HAI) (Mirza, 2011). The presence of most clinically evident infections 48 hours after patient admission to healthcare settings is considered hospital-acquired. Healthcare-associated infections in hospitals are caused by various organisms, displaying symptoms ranging from minor discomfort to severe disability and sometimes death. The consequence of nosocomial infections extends the hospitalization period and subsequently increases hospital expenditure (Yau et al., 2011). Beggs et al. (2008) suggested in their study that *"The clinical role of general ward ventilation may have been underestimated and that through improved ward ventilation, it may be possible to reduce environmental contamination and thus reduce nosocomial infection rates."*

Hence, preventing airborne infection from spreading in hospital environments requires a holistic approach that involves implementing airborne prevention strategies, including; administrative controls, environmental and engineering controls, and employment of particulate respirators by healthcare workers whenever necessary (J. Atkinson, 2009). However, this research is interested in implementing environmental and engineering controls as an airborne prevention strategy in a healthcare facility.

These will be achieved by implementing sustainable, energy-efficient ventilation systems that consider various building orientations, sizes, and materials selection.

3.7 Natural Ventilation and Thermal Comfort

The indoor environment of buildings is a key concern for the health and well-being of occupants. Many factors influence the indoor environment, but they can generally be assessed via thermal comfort, indoor air quality (IAQ), visual comfort, and acoustic quality (Guideline 2015). ASHRAE standard (2013) defines thermal comfort as *"that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation."* Generally, six primary factors directly affect thermal comfort, i.e., metabolic rate, clothing insulation, air temperature, radiant temperature, humidity, and airspeed. Among these, airspeed plays an essential role in determining thermal comfort conditions in hot-humid climates.

Air movement lowers the indoor temperature by replacing the warm air inside the space with the cooler air from the outside. It also affects the radiant temperature by cooling the building's structure and removing the heat stored in its mass. In addition, airspeed affects the human body’s thermal condition directly in two main ways (S. Omrani et al., 2017). Firstly, air movement over the skin surface affects thermal sensation by accelerating convective heat transfer). Secondly, it reduces the discomfort from skin wetness by increasing the sweat evaporation rate. Accordingly, higher airspeed extends the comfort zone and allows higher temperature tolerance. Evidence shows that thermal comfort influences the health and efficiency of workers at work (Taylor et al., 2008; Wagner et al., 2007).

3.7.1 Natural Ventilation and Thermal Comfort Studies in Tropical Hospitals

Several studies have set thermal comfort standards for hospital occupants, including patients and hospital personnel in the tropics. The indoor thermal environment also affects diseases and affects the process of patient healing. However, the definition of thermal comfort as part of the patients' healing process has yet to be further studied. Table 3-8 summarizes some of the key findings of previous thermal comfort research conducted in tropical countries over the last 12 years.

Table 3-8: Thermal comfort studies in hospitals in the tropics

Study	Authors/year	Findings
Thermal Comfort Study of Hospital Workers in Malaysia	Y H Yau et al., Malaysia	The comfort range found 25.3-28.2oC, higher than ASHRAE (2003)
The Ventilation of Multiple-Bed Hospitals in the Tropics: A Review	Yau et al., 2011	Recommend further Study on Multi Bed ward ventilation
Field evaluation of thermal comfort and indoor environment quality for a hospital in a hot and humid climate	(Wang et al., 2012) Taiwan	The operative temperature range found 22.9°C-26.3°C, 1°C lower than ASHRAE comfortable zone.
Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Centre (UKMMC)	(Azizpour et al., 2013)Malaysia	The study confirms that in hot–humid regions, the "neutral" point on the ASHRAE scale shifts to +0.7
Perceptions On Thermal Comfort In General Wards For Malaysian Hospitals	Kushairi et al., 2015 Malaysia	Findings showed that acceptance and tolerance with the space are subject to the admitted duration and working hours. Further investigation is suggested.
Clarifying thermal comfort of healthcare occupants in the tropical region: A case of the indoor environment in Thai hospitals	(Sattayakorn et al., 2017) Thailand	The comfort range for the patient, visitor, and medical staff is 21.8–27.9, 22.0–27.1, and 24.1–25.6 °C, respectively, which is warmer than suggested by the Thai standard.
The Relation between Thermal Performance and Architecture Design Aspects in Lowland Warm Humid Tropics Ward	(Mulia et al., 2018) Indonesia	The orientation of the building is a dominant factor concerning the hospital wards' thermal performance.
Assessment Of Thermal Comfort of Non-Air-conditioned In-Patient Hospital Wards in Dhaka During Warm Humid Periods	Sadia A. 2018 Dhaka	The comfort range found 29.46 ºC to 31.46 ºC

The results of the previous research explicitly demonstrate that comfort temperatures in tropical climates are significantly higher than those suggested in Europe and North America. Most studies have found that the thermal comfort needed in hospital wards is more than the ASHRAE standards in the tropics, which need to be addressed.

3.7.2 Thermal Comfort Studies in Bangladesh

While numerous thermal comfort studies on naturally ventilated buildings in various tropical countries have been conducted since 1960, only a few studies have been conducted on naturally ventilated buildings in Bangladesh. Table 3-9 presents some studies on thermal comfort in Dhaka with key findings.

Table 3-9: Thermal comfort studies in Dhaka, Bangladesh

Title	Author/year	Findings
Indoor thermal comfort evaluation of naturally ventilated rural houses in Dhaka region, Bangladesh	Shajahan A., & Ahmed, Z. (2016)	Thermal comfort band 29-34ºC with neutral temperature 31.5ºC
Thermal Comfort of Bangladesh Traditional House In A High-Density Environment with the Worst Surroundings Condition in Dhaka City. A case study at a Bangladesh Traditional House at Gulshan in Dhaka City.	Ahmed, H., & Rashid. R. (2015)	Comfort zone analysis for the winter season is 17-32°C and for summer is 24-32°C
Assessment Of Thermal Comfort Of Non-air-conditioned In-patient Hospital Wards In Dhaka During Warm Humid Periods	Sadia, A. (2018)	The acceptable temperature range is 29.46- 31.46 ºC, and the "Neutral" temperature is 30.45ºC. Neutral relative humidity was 80.3%.
Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments	Ahmed, K. S. (2003)	Average relative humidity of 70%, the boundaries of average air temperature for outdoor comfort vary between 28.5 -32.8ºC
Perception of Indoor Temperature of Naturally Ventilated Classroom Environments during Warm Periods in a Tropical City	Tariq, T., & Ahmed Z. (2014)	Neutral Temperature 30.2°C (with no air movement) Comfort range is 29.89-30.54°C
Thermal comfort and building design in the tropical climates	Mallick, F. H. 1996	People feel comfortable with Air temp. 24-32ºC RH – 50-90% without or in little air movement.

In 1987, Ahmed (1987) first proposed the adaptation of Humphreys, M.A., and Nicol, J.F., (1970) "neutral" temperature model to predict the comfort zone in the climatic context of Bangladesh. It was later found to be a better fit for the local context of the Dhaka division than the PMV-PPD index.

Later in 1994, (Mallick, 1996) used the Bedford scale (Nathan & Scobell, 2012) and the ASHRAE scale to identify comfort conditions in Dhaka's residential housing. The study discovered that if people wear regular clothes and engage in usual household activities, their comfortable indoor temperature range is 24-32ºC with a relative humidity range of 50-95 percent and no air movement. Slow (up to 0.15 m/s) airflow, on the other hand, can make a difference in comfort temperature and allow people to withstand comparatively higher humidity (Table 3-10).

Table 3-10: Comfort zone for urban housing of Dhaka, Bangladesh (Mallick, 1994)

Findings				Remarks
Fan speed	Air movement (m/s)	Comfort range °C	Mean comfort temp. °C	People feel comfortable Air temp. 24-32°C RH – 50-90% without or in little air movement Dhaka region-based research
None	0	24-33	28.9	
Slow	0.15	24-33	29.5	
Medium	0.3	26.4-35.2	30.9	
Fast	0.45	27-35.8	31.6	

These research findings agree with previous thermal studies of tropical regions, showing that people have a more comprehensive range of acceptability to environmental conditions in naturally ventilated spaces than ASHRAE and ISO standards. The literature survey found that no particular research was performed on Bangladeshi hospital wards. However, other studies have shown that the thermal comfort zone (Dhaka) is 24-32°C.

3.7.3 Thermal Comfort Models

In the last decades, researchers have explored people's thermal, physiological, and psychological responses in their environment to develop mathematical models to predict these responses. Researchers have empirically argued building occupants' thermal responses to the combined thermal effect of the environmental, personal, and physiological variables that influence thermal comfort.

Two well-known thermal comfort models are used to establish the thermal comfort conditions in air-conditioned and naturally ventilated buildings, namely (i) Predicted Mean Vote (PMV) model (Fanger, 1972) and (ii) the adaptive model (De Dear & Brager, 2001).

3.7.3.1 Fanger's PMV/PPD Model

Fanger's model of comfort (Fanger, 1972) is perhaps one of the first predictive models developed. The model was developed based on the physiology of the human body heat exchange with the environment. Air temperature, radiant temperature, humidity, airspeed, clothing insulation, and metabolic rate are incorporated, and the result is an index called PMV (Predicted Mean Vote). PMV is a seven-point physiological scale ranging from -3 to +3, where each scale indicates a thermal sensation as below (Table 3-11):

Table 3-11: Fanger's thermal sensation model

-3 Cold	-2 Cool	-1 Slightly cool	0 Neutral	1 Slightly warm	2 Warm	3 Hot

PMV predicts a group of people's average thermal sensation vote in a given environment. Using the experimental data, Fanger correlated a Predicted Percentage of Dissatisfaction (PPD) index to the PMV. The PPD calculation using PMV is presented in Eq. 3-1 (Awbi, 2003):

$$PPD=100-95\exp-\{0.03353(PMV)^{4}+0.2179(PMV)^{2}\} \qquad \text{Eq. 3-1}$$

The PPD index estimates the number of people dissatisfied with a given thermal climate. Individuals who vote –3, –2, –1, 1, +2, and +3 on the PMV scale are considered thermally unsatisfied in this index. Figure 3-6 depicts its evolution as a function of PMV.

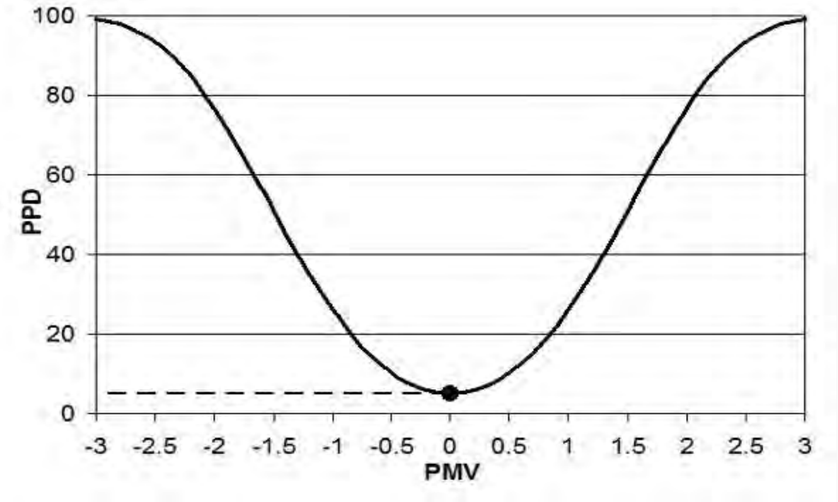


Figure 3-6: PPD as a function of PMV (Awbi, 2003)

ASHRAE standard (ASHRAE, 2013) considers an environment within the comfort zone when the percentage of dissatisfaction is less than 10%, which is equivalent to 0.5>PMV>-0.5. For a PMV value between –0.85 and +0.85, the percentage of dissatisfaction (PPD) is 20%. As a result, it can be three kinds of comfort zones, depending on the acceptable ranges PPD and PMV (Orosa, 2010).

Table 3-12: Predicted Percentage of Dissatisfaction (PPD) based on the (PMV)

Class	A	B	C
PMV	$-0.2 < PMV < 0.2$	$-0.5 < PMV < 0.5$	$-0.7 < PMV < 0.7$
PPD	<6	<10	<15

Class A, B, and C in Table 3-12 describe the range of thermal sensation of the PMV equation. Class A represents the highest satisfaction of the environment. In contrast, class B is the moderate requirement of satisfaction level, and class C is the minimum requirement of examination criterion within the thermal comfort criterion. (Gilani et al., 2015)

The PMV/PPD model has been adopted in several standards, such as ASHRAE 55 (2013) and ISO 7730 standard (2005) for thermal comfort assessment. However, the PMV model under-predicts the thermal comfort condition in naturally ventilated buildings (S. Omrani et al., 2017). This under-prediction is due to the steady-state assumption of thermal comfort in the PMV model and neglecting the adaptation of humans to their environment.

3.7.3.2 Adaptive Model

The adaptive comfort model was developed based on an extensive field study (De Dear, 1998) to predict the thermal condition of naturally ventilated buildings. The adaptive model complements the traditional PMV model by accounting for the adaptation of humans. Rather than predicting thermal sensation votes, the adaptive model is a regression equation representing the acceptable indoor operative temperature as a function of mean outdoor temperature for 80% and 90% acceptability limits (Figure 3-7). The adaptive comfort model is now included in the ASHRAE 55 standard for assessing thermal conditions in naturally ventilated buildings.

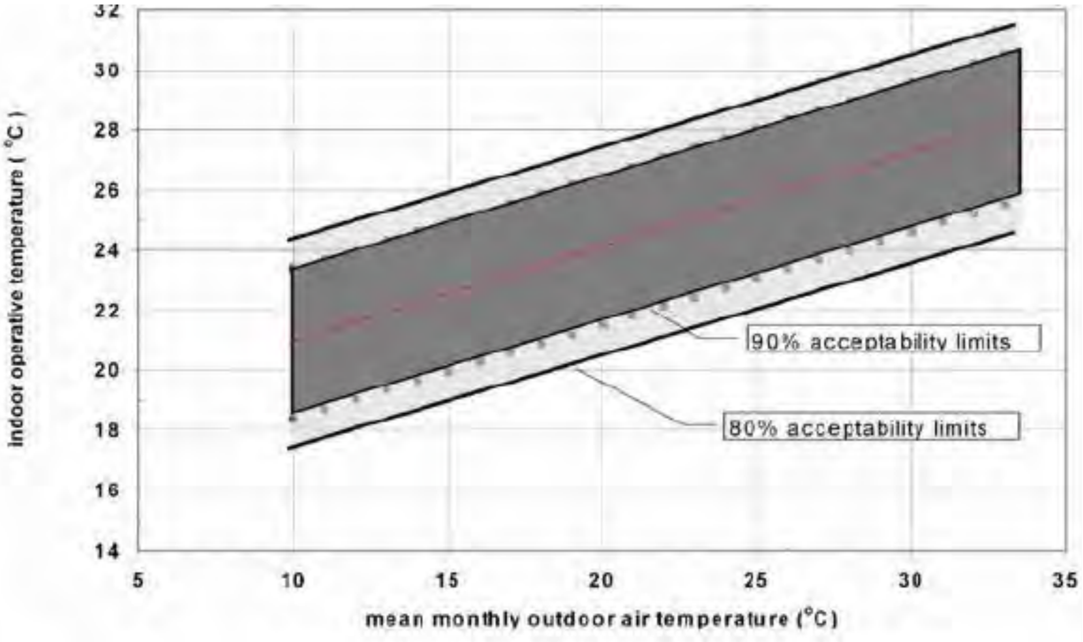


Figure 3-7: Acceptable operative temperature range for naturally ventilated buildings (ASHRAE, 2013)

The use of the adaptive thermal comfort model in free-running buildings over the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) models has proven to be more reliable (Alfano et al., 2014). Although considered in the model development process, there is no direct input for the four environmental parameters, metabolic rate, and clothing insulation in the adaptive comfort model. Therefore, it is not an appropriate model for the current study.

3.7.3.3 Extended PMV Model

Fanger and Toftum (2002) introduced an extension for the traditional PMV model appropriate for non-air-conditioned buildings using the data from the RP-884 database (R. J. De Dear, 1998). Extended PMV adds two corrections to the traditional PMV: the expectancy factor and reduced metabolic rate. Expectancy factor value is defined based on hot weather and the dominance of building type in the cooling system. Table 3-13 presents low, moderate, and high expectancy factors based on location and according to a period of warm weather. The difference in expectation of occupants of naturally ventilated buildings with air-conditioned buildings is addressed by introducing the expectancy factor (e).

Table 3-13: Expectancy factor based on the location and weather ((Fanger & Toftum, 2002)

Expectation	Classification of non_air_conditioned building		Expectancy factor, e
	Location	Warm periods	
High	In regions where air-conditioned buildings are common	Occurring briefly during the summer season	0.9-1.0
Moderate	In regions with some air-conditioned buildings	Summer season	0.7-0.9
Low	In regions with few air-conditioned buildings	All seasons	0.5-0.7

The activity level is the other parameter considered in the extended PMV model. People appear to reduce their activity levels unintentionally when they feel warm (Fanger & Toftum, 2002). This decrease is 6.7%, with each scale unit rise in the PMV index above the neutral point. Therefore, in the case of PMV values above zero, a new metabolic rate must be obtained and included in the recalculation of the standard PMV. The PPD can then be determined based on the expanded PMV value obtained.

3.7.3.4 Adaptive Comfort Based on Thermal Neutrality

Several studies on Adaptive Thermal Comfort have been conducted to assess the thermal comfort requirements for naturally ventilated buildings in hot-humid climates. Humphreys (1978), in his research, suggested a formula to predict neutral temperatures. He defines a 'neutral temperature' where the occupant experiences thermal equilibrium, which he is not aware of warmth and not chill. The following established adaptive comfort equations are used in tropical climate regions.

Table 3-14: Several established adaptive comfort equations

Proposed By	Equation	Comfort zone	Remarks
Humphreys (1978)	$T_{in} = 0.831\ T_{out} + 2.56$	±2° C	Several studies suggested the best model for applying to the climate of Dhaka
Toe & Kubota (2012)	$T_{in} = 0.50\ T_{out} + 15.4$	-	Reanalyzed the ASHRAE RP-884 Database
Indian National Building Code (2016)	$T_{in} = 0.54\ T_{out} + 12.83$	±2.38°C	

Note: T_{in} is the indoor operative temperature in °C is neutral temperature, and T_{out}, the outdoor temperature is the 30-day outdoor running mean air temperature in °C

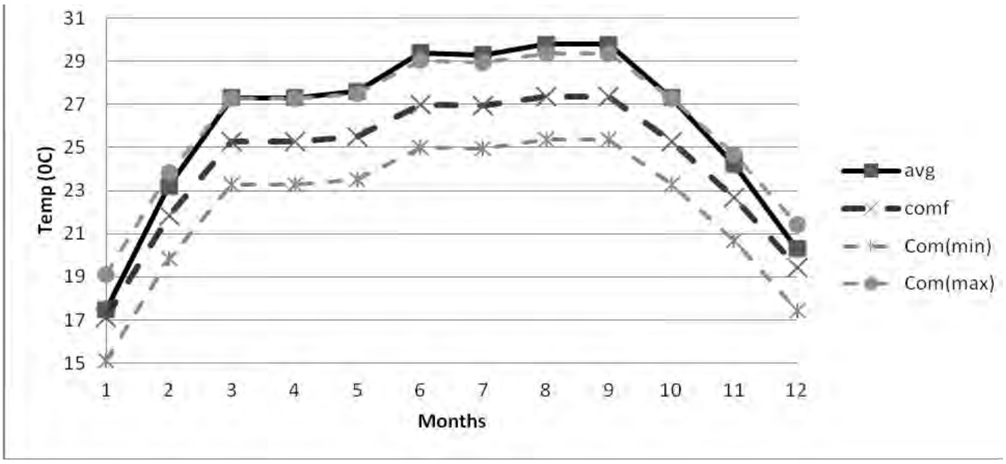


Figure 3-8: The neutral temperature of the study area (2020)

Figure 3-8 shows the temperature of neutrality of the research area (Dhaka) using Humphrey's (1978) equation. The possibility of experiencing discomfort: June, July, August, and September.

3.7.3.5 SET Index*

Another index developed for the calculation of thermal sensation is Standard Effective Temperature (SET*) ASHRAE 55 defines SET* as the temperature of an environment at 50% relative humidity and average airspeed of below 0.1 m/s, where air temperature and radiant temperature are equal (Vinet & Zhedanov, 2011). Figure 3-9 represents the acceptable range of operative temperature as a function of the elevated airspeed for 0.5 and 1.0 clo clothing values. SET* is the recommended comfort model of ASHRAE-55 (ASHRAE, 2013) for cases with an indoor airspeed greater than 0.2 m/s.

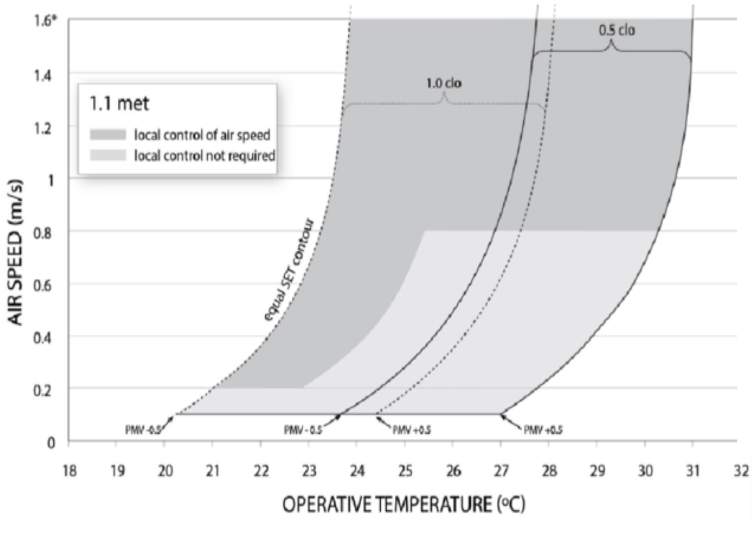


Figure 3-9: Operative temperature as a function of airspeed (ASHRAE, 2013)

3.8 Natural Ventilation and Infection Risk in Hospital Wards

The transmission of airborne diseases in healthcare facilities is an increasingly important concern. The design of effective ventilation systems plays a key role in preventing infections (WHO Guidelines, 2009). Moreover, ventilation can reduce the concentration of airborne pathogens by removing or diluting airborne droplet nuclei. Studies have shown that the spreading of infection among health care workers was strongly associated with inadequate ventilation in general patient rooms and with type and duration of work (Menzies et al., 2000).

The facts linking transmission of contagious diseases such as measles, tuberculosis, chickenpox, smallpox, influenza, and SARS to ventilation and air movement in buildings are sound and convincing (Li, Yuguo, et al., 2007). A study by Hou and Ma (2008) established that the air change rate, airflow direction, and airflow pattern are the key factors influencing ventilation performance in Severe Acute Respiratory Syndrome (SARS) wards.

ICDDR, B (2009) conducted a study in three Bangladeshi tertiary care hospitals to identify the respiratory symptoms in patients hospitalized. Results found that the patients on these research wards often developed respiratory infections acquired in hospitals, including 1 in every 20 patients hospitalized in 1 ward (Gurley et al., 2010). The study suggested some effective prevention of hospital-acquired respiratory disease, including improved ventilation and limited visitors. Natural ventilation decreases airborne infection risk by exploiting windows and doors opening, compared to expensive mechanical ventilation systems (Gilkeson et al., 2013). The interesting feature of natural ventilation in contrast to mechanical ventilation is that it is widely used in healthcare facilities in limited-resource regions (Qian et al., 2010).

However, architectural elements can enhance and promote the effectiveness of ventilation in reducing airborne infections (Adamu & Price, 2015). Hegazy et al. (2019) identified an interrelation between the disciplines of architecture and ventilation. The study demonstrates that natural driving forces, principles of ventilation, ventilation variables, and design variables are closely linked to infection control in naturally ventilated hospital wards. Figure 3-10 shows the interrelationship between architectural/ventilation disciplines.

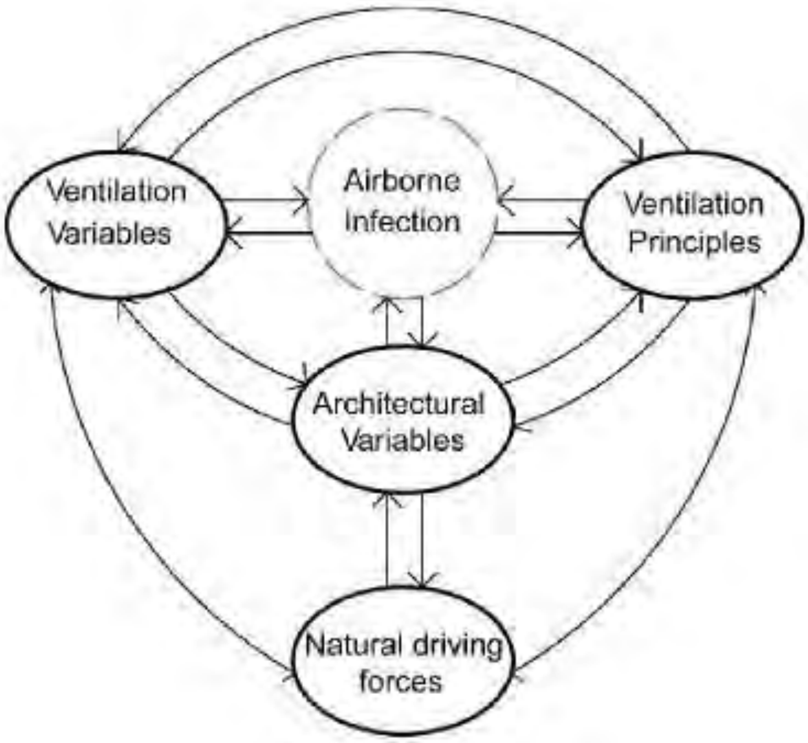


Figure 3-10: The interrelationship between architectural and ventilation disciplines for preventing airborne infection (Hegazy et al., 2019)

Additionally, three major concerns need to be addressed when using natural ventilation to control infections (Qian et al., 2010). The rate of ventilation produced by natural ventilation is the first consideration. Second, airflow direction and natural ventilation cannot regulate the airflow path through the doorway. The third is thermal comfort when using natural ventilation, particularly if the outdoor air exceeds comfort temperatures. Therefore, preventing the spread of airborne infection in hospital environments requires a systemic approach involving the implementation of airborne prevention measures, including administrative controls, environmental and engineering controls, and the use of particulate respirators by healthcare staff where appropriate (J. Atkinson, 2009).

However, limited studies have been conducted in Bangladesh, which created a noticeable knowledge gap in ventilation studies. This knowledge gap is more prevalent in open ward facilities, accommodating most patients in tropical hospitals. Table 3-15 shows various ventilation and infection control studies conducted with their areas, climates, year, and findings.

Table 3-15: Natural ventilation and airborne infection related studies

S/n	Study	Authors/ Year	Area	Findings
1	Natural Ventilation for the Prevention of Airborne Contagion	Escombe, et al. (2007)	General wards Lima, Peru	Natural ventilation reduces the risk of airborne contagion.
2	The ventilation of multiple-bed hospital wards: Review and analysis	Beggs et al., 2008	Multi Bed Wards	Improving ward ventilation may reduce environmental contamination and reduce nosocomial infection rates.
3	Natural ventilation for reducing airborne infection in hospitals	Qian et al., 2010	Wards, Hong Kong	The high ventilation rate provided by natural ventilation can reduce the cross-infection of airborne diseases.
4	Natural Ventilation in Thai Hospitals: A Field Study	Inkarojrit 2010	Hospital wards. Thailand	Natural ventilation is suitable for controlling infection in hospitals in tropical climates when windows are opened.
5	Rethinking hospital general ward ventilation design using computational fluid dynamics	Yam et al., 2011	General Wards	Results reveal that ventilation performance and the removal of microbes can be significantly improved.
6	Infrastructure and Contamination of the Physical Environment in Three Bangladeshi Hospitals: Putting Infection Control into Context	Rimi, N. et al., 2013	General Wards, Bangladesh	Physical structure and environmental contamination significantly influence infection spread.
7	The association between temperature, rainfall, and humidity with common climate-sensitive infectious diseases in Bangladesh	Chowdhury, F.R. et al., 2018	Hospital, Bangladesh	The findings support a relationship between weather patterns and disease incidence.
8	Assessment of naturally ventilated hospital ward from an infection control perspective using key design indicators	Hegazy, et al., 2019	General Wards, Cairo, Egypt	The study inferred the probability of infection through natural ventilation performance.

3.8.1 Causes for Hospitalizations at Primary Level Hospitals in Bangladesh

Collecting information about the causes of hospitalization is essential in preparing and implementing healthcare policies and tracking the country's healthcare services. Such knowledge is also critical for designing any ventilation strategies for controlling the infection rate in hospitals. Ahmed, S. et al. (2010) conducted a study at primary level hospitals in Bangladesh on the causes of hospitalizations. Of all the causes, diarrheal disease was the leading cause of hospitalization (25.1%), followed by injuries (17.7%) and respiratory tract diseases (12.6%). Over 8% of the hospitalized patients, however, remained undiagnosed. Figure 3-11 presents the percent distribution of hospitalized patients by gender and five leading causes of illness in primary hospitals of Bangladesh, 1997-2001.

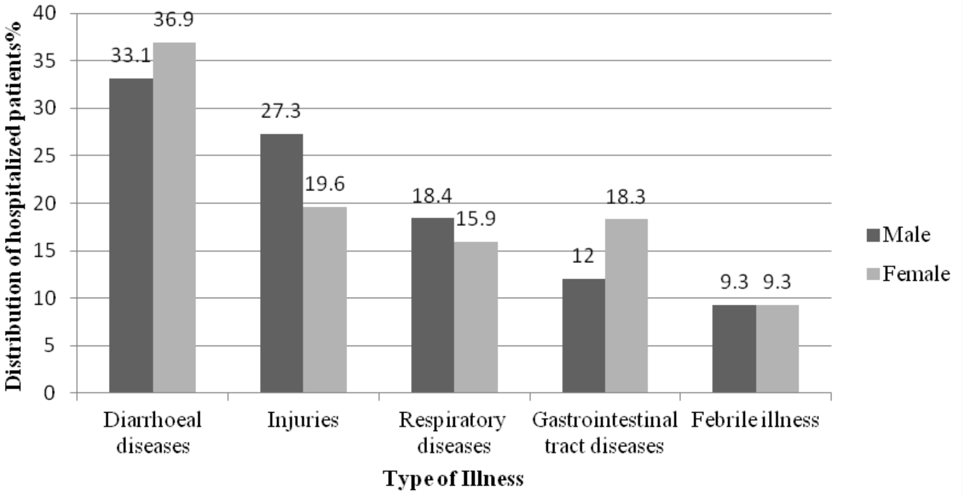


Figure 3-11: Percent distribution of hospitalized patients by gender and five leading causes of illness in Bangladesh (S. Ahmed et al., 2010)

Influenza A is the most common among respiratory diseases in primary hospitals in Bangladesh (ICDDR, 2009). Additionally, seasonal influenza in hospital wards leads to many nosocomial infections. Short-term flu-like fever is a prominent Bangladeshi public health problem usually caused by viruses, most often associated with influenza (Zaman, R. U. et al., 2009). Further, influenza has been seen in many hospital outbreaks, and typically influenza activity happens during the peak annual season (Eibach et al., 2014). This study uses the most common influenza strain, H3N2 (Influenza A), commonly known as seasonal flu.

ICDDR, B, the Institute of Epidemiology, Disease Control and Research (IEDCR) of Bangladesh, and the Centers for Disease Control and Prevention (CDC), United States, collaborated on a report (2009) to expand influenza surveillance in Bangladesh. Findings indicate that influenza is widespread across Bangladesh across all age groups. Epidemics of human influenza occur in Bangladesh, mainly during the rainy season. Figure 3-12 shows the seasonality of influenza in Bangladesh (2007-2008).

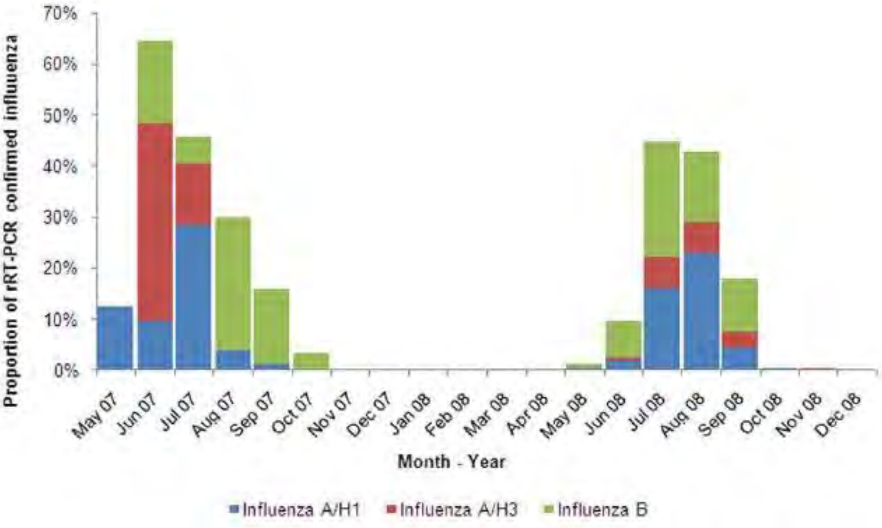


Figure 3-12: Seasonality of influenza in Bangladesh.

Although seasonal influenza has been used as a primary factor for this study, if the recommended ventilation guidelines are not adequate, other diseases transmitted via the airborne route may also be harmful to healthcare settings. Influenza was selected for this study due to the seasonal occurrence of the virus and multiple outbreaks reported in hospitals and significantly impacted people in patients' rooms due to design and ventilation.

When writing this report, no official number of COVID-19 patients admitted to primary care in Bangladesh could be established. However, numerous news sources indicated that many COVID patients had been admitted to various upazilla health complexes.

3.8.2 Risk Assessment Models

Models use some underlying assumptions and mathematics to find parameters for various infectious diseases and use those parameters to predict the future course of an outbreak and to evaluate strategies to control an epidemic (Bernoulli & Blower, 2004). The purpose of building an infection risk model is to help researchers understand the retrospective outbreaks efficiently and help designers optimize the design of health facilities, such as the ventilation system. As a result, energy efficiency and airborne disease control could be achieved simultaneously. Currently, there are two approaches to quantitative infection risk assessment of respiratory diseases, which can be transmitted via the airborne route (Sze To & Chao, 2010): (1) The Wells–Riley model, and (2) The dose-response model. The Wells–Riley model is directly related to the ventilation rate. It is, therefore, an appropriate model for the current study. The following section provided a detailed presentation of the Wells – Riley model.

3.8.2.1 The Wells-Riley Model

Riley and colleagues created the Wells-Riley equation while conducting an epidemiological analysis on a measles outbreak (Riley et al., 1978). The equation is called the Wells-Riley equation since it is based on Wells' (1955) principle of quantum of infection. The Wells-Riley model has been widely used in clinical settings to examine ventilation techniques and their relationship to airborne infections (Escombe et al., 2007). However, this model was created in stages. The Wells–Riley equation was derived as follows:

$$P_I = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \qquad \text{Eq. 3-2}$$

Where P_i is the probability of infection, C is the number of infection cases, S is the number of susceptible, I is the number of infectors, p is the pulmonary ventilation rate of a person, q is the quanta generation rate, t is the exposure time interval, and Q is the room ventilation rate with clean air, typically outdoor air (AIVC, 2016).

The quanta generation rate, q (infectivity), cannot be measured directly but can be estimated epidemiologically from an epidemic case. The existing literature on quanta generation rates (q) is quite limited and varies according to the type of disease and the original epidemiological case study. Published values of q for several infectious aerosols are shown in Table 3-16.

Table 3-16: Quanta generation rates of some common diseases

Disease Name	Quanta generation rates (q)	References
Influenza	15 to ~500 per hour*	(Beggs et al., 2010; Escombe, A. R. et al., 2007; Sze To & Chao, 2010)
Rhinovirus	1 to ~10 per hour	(Rudnick & Milton, 2003)

Tuberculosis	1 to ~50 per hour**	(Beggs et al., 2010;)
SARS	10 to ~300 per hour	(Liao et al., 2005; Qian et al., 2009)
Measles	570 to ~5600 per hour	(Riley et al., 1978)
COVID 19	15 to ~50 per hour	(Dai & Zhao, 2020)

Note: * 67 and 100 per hour are both commonly used **13 per hour has been commonly used

The Wells–Riley equation assumes well-mixed room air and a steady-state infectious particle concentration, which varies with the ventilation rate. The Wells–Riley equation provides a simple and quick assessment of airborne infectious diseases' infection risk. Many epidemic modeling studies have used the Wells–Riley equation as their mathematical models (Gilkeson et al., 2013).

In the Wells–Riley model, the pathogen infectivity described in the rate of quanta generation always refers to the human pathogens' infectiousness. It does not, therefore, require interspecies extrapolation of the infectivity. Besides, this model allows the air change rate or disinfection to be considered in a well-mixed model. Hence, in this study, the Wells-Riley model demonstrated the significance and effect of airborne particle spatial distribution on infection risk.

3.9 Indoor Environmental Parameters for Hospital Wards

Florence Nightingale (1859) initially mentioned the importance of the indoor environment for patient healing and is one of the key issues that health professionals, environmental psychologists, consultants, and architects prioritize (R. S. Ulrich, 1992). The indoor environment controls occupants' thermal comfort infection rates and influences the overall patient outcome (Katz, 2017). In addition, adequately designed ventilation systems can improve patient recovery processes, reduce hospital stays, reduce medical errors and infection rates, and improve indoor air quality (IAQ) (Khodakarami & Nasrollahi, 2012).

In addition, Shajahan et al. (2019) established a positive association between the levels of infection and the parameters related to the indoor environment. Indoor conditions cover various parameters, including (a) ventilation rates, (b) indoor air velocity, (c) indoor temperature, and (d) relative humidity. Each of these will be further expanded in the following pages.

3.9.1 Ventilation Rates in Hospital Wards

The ventilation rate in buildings is the number of times within an hour when a volume of air equal to the volume of a room/building is exchanged with fresh outdoor air. It can be expressed in terms of Air Change per Hour (ach), which is also specified in liters per second (liter/s) or cubic meters per hour (m3/h). The minimum ventilation rate is essential to dilute odors and the indoor CO_2 concentration. To satisfy these requirements, various levels of fresh air are necessary, which is significantly dependent on the occupants' occupation and activity level, which eventually influences the production rate of occupant-related pollutants (Allard & Santamouris, 1998). Memarzadeh and Manning (2000) evaluated the efficacy of a ventilation system with ventilation rates in a typical single-patient room by calculating the various ventilation indices. The results showed that a ventilation rate of 4 ACH provides an adequate condition and can be optimized with 5 or 6 ACH. Moreover, a higher ventilation rate can provide a higher dilution capability and reduce the risk of airborne infections (Menzies et al., 2000).

Air change rate can be defined as the ratio of air supply Q (t) into a room/space relative to the volume of the room/space V. It is generally expressed as air change per hour (ach-1) (Laussmann et al., 2012). The following equation (Eq. 3-6) expresses this definition:

$$\Lambda (t) = Q (t)/V \qquad \textit{Eq. 3-3}$$

Λ (t) is the ventilation rate or air change rate [h^{-1}],

Q (t) is the air supply into a room [m^3/s],

V is the room's volume [m^3], and t = time [s].

Pantelic and Tham (2012) conducted a study that examined the impact of supply flow rate, infectiousness, and exposure time on the airborne transmission model of infectious diseases. The key findings were an increase in supply flow rate up to 3 ACH that rapidly decreases the occupants' infection rate. However, an increase above 6 ACH results in a minor improvement in the defense against occupants' infection. Figure 3-13 shows the result of the experiment.

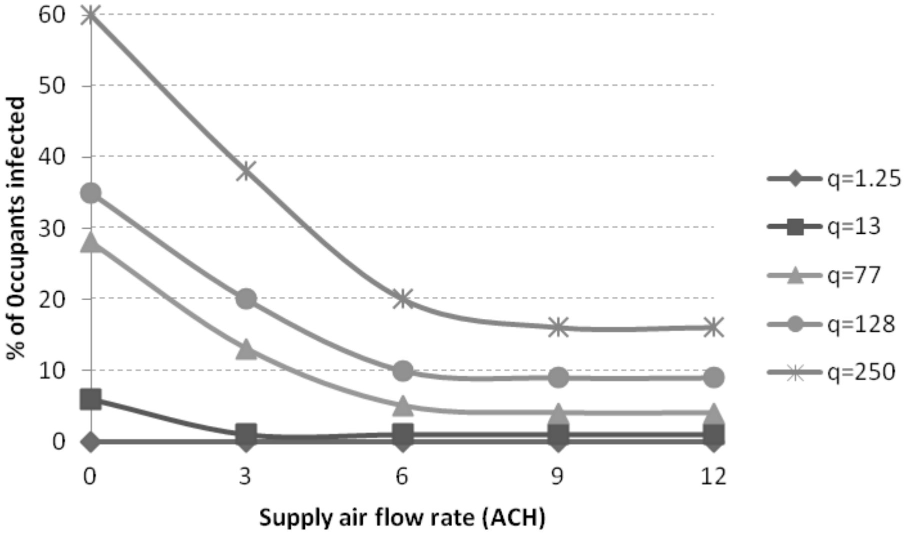


Figure 3-13: Airflow rate and ability to protect occupants from airborne infectious disease transmission (Pantelic & Tham, 2012)

3.9.2 Indoor Air Velocity

There are two different ways air velocity can affect the human body. The first effect is the determination of the convective heat exchange of the body. The second effect influences the evaporative ability of the air and, consequently, the cooling efficiency of sweating (Givoni, 1976). Hence, air movement creates a physiological cooling effect by increasing the evaporation from the skin (Szokolay, 2008).

Furthermore, air velocity is associated with sensible heat released through convection and latent heat released through evaporation, and, therefore, the quality of thermal comfort indoor spaces is influenced by draught (Orosa & Oliveira, 2012). The crucial objective is to ensure a comfortable air velocity at the occupants' body surface, which could be provided through cross ventilation, which depends on the wind effect (Szokolay, 2008). Table 3-17 shows the average subjective reactions, to different air velocities, under normal conditions.

Table 3-17: The subjective reactions to various air velocities (Szokolay, 2008)

Air Speed (m/s)	Subjective Reactions
<0.25	Unnoticed
0.25-0.50	Pleasant
0.50-1.00	Awareness of air movement
1.00-1.50	Draughty
.1.50	Annoyingly Draughty

Moreover, indoor air velocity should not exceed 0.9 m/s in the summer season and should not go below 0.15 m/s during the winter (Orosa & Oliveira, 2012). However, Liping and Hien (2007) state that high air velocity between 0.8-1.2 m/s is often required to attain thermal comfort at midday (11:00-14:00). This is because of the high temperature associated with the noon periods. However, due to the variation in metabolic rates and clothing among patients and hospital staff, a 0.25 m/s or lower local airspeed is considered comfortable and acceptable for occupants (Yau et al., 2011).

However, air ventilation rates are inadequate to monitor the spread of infectious disease within a hospital setting. Along with ACH, the risk of contamination depends on the air velocities and air distribution pattern.

Table 3-18: A summary of recommended indoor air velocity studies

Source	Description/Summary
Givoni (1995)	Direct passive cooling can be achieved only when outdoor air temperature equals or less than 26ºC, and indoor air temperature is more than 26ºC. Airflow rates between the opposite openings are the leading indicators besides outdoor air temperature.
ASHREA (2004)	Thermal comfort can be extended from 26ºC to 29ºC, at an indoor air velocity of 0.7 m/s and up to 33.5ºC, at an indoor air velocity of 1.5m/s as the possible upper limit. Air velocity is the leading indicator in this definition.
Rofail (2006)	Indoor air velocity can decrease the apparent temperature by 1ºC if air velocity equals 3.5 m/s. Thermal comfort is preferable more than uncomfortable air velocity in hot times. every 0.5m/s of air velocity can achieve 2ºC dropping in the apparent temperature
Kang and Carillo (2007)	Comfortable indoor air velocity can be determined based on human skin. Minimum indoor air velocity equals 0.3 m/s. Comfortable indoor air velocity is 1 m/s. Possible maximum indoor air velocity in 1.5 m/s. This maximum value limits air velocity even though thermal comfort needs more than 1.5 m/s.
Zhang, X. (2009)	The indoor velocity of 0.7m/s can achieve acceptable indoor conditions at 29ºC.
Liping and Hien (2008)	Indoor air temperature 34ºC and relative humidity 65%, indoor air temperature 31ºC and relative humidity 90%.
Maarof & Jones (2009)	Continuous air movement is more important than undesirable conditions of air draft, particularly at indoor relative humidity ≥70%.

3.9.3 Indoor Air Temperature

In general, temperature is a measurement of the degree of heat intensity. The human body exchanges heat through heat conduction mechanisms to achieve thermal balance. The body's thermal heat is absorbed by 30 percent convection, 40 percent ultraviolet, 20 percent evaporation, and 10 percent respiration (Ceylan, A., 2011). The word temperature refers to dry-bulb temperature values determined and reported in the shade by meteorology stations. The body temperature is maintained between 36 and 37°C so that the organs do not get damaged and function properly.

According to CIBSE (1997), increased air movement can provide a sense of freshness and enhanced occupant satisfaction with the internal environment, even with similar indoor and outdoor temperatures. However, the thermal comfort requirement for a hospital patient is different from healthy people in terms of temperature (Yau et al., 2011). In the study carried out by Hwang et al. (2007) in the summer season, the preferred temperature for hospital patients is higher than thermal neutrality in 0.4-0.6oC but lower for the healthy people range 0.8-1.0ºC. The comfort perceptions are determined by local conditions, including adaptation to high temperatures and humidity (Mallick, 1996).

Further, the temperature is one of the significant factors influencing the transmission and survivability of microorganisms (Memarzadeh, 2012). The optimum temperature to control the survival of airborne influenza viruses is as high as 30°C at 50% relative humidity (Tang, 2009), which will create an uncomfortable indoor environment as per ASHRAE Standard 55. Through an experimental study, Lowen et al. (2007) concluded that at 20°C, influenza virus transmission is dependent on humidity. However, the transmission was eliminated at a higher temperature (30°C) regardless of relative humidity.

3.9.4 Relative Humidity

In addition to temperature and air movement, humidity is another internal climate characteristic. The amount of water vapor in a given space is called Humidity (Bradshaw, 2006). According to Szokolay (2008), the effects of medium humidity levels between 30 to 65% on comfort is negligible; however, with high humidity levels, the degree of evaporation from the skin and in respiration is restricted, thereby limiting the dissipation mechanism, whereas very low humidity levels cause drying out of the mucous membrane (mouth and throat) in addition to skin, and consequently creating discomfort.

CIBSE guide recommends that the indoor relative humidity for most functions be maintained between 40 and 70%. Even though it is difficult for natural ventilation to control humidity, relative humidity levels in non-air-conditioned buildings will hardly exceed 70%, except a substantial amount of moisture is produced internally (CIBSE, 1997). However, human tolerance to variations in humidity is much higher than tolerance to variations in temperature, but it is also crucial to control humidity in building (Bradshaw, 2006).

Further, evidence has confirmed that relative humidity (RH) influences infection control in hospital buildings because it is linked to the growth and transfer of airborne bacteria. (Balaras et al., 2007). Furthermore, high humidity levels cause moisture to be absorbed in building materials, promoting microbial growth. Humid temperatures can also increase the settling rate of aerosols when heavy droplets become dry and remain suspended in the air for an extended period. (Fernstrom & Goldblatt, 2013). Dry conditions (20% and 35% RH) were also found to be more favorable for the spread of the influenza virus than either intermediate (50% RH) or humid (80% RH) conditions (Lowen & Steel, 2014). Table 3-19 shows how humidity in the air increases a human’s perception of temperature, higher than the actual air temperature.

Table 3-19: Impact of RH (%) on the sensed temperature

Relative Humidity %	**Air Temperature (oC)**						
	21.1	**23.9**	**26.7**	**29.4**	**32.2**	**35.0**	**37.8**
0	17.8	20.6	22.8	25.6	28.3	30.6	32.8
10	18.3	21.1	23.9	26.7	29.4	32.2	35.0
20	18.9	22.2	25.0	27.8	30.6	33.9	37.2
30	19.4	22.8	25.6	28.9	32.2	35.6	40.0
40	20.0	23.3	26.1	30.0	33.9	38.3	43.3
50	20.6	23.9	27.2	31.1	35.6	41.7	
60	21.1	24.4	27.8	32.2	37.8	45.6	
70	21.1	25.0	29.4	33.9	41.1		
80	21.7	25.6	30.0	36.1	45.0		
90	21.7	26.1	31.1	38.9			
100	22.2	26.7	32.8	42.2			
	Sensed Temperature (oC)						

3.10 Design Related Parameters

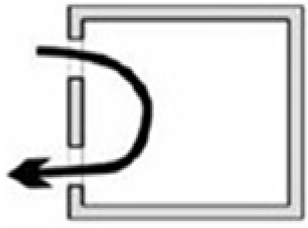
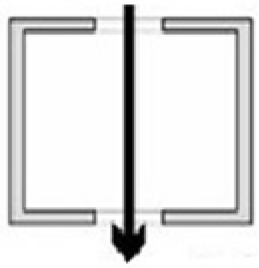
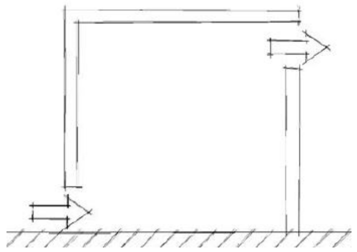
Natural ventilation in buildings may be influenced by several factors, some of which are not regulated by designers, such as outdoor weather conditions and site density. At the same time, some can be addressed through appropriate design. In the current study, the latter are termed “design-related parameters” and explained in this section.

3.10.1 Natural Ventilation Modes

Natural ventilation uses natural forces rather than mechanical systems to drive airflow through space to improve occupants' indoor air quality and thermal comfort and reduce energy consumption. Among the design-related parameters that influence natural ventilation, ventilation mode has the most significant effect (Fung & Lee, 2015). Natural ventilation mode can be defined based on the aperture placements and the ventilation mechanism (Table 3-20).

With regard to the opening configuration in buildings, natural ventilation can be divided into single-sided ventilation, cross-ventilation, and stack ventilation (Awbi, 2003). Single-sided ventilation allows one or more openings to existing on the single side of an enclosed building. At the same time, cross-ventilation occurs when there are openings on two or more sides of a building (Mohammed et al., 2013). Stack ventilation draws fresh and cool air from openings at the bottom of a building and then prompts an outflow through openings at the top.

Table 3-20: Various natural ventilation modes

Single-sided ventilation	Cross-flow ventilation	Stack ventilation
		

The air in single-sided ventilation supplies and exhausts from the same side of the enclosure may not circulate through the whole space. Moreover, from the infection prevention point of view, WHO (2017) does not recommend single-sided ventilation.

The guideline recommends cross-ventilation for infection control over single-sided ventilation.

As elaborated in Section 3.5.3, higher pressure differences result in higher ventilation rates. The pressure difference produced by wind is far greater than the pressure differential resulting from buoyancy and temperature difference (Evola & Popov, 2006). Accordingly, wind-driven ventilation is much more effective than stack ventilation. The current study, therefore, only focuses on wind-driven cross ventilation.

3.10.2 Building Height

The main challenge associated with natural ventilation design in high-rise buildings is the higher pressure differences created by wind and buoyancy due to the higher heights (D. Etheridge, 2011). Wind speed and wind pressure both increase with building height, resulting in a building experiencing a more comprehensive pressure range across the façade (Ilgin & Gunel, 2007). The wind pressure loading on a building varies significantly with height, with upper levels experiencing higher wind pressure loads than lower levels. Figure 3-14 illustrates a schematic of the atmospheric boundary layer showing the correlation between wind speed and height.

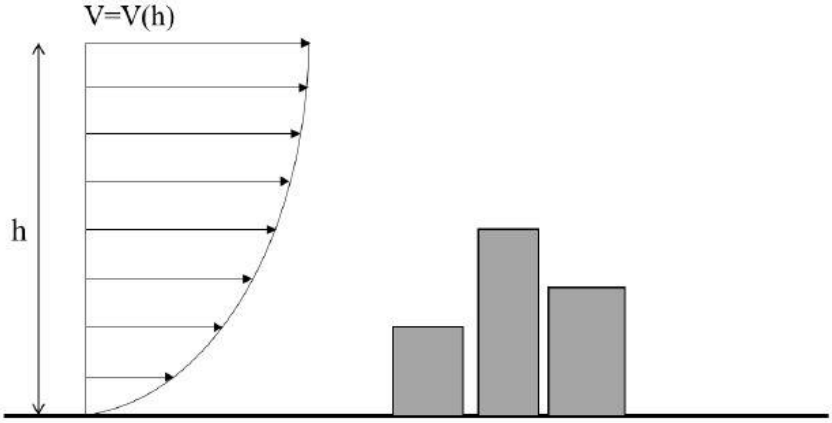


Figure 3-14: Schematic atmospheric boundary layer profile

The current study only discusses low-rise health care facilities. Besides, building height issues have not been addressed.

3.10.3 Orientation

The orientation of the building in terms of wind direction greatly affects the efficiency of natural ventilation. Building orientation indicates the direction faced by the room's external elevation, and its choice is determined by many considerations, including the view in all directions, the location of the buildings relative to the nearby access road, the topography of the site, the location of the source of noise, and the nature of the climate (Givoni, 1976).

The maximum pressure on the windward side of the building is produced when the elevation is at right angles to the wind direction, so it seems obvious that, in this case, the greatest indoor air velocity is obtained (Szokolay, 1980). However, in Figure 3-15, case b would generate a higher velocity along the windward faces. As a result, the wind shadow will be much larger, and the negative pressure (suction effect) will rise, resulting in increased indoor airflow.

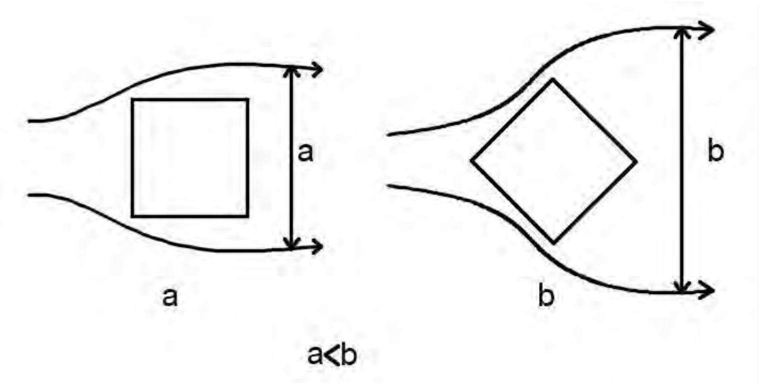


Figure 3-15: The effect of direction on the width of the wind shadow

Studies have established that building indoor air velocity is higher in cross-ventilated cases than other ventilation types (Bangalee et al., 2014). Givoni has observed that wind incidence at 45° would increase the average indoor air velocity and provide a greater distribution of indoor airflow. However, Mohammed M. A. (2015) confirmed in his study that the average indoor airspeeds for wind flow with an oblique angle of attack to the openings (30° and 60°) are higher compared to the cases with perpendicular (90°) angle of attack.

3.10.4 Openings

Among the design-related parameters, the effect of the openings on natural ventilation is perhaps one of the most studied areas. Openings in buildings are generally classified into purpose-provided (ventilation) and adventitious (infiltration) openings. Any type of purposefully installed openings to provide ventilation, such as air vents and openable windows, are called Purpose-provided openings. On the other hand, the adventitious openings are not purpose-provided due to component openings such as gaps in openable components and background openings such as envelope cracks (D. W. Etheridge & Sandberg, 1996). Bangalee et al. (2012) have studied the effect of surrounding structures and the number and configuration of the openings on a cross-ventilated building. The findings show experimentally and numerically that the opening size and location significantly impact the indoor airflow rate of naturally ventilated buildings. The study also suggested that openings in hot and humid regions should be placed according to the prevailing breeze to flow through the internal space.

Liping et al. (2007) claim that ventilation and indoor air quality can be improved by increasing the window to wall ratios (WWR), but it would also increase solar heat gain. They claimed that the optimum window to wall ratio equals 0.24, and horizontal shading devices are needed for the four orientations to improve indoor thermal comfort, especially for large windows.

3.10.4.1 Inlet and outlet openings positions

Tecle et al. (2013), in their study, showed a comparative analysis for the relationship of the inlet to outlet openings in high and low wind velocity. Under high wind conditions, the width of the inlet opening is greater than the width of the outlet opening. However, in low-wind conditions, the width of the inlet opening is less than the width of the outlet opening. Moreover, the center locations of the inlet and the outlet openings are desirable because the wind velocity is higher at central locations.

Moore (1993) showed how adjacent opening locations could create different airflow paths in his study. Best conditions were attained when the two openings were located in the farthest corners of the room.

3.10.4.2 Relative vertical level of inlet and outlet openings positions

The relative vertical level of the inlet and outlet openings plays an important role in cross-ventilation. Staggered openings in both horizontal and vertical levels at the oppositely facing sides create longer airflow paths than the facing openings (Rizk et al., 2018). Thus, these longer airflow paths of staggered openings help achieve thermal comfort by directing airflow paths for human activities (direct passive cooling). According to the vertical level, the best case of the staggered openings is attained when the inlet opening is at the lower level and the outlet opening at the upper level of the leeward side. In contrast, in this case, a horizontal level is attained when the inlet and outlet openings are at the different corners of the oppositely facing sides. Figure 3-39 shows the staggered openings, and Figure 3-39b shows the facing openings. The staggered openings can achieve an average indoor air velocity of 35% of wind velocity less than the facing openings that can achieve an average indoor air velocity of 50% of wind velocity, as studied by Givoni (1976).

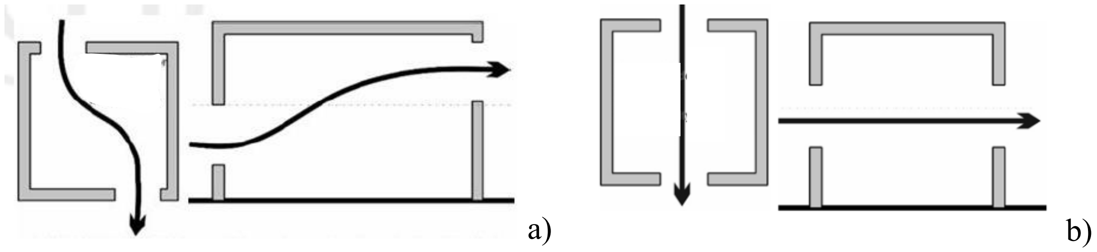

a) b)

Figure 3-16: a) Staggered openings, b) Facing openings (Rizk et al., 2018)

Karava et al. (2011) investigated the inlet and outlet openings' relative vertical level. The average indoor air velocity was higher in the aligned cases than in the staggered cases, as shown in Figure 3-17. The average inside air velocity was 60% of the wind speed, which is more suitable for high wind speeds. The average indoor air velocity for the staggered cases, on the other hand, was 35-45 percent of the wind velocity, which makes it appropriate for areas with low wind velocity.

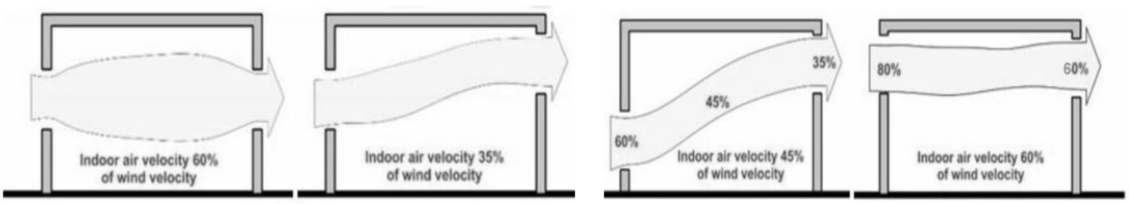


Figure 3-17: The effect of the relative vertical level of the inlet and outlet openings

3.10.4.3 Relative aperture sizes

Table 3-21 illustrates the effect of inlet and outlet sizes in cross-ventilated spaces. The size of the openings can change the average indoor air velocity. In their study, Kang and Carillo (2007) demonstrate that the inlet to outlet openings width ratio and the size of the openings can change the average indoor air velocity from 30% to 50% of wind velocity.

Table 3-21: Effect of inlet and outlet sizes in cross-ventilated spaces

Inlet opening width to outlet opening width	Average indoor air velocity (% of wind speed)	Maximum indoor air velocity (% of wind speed)
1/1	36	65-102%
1/2	39	92-131%
1/3	44	137-152%

The opening size controls the ventilation rate and air velocity within the interiors. Inlet and outlet openings should have nearly equal dimensions to maximize the airflow rate (WHO, 2009). Therefore, the present analysis considered only the inlet and outlet of the same size for the various simulation studies.

3.10.4.4 Balcony

Balconies are another façade design component that might impact a building's natural ventilation effectiveness. Balconies are a common architectural element in tropical climates, serving as a private outdoor space while potentially improving internal air flow (Sara Omrani et al., 2015). They analyzed parameters such as balcony type (open and glazed balconies, Figure 3-18), balcony depth, ventilation mode, wind angle, and orientation. This study verified that an open balcony achieves a higher indoor air velocity than a semi-enclosed balcony and that the balcony depth decreases the air velocity.

Several recent studies emphasized that access to balconies is one of the most desired architectural features and stressed that this architectural archetype could increase the inhabitants' satisfaction and perception of livability in cities. Moreover, the current COVID-19 crisis highlighted this collective will to have a private outdoor space in dwellings (Ribeiro et al., 2020). Further pointed out that balconies significantly influence indoor air movement, increasing internal air velocity. Izadyar et al. (2020) experimented with investigating the effect of balcony provision on pressure distribution on the building façade. They found wind pressure distribution alters on the windward side but not significantly on the leeward side, and provision of the balcony would increase wind pressure in most cases they studied. According to many studies, a balcony can significantly transform the airflow pattern inside and outside buildings. It was proved that the presence of a balcony could improve natural ventilation on the indoor ambient, increase thermal comfort, and consequently reduce the need for mechanical ventilation and, therefore, reduce the energy consumption in buildings (Z et al., 2011). This effect is particularly relevant in humid tropical climates where comfort conditions in the buildings can be achieved by attaining sufficient interior air velocity and increasing the uniformity of indoor air distribution.

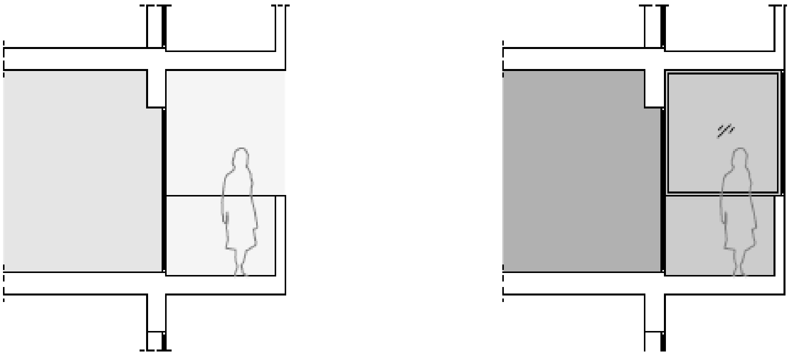


Figure 3-18: Open balcony & glazed balcony (Ribeiro et al., 2020)

3.11 Ventilation Prediction and Performance Evaluation Tools

Proper assessment and prediction methods are requirements for successfully implementing natural ventilation in the building design. Efficient provision of natural ventilation to buildings will save energy and resources compared to mechanical ventilation due to low maintenance costs and zero energy consumption (Aynsley, 2014). However, the projection of the natural ventilation performance of buildings can be challenging due to the complex physics involved and the integration of optimal results into the early design phases (S. Omrani et al., 2017). Effective methods should also be used to test the ventilation efficiency of the building during the design process. Several methods are available for the prediction and evaluation of natural ventilation performance. The appropriate method(s) must be chosen based on the project resources, requirements, and design stages. These methods are presented in the following sub-sections.

3.11.1 Computational Fluid Dynamics (CFD) and Experimental Method

Many approaches for natural ventilation studies have been identified during the literature review process. The majority of the publications reviewed for this study used CFD combined with experimental measurements. This combined approach is used for three key purposes: 1) to illustrate the data obtained from the experiments and to test different parameters; 2) to provide insight into flow physics that is not readily attainable by experiments, and 3) to verify the CFD model in order to include it in other related studies.

CFD simulation models can provide researchers with comprehensive information on indoor environment design parameters such as air velocity, temperature, airflow patterns, volumetric flow rate, turbulent intensity, and other characteristics that can be easily and accurately obtained from these parameters. CFD models are recommended as a cost-effective solution to indoor environment design. CFD solves the governing Navier-Stokes equations to directly solve the fluid dynamic properties governing airflow movement (Srebric, 2011).

Validating CFD results against experimental data increases accuracy and reliability. Tracer gas techniques are among the most popular full-scale experiments in natural ventilation studies. CFD study will provide accurate airflow information relative to experimental point results (Mohammed, 2015). Table 3-22 presents some studies on opening parameters with CFD and experimental methods.

Table 3-22: CFD and experiments methods

Parameters	Researchers
Opening size and configuration	(Shetabivash, 2015)
Ventilation type	(S. Omrani et al., 2018)
Building orientation	(Gough et al., 2019)
Facade design	(Aflaki et al., 2015)
Openings with mosquito net	(Mohammed et al., 2014)

The reviewed literature demonstrates that CFD is the most commonly used method for evaluating and predicting natural ventilation performance. CFD provides a validated numerical model from which further, more detailed analysis can be derived.

3.11.2 The Percentage Dissatisfied (PD) with Ventilation

The percentage dissatisfied (PD) expresses the occupant dissatisfaction with the vertical air temperature difference. The first step in designing any natural ventilation system is determining the quantities of airflow required to meet indoor air quality and thermal comfort (CIBSE, 1997). That is attributable in most standards and guidelines to the correlation between indoor air quality and the necessary ventilation level. As a substitute, ventilation rates are specified for different categories of space and occupation (B. W. Olesen & Olsen, 2004). This is because the primary use of ventilation is to satisfy indoor air quality requirements, which is the basis for determining minimum air change rates (CIBSE, 1997). Figure 3-19 illustrates the level of dissatisfaction caused by a standard person at different ventilation rates. In the present study, the relationship between indoor air quality dissatisfaction level and ventilation rates in Figure 3-19 was employed to determine the occupants' dissatisfaction with different ventilation rates obtained in the simulation results.

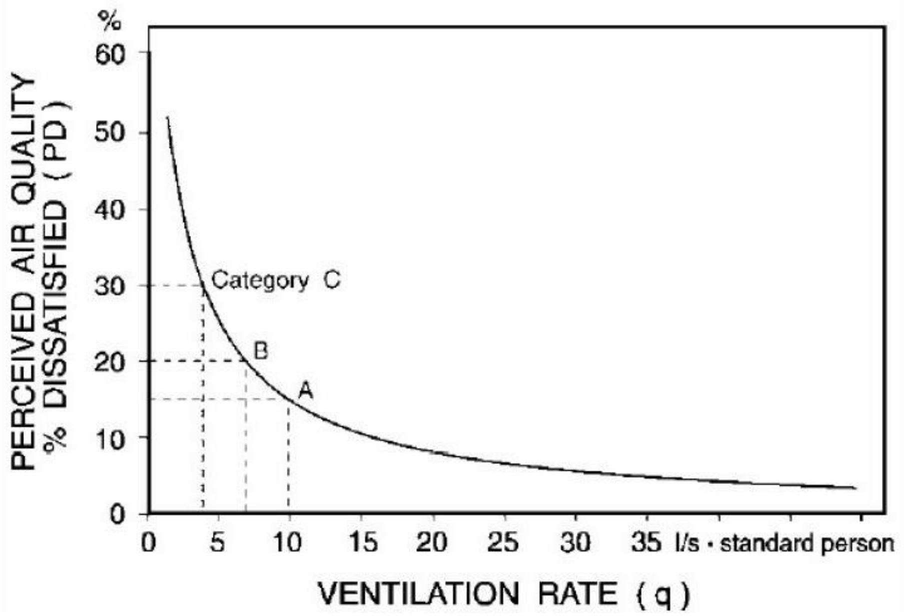


Figure 3-19: Dissatisfaction caused by a standard person at different ventilation rates (B. W. Olesen & Olsen, 2004)

3.11.3 The Draught Risk Model of Air Velocity

According to ISO 7730:2005, the draughts create an unwanted local cooling in the human body. Fanger and Pedersen had found in 1977 that a fluctuating air velocity is felt more uncomfortable than a constant velocity. The study demonstrated that humans dislike velocity fluctuations, whether periodic or occurring in the random manner typical for a turbulent flow. The risk of airflow can be expressed as a percentage of annoyed persons and calculated using Eq. 3-4. The draught risk is lower for non-sedentary activities and individuals with neutral thermal sensation conditions (Orosa, 2010). In the present study, the equation (Eq. 3-4) was used to evaluate the draught risks of simulated cases.

$$DR= (34-t)\ (v-0.05)0.62(0.37vT_u+3.14) \qquad \textit{Eq. 3-4}$$

Where v is the air velocity (m/s), t is the air temperature (ºC), and T_u is turbulence intensity (%)

3.11.4 Indoor Ventilation Conditions Assessment Criteria

The knowledge of the distribution of air velocities within ventilated space is equally important as the overall airflow within that space when assessing ventilation for human comfort. The evaluation of ventilation in indoor space requires quantitative assessment criteria. These criteria, as employed in various studies as collected by Hegazy et al. (2019), include the following:

a) Ventilation Rate - Number of Air Changes per Hour (ACH)

b) Airflow direction

c) The average speed at occupancy level (at about 1 m above the floor)

d) The average turbulent intensity of air at any point in the space

e) Infection Control Risk Model

3.12 Ventilation Guidelines, Codes, and Standards in Hospital Wards

Several organizations are responsible for guiding the design of healthcare facilities worldwide. Unfortunately, the Bangladesh National Building Code (BNBC) does not have specific guidelines for naturally ventilated hospital wards. The AIA and

ASHRAE work as the basis for health building design in various locations. The comparison of the various guidelines for these organizations is shown in Table 3-23.

Table 3-23: Comparison between guidelines and codes used in the hospital wards

Code	Country	ACH	Min. avg ventilation rates	Pressure Relationship	Design Air Temp (°C)	Design Relative Humidity (%)	Air Velocity m/s
AIA	USA	6	NS	Neutral	21-24	NS	NS
MHRA	Europe	6	60	Neutral	18-28	30-60	NS
ASHRAE	USA	6	60	Neutral	23-27	30-60	0.15-0.8
HTM 2025	UK	NS	NS	Neutral	20-22	40-60	-
WHO	UN	6	60	Neutral	NS	NS	-
CIBSE,	UK	4-6	50	NS	-	40-70	-
ENV	Singapore	6	-	NS	22.5-25.5	< or = 70%	0.25-0.8
DOSH	Malaysia	5	-	NS	22-28	44-79	>1

*NS= Not specified

3.13 Chapter Conclusion

The literature review is generally performed to provide the necessary information and consideration considerations in conducting any research work. This chapter introduces and discusses the general background of natural ventilation and various factors influencing thermal comfort and infection in hospital wards. In developing countries with limited resources, the application of open multi-bed wards dominates the hospital environments.

Natural ventilation as a passive cooling system has numerous advantages, such as energy-saving, infection control, and thermal comfort. On the other hand, there are limitations, such as limited control. Despite the limitations, it is a feasible solution, especially for resource-limited tropical climates. However, there are minimal regulations in the building codes and standards regarding the practical application of natural ventilation in hospital wards in the tropics. The available codes focus more on minimum ventilation requirements with no specific requirements for infection control in hospital wards. The literature survey found that no particular research was performed on Bangladeshi hospital wards. However, other studies have shown that the thermal comfort zone (Dhaka) is 24-32°C.

In addition to the climatic-driven forces such as wind, natural ventilation is influenced by a range of design features, including ventilation mode, building height, the design of openings, and internal obstacles. Natural ventilation, therefore, can be improved by the appropriate integration of these design features. Among the design-related parameters, the opening design has been extensively explored, while ventilation mode and orientation of the opening can benefit from more in-depth investigations. Besides, there is a lack of holistic models that connect different design features in a single chart that can be used as a guideline for the natural ventilation design of hospital wards in the tropics.

In this chapter, the previous studies on natural ventilation and indoor air quality have been presented, which helpfully identified knowledge gaps in ventilation and infection control studies in hospital wards of the tropics. The effect of ventilation rate in buildings has been discussed. It has been established that reduced ventilation rate in buildings, especially in hospital wards, enhances the probability of airborne diseases such as influenza and rhinovirus. Moreover, the various prediction models on infection control and ventilation in hospital wards and their limitations have been presented. Thus enhancing the ventilation rates in the hospital wards suggests improving infection control.

Thermal comfort is an appropriate criterion for assessing natural ventilation performance. The extended PMV and SET* indices are deemed suitable for this purpose. A comfort model reasonably predicts thermal conditions in naturally ventilated buildings is needed.

The study identified various ventilation guidelines/standards applicable to patients' rooms in a hospital environment. Both AIA and ASHRAE required that the minimum total air change rate of 6-ach-1 be provided in patients' rooms or hospital wards. In this study, these criteria will be applied in ascertaining the performance of different natural ventilation strategies. It has been established that air change rates, airflow direction, and airflow patterns are the key factors influencing ventilation performance in buildings. Moreover, the indoor ventilation condition assessment criteria, including airspeed at inlet openings, the maximum airspeed at any point in the space, average airspeed in the space, and occupancy level, have been identified and used in the analysis of the results.

The strategies for assessing indoor environmental conditions in buildings have been presented and discussed, including ventilation rates/air change rates, indoor air temperature, indoor air velocity, and adaptive comfort based on thermal neutrality.

The study determined an adaptive thermal neutrality temperature of between 24.2oC in the wet season and 29.2oC in the dry season is required to achieve thermal comfort indoors. The effect of draught in the study area is insignificant because, in naturally ventilated buildings in hot climates, indoor airspeed regularly extends from 1 to 2 m/s.

Furthermore, the literature review also assisted in identifying and analyzing different ventilation prediction models. The CFD modeling approach with full-scale measurement was selected for the purpose of this study due to its numerous advantages over the other approaches.

CHAPTER FOUR

PHYSICAL, ENVIRONMENTAL, AND SOCIAL ASSESSMENT OF THE CASE STUDY HOSPITAL WARD

Chapter Structure

4 CHAPTER FOUR: PHYSICAL, ENVIRONMENTAL AND SOCIAL ASSESSMENT OF THE CASE STUDY HOSPITAL WARD

4.1 Introduction

The literature review was presented in the previous chapter (chapter 3). In this chapter (chapter 4), the selected hospital ward's physical, environmental, and psychosocial perception has been examined and analyzed. This chapter's findings link hospital occupants' experiences and actual hospital wards measurements to ventilation and infection control problems identified in the literature. It is achieved by evaluating the chosen hospital's current condition through physical observation, environmental evaluation, and psychosocial interpretation.

The chapter (chapter 4) was designed to respond to objective number 1 (one). The first part of the chapter, which describes the existing hospital ward's design parameters, was intended to respond to research objective 1 (one): **"*To investigate the nature of existing ventilation systems used in hospital wards in Dhaka.*"**

4.2 Selection of the Case Study Ward

In Bangladesh, primary health care includes UHC, MCWC, UHFWC, CC, and government-registered private hospitals. Except for CC, all categories of hospitals were chosen at random and analyzed for this study. HED is the department that undertakes the construction of the primary level of health facilities such as UHC and CC. HED undertakes all the work for UHCs and CCs, such as designing, construction tender, and maintenance. Plans of studied UHCs were collected from HED, Dhaka head office (see Appendix L).

The majorities of primary hospitals are two-story buildings, naturally ventilated, and have a single-sided corridor in general. Further, most of the UHC hospitals are prototypical. The MCWC and UHFWC rooms were not completely furnished, and the equipment was in poor condition in some situations. There was a shortage of basic services, such as water and power. The toilets were unsatisfying. As a result, they were not considered for this study.

Because of its ease of access, SHMH, Manikganj, was selected as the base case in this study as it also represents the naturally ventilated primary hospitals of Bangladesh. SHMH, like every other private hospital, naturally ventilated prototypical floor plans with single-sided corridors. Rooms were completely furnished with basic services. The tracer gas test was performed only on this ward since the authority approved permission to move the admitted patients while the test was being performed. The date and time of these measurements were dependent on the availability of access from the management of these hospitals. Table 4-1 shows some studied hospital wards with some basic information.

Table 4-1 Investigated primary level hospital wards with their basic information

S/N	**Investigated Multi-Bed Ward Parameters**	**Multi-Bed Wards and Evaluations**					
		UHC Puthiya, Rajshahi	**UHC Poba, Rajshahi**	**MCWC Kaliganj, Gazipur**	**UHC Saver, Dhaka**	**UHC Mohonpur, Rajshahi**	**SHMH, Manikganj, Dhaka**
1.	Ward Floor Area	66.33 m2	59.22 m2	54.81 m2	68.56 m2	63.59 m2	53.17 m2
2.	Ward Shape and Form	Rectangular Flat	Rectangular Flat	Rectangular Flat	Rectangular flat	Rectangular Flat	Rectangular Flat
3.	Ward Level	First Floor	GN Floor	GN Floor	GN Floor	GN Floor	GN Floor
4.	Ward Height	3 m	3.1 m	2.9 m	3.1 m	3 m	2.91 m
5.	Ward Orientation	North-south	North-south	North-south	North-south	North-South	North-South
6.	Number of windows & type	4 nos Sliding	3 nos Sliding	4 nos Sliding with High window	4 nos Sliding with High window	7 nos swing	4 nos Sliding
7.	Ward Window size	1.82m x 1.30m	1.77m x 1.31m	1.80m x 1.29m	1.50m x 1.31 m	.76m x 1.31 m	1.82m x 1.30m
8.	Ward openable window area	5.5 %	5.82 %	6.15 %	5.09%	8.68%	4.12%
9.	Number of doors	3	1	2	2	1	2
10.	Ward Occupancy	12 Beds	10 Beds	8 beds	10 beds	10 Beds	10 Beds
11.	Occupant density	5.52 m2/person	5.92 m2/person	6.85 m2/person	6.84 m2/person	6.35 m2/person	5.31 m2/person
12.	Ward Balcony Orientation	South	South	South	South	South	South
13.	Ward Balcony Depth	1.80m	1.50m	1.80m	2.10m	2.20m	2.06m
14.	Conveniences	No	No	Yes	Yes	Yes	Yes
15	Images						

4.3 The Physical Properties of the Existing Hospital Wards

The information about a hospital ward's physical properties is significant in studying their indoor air quality and ventilation. This is since the knowledge of building parameters, such as general outdoor and indoor physical parameters, multi-bed ward parameters, opening characteristics, furniture characteristics, building components, and ventilation systems, help to link the fundamental problems of indoor air quality, ventilation, and infection to their causes and consequences.

4.3.1 Selected Hospital Building Parameters

The general outdoor and indoor physical parameters of the selected hospital in the study area have been documented. These parameters include the number of storeys, surrounding vegetation, building density, and existing ventilation type. The selected case-study hospital was a low-rise building. The studied multi-bed ward in the SHMH was located on the ground floor level with a balcony like a corridor in the entrance. Balconies are essential as a sun-shading device in buildings. The hospital ward has vegetation cover in its surroundings. This vegetation cover is important in changing the microclimate of the surroundings and shields the wards from dust.

The density of the selected hospital was isolated from the surrounding buildings. Furthermore, the hospital's ventilation system was natural ventilation assisted by ceiling fans to enhance air circulation when needed. Table 4-2 shows various building parameters characterizing the selected hospital in the study area.

Table 4-2: The building parameters of the selected hospitals in the study area

S/N	Building Parameters	SHMH
1.	Number of storeys	2
2.	Availability of Balcony/corridor	Yes (depth is 35% of the width of the ward)
3.	Surrounding vegetation	Trees & open fields
4.	Building Density Nearby	More than 50m
5.	The existing type of ventilation	Natural with ceiling fan assisted

4.3.2 Hospital Multi-Bed Wards Parameters

The planning and design of multi-bed hospital wards differ from one hospital to the other, depending on the type and requirement of the hospital. Moreover, one of the significant factors of consideration while designing hospital wards is the type of patients to be accommodated. The shapes and forms of the studied ward were rectangular with flat wall surfaces and the floor areas around 53.17 $m^{2,}$ as illustrated in Table 4-3. The ward shape is usually determined by the building's general shape where the ward was situated, and a studied hospital building was rectangular in shape. Furthermore, the hospital ward investigated was linked to a larger building. In terms of story heights, the investigated hospital ward of SHMH is located on the ground floor.

Moreover, the investigated hospital multi-bed ward was oriented toward the North/South direction and the floor to ceiling height of 2.91 m. The hospital ward where the measurements were conducted has been marked with dotted lines in Figure 4-1. The North-South orientation in the wards is probably adapted to benefit from the south-easterly monsoon wind that is usually moderate and comfortable. The North-westerly trade wind is cold and dusty (Islam, M. M. et al., 2015). However, it can provide enough ventilation to remove indoor air pollutants. This type of orientation will also assist in controlling solar radiation by the openings on the North and South façade. The interior spaces in the ward investigated had no partitions.

Furthermore, the investigated hospital multi-bed ward had no indoor staircase to suggest vertical air movement between spaces. However, there was a space allocated to nurses within the ward. Conveniences (toilets) are an essential consideration in designing and planning hospital multi-bed wards. The benefit of placing toilets inside ward spaces is easy accessibility, while if not properly handled, the downside is odor. The toilets in the investigated multi-bed wards were situated within the wards' space.

The number and design of the access in and out of the multi-bed ward are essential and are usually planned according to the occupancy and type of patients to accommodate these wards. In SHMH, there were two exits, as shown in Figure 4-1. Besides, in SHMH, the number of beds was ten, as shown in Table 4-3. This considered only the number of patients' beds with no provision for the families and staff of the ward. In addition, for SHMH, the occupant densities in the ward were 5.31 m2 / person. According to ASHRAE Standard 62, occupant density for health care is 9.29 m2/patient.

Table 4-3: The building parameters of the selected multi-bed wards

S/N	Multi-Bed Ward Parameters	Multi-Bed Wards and Evaluations
1.	Investigated ward floor area	53.17 m2
2.	Investigated Ward Shape and Form	Rectangular Flat
3.	Isolated or space within a building	Linked to buildings
4.	Investigated ward level	GN Floor
5.	Investigated ward height	2.91 m
6.	Ward orientation	North-south
7.	Internal partitions	No partition
8.	Staircase inside the ward	No
9.	Nurses area	yes
10	Doctors room	no
11.	Utility rooms	No
12.	Conveniences (toilets)	Yes (at one side)
13.	No of access and entrance Lobby	2(from the toilet & nurse station) corridor)
14.	Investigated ward occupancy	10 Beds
15.	Occupant density	5.31 m2/person

The multi-bed ward studied includes only female general wards in hospitals, as illustrated in Table 4-4 and Table 4-5 and Figure 4-1 to Figure 4-3.

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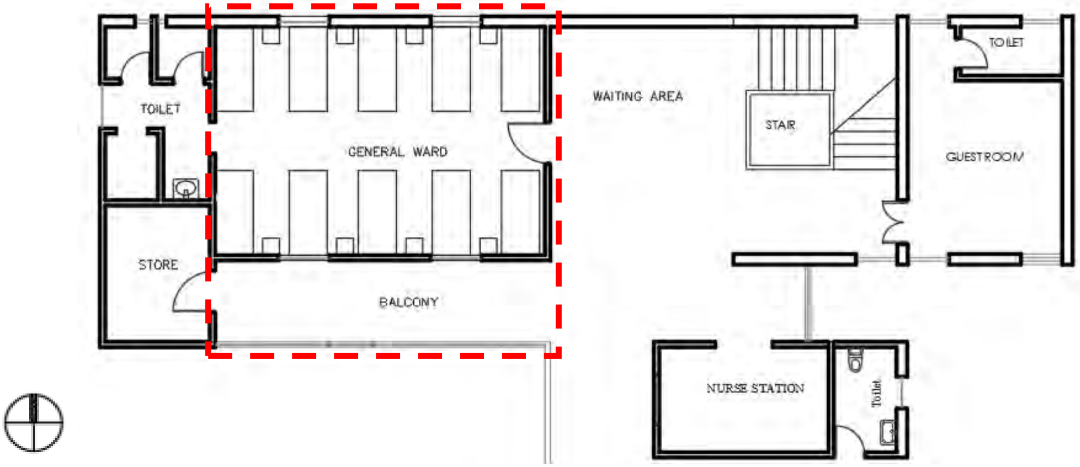


Figure 4-1: The part plan of Sahera Hasan Memorial Hospital (SHMH)

Table 4-4: The surroundings of SHMH

North *(4 story building)*	*South* *(Open courtyard)*	*East* *(Connected to the main building)*	*West* *(Trees)*
			

Table 4-5: The images of SHMH

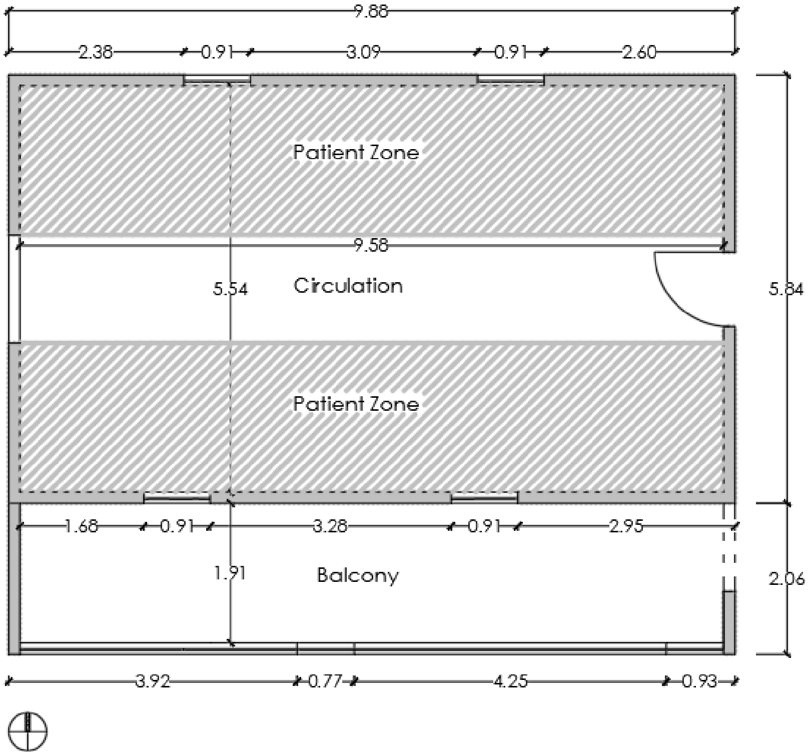
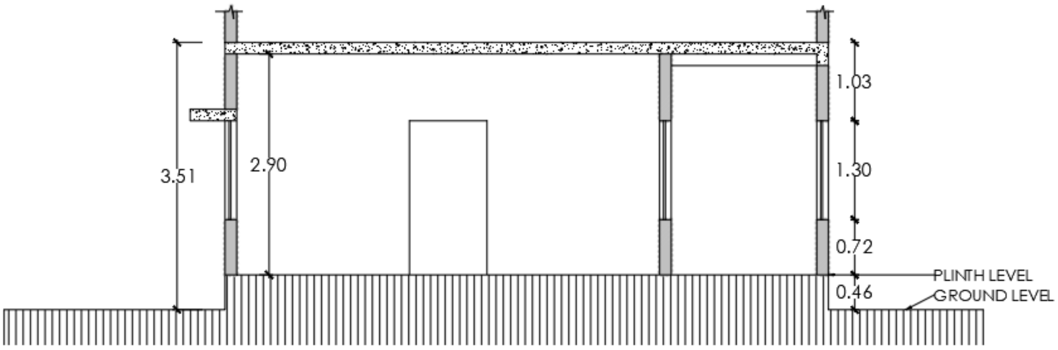
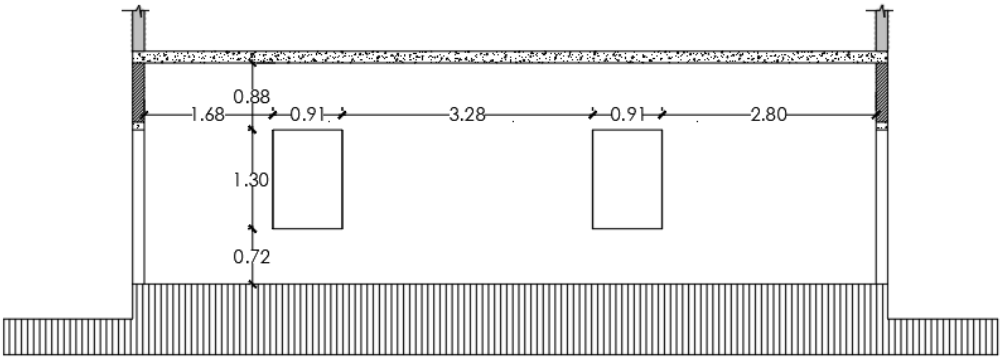


Figure 4-2: Plan showing opening positions of the ward



SECTION aa



SECTION bb

Figure 4-3: Showing section aa and section bb of the ward

4.3.3 The Characteristics of the Multi-bed Wards Openings

The study of the various characteristics of openings is used to analyze their compliance with ventilation rate requirements. The nature, size, and type of openings such as windows and doors are important when designing natural ventilation and improving indoor air quality in buildings. The number of windows in the investigated multi-bed ward was 4 for SHMH. Two on the windward side and two on the leeward side. The efficiency of these windows in providing the required natural ventilation and improving the indoor air quality will only be determined by measuring the ventilation rate in the buildings. However, these windows were all sliding. The disadvantage of sliding windows is that it only provides a 50% operable area for direct airflow into the buildings. The sizes of these windows were equal with roughly North-South orientation, as shown in Table 4-6.

All the windows used in the selected hospital's ward were flat rectangular windows made of single glazing with aluminum frames. Furthermore, no high-level windows were present. The number of entrance doors to the chosen hospital was two. One door was linked from the outside and the other to the toilets. In addition, the door materials used in these hospitals are made of wood and steel frames. Both these doors were single rectangular swinging with a height of 1 m x 2.1 m. The curtain materials used for these openings are made of polyester and cotton. Table 4-6 displays in-depth the opening features of the multi-bed wards.

Table 4-6: Multi-Bed ward openings characteristics

S/N	Multi-Bed Ward Opening Parameters	SHMH
1.	Number of windows	4
2.	Type of Windows	Sliding windows
3.	Size of Windows	1.82 m x 1.30m
4.	Forms and Materials of Windows	flat Aluminum frame glazed windows
5.	High-level windows	No
6.	Number of Doors	2 (from toilet & corridor)
7.	Type of Doors	Single wooden door
8.	Size of Doors	1m x 2.1m
9.	Forms and Materials of Doors	Flat timber and wood
10.	Types and Materials of Curtains	Cotton
11.	Types and Materials of Netting	No Netting

"Natural ventilation shall be through windows, doors, louvers, or other approved openings to the outdoor air with ready access to and controllable by the building occupants" International Code Council Inc., (2009). The existing hospital ward in the study area were typical rectangular wards with windows in the longer perimeters, as illustrated in Figure 4-2. The window system used in the hospitals examined was sliding windows. According to the International Mechanical Code (IMC), "The minimum openable area to the outdoors shall be 4% of the floor area being ventilated, and when the openable area is provided through adjoining rooms, the openable area must be >8% of the floor area of the interior room". However, based on the findings obtained from the examined existing hospital ward, the International Mechanical Code standard for operational areas has been met, with a window operating area of 8.89 percent, as shown in Table 4-7.

Table 4-7: Window area with the hospital ward's floor area of SHMH

S/N	Area	Opening type	Floor Area	Opening Area	Effective Ventilation Area	Operable Area %
1	Patient Ward	Sliding	9.88m X 5.84m = 57.7m2	0.91m X 1.30m X 2	2.37 m2	4.12%
2	Balcony	Fixed glass	9.88m X 2.06m = 20.35m2	0.55m X 1.30m X 2	1.43 m2	7.02%

4.3.4 The Furniture Characteristics of the Multi-bed Wards

Furniture in buildings remains among the significant contributors of contaminants in the indoor environment because they emit certain chemicals such as Formaldehydes, Volatile Organic Compounds (VOC), and harmful dust in higher concentrations. The major types of furniture obtainable in the hospital ward include beds and chairs. Furniture types obtainable in the hospital ward studied include steel frame steel beds, steel and timber chairs, and timber side tables, as shown in Table 4-8.

Table 4-8: Multi-Bed ward furniture characteristics

S/N	Multi-Bed Ward Furniture	SHMH
1.	Furniture Types	Steel bed and side table
2.	Number of Beds	Ten beds
3.	Material and type of waiting for chairs	Wooden/plastic

4.3.5 The Building Components of the Multi-bed Hospital Wards

The wall type used in the multi-bed ward was a flat vertical masonry wall characteristic of local structures, and the ward's masonry material was brick walls with a plastered surface. There was no insulation in the walls.

The flooring system used in the hospital under investigation was reinforced concrete floors with tile finishing. Tile skirting was not used in the SHMH hospital at the interior meeting point of the wall and flooring system. The type of ceiling used in multi-bed hospitals includes a plastered ceiling. The colors of these ceilings were white. Table 4-9 shows the various components of the multi-bed ward and their characteristics.

Table 4-9: Various components of the multi-bed wards and their characteristics

S/N	Multi-Bed Ward Ceiling	
01	Type ceiling	RCC Ceiling with plaster
02	Ceiling color	White
03	Ceiling shape/form	Flat/Square
04	Ceiling skirting	No
	Multi-Bed Ward Floor	
01	Types of floor finishing	Tile floor finishing
02	Type of floor tiles	Matt
03	Tiles shape and form	Flat rectangle
04	Tiles color	Cream
05	floor Skirting	No Skirting
	Multi-Bed Ward Wall	
01	Wall type	Normal flat Masonry wall
02	Walling Material	Brick wall
03	Wall shape and form	Flat vertical
04	Type and color of paint	Milk color emulsion

4.3.6 The Ventilation Parameters of the Studied Multi-bed Wards

The ventilation system in the selected multi-bed hospital wards was natural ventilation through windows. The windows were sliding windows with steel burglaryproof bars. Natural ventilation from windows was supported by ceiling fans. The characteristics of the ventilation system have been shown in Table 4-10

Table 4-10: Multi-bed ward ventilation parameters

S/N	Multi-Bed Ward Ventilation	SHMH
01	Natural Ventilation	Windows
02	Hybrid Ventilation	Fans and windows
03	Ceiling Fans	8 nos

4.4 Environmental Properties of the Existing Hospital Wards

According to the ASHRAE Handbook of Fundamentals (ASHRAE, 2011), the patient room should have a minimum Air Change Rate (ACR) of 6 ach-1. The maximum relative humidity of 60% and a design temperature of 21ºC to 24ºC have been recommended. Between 2nd December 2020 and 4th December 2020, the studied hospital ward's indoor and outdoor temperature (Figure 4-5) and relative humidity were measured. The date and time of these measurements depend on the availability of access from hospital management. The results showed that the measured ward's indoor temperature was an average of 24.6ºC. Indoor temperatures were slightly cooler than outdoors. Nevertheless, the relative humidity measurements were average 70%, as illustrated in Figure 4-5

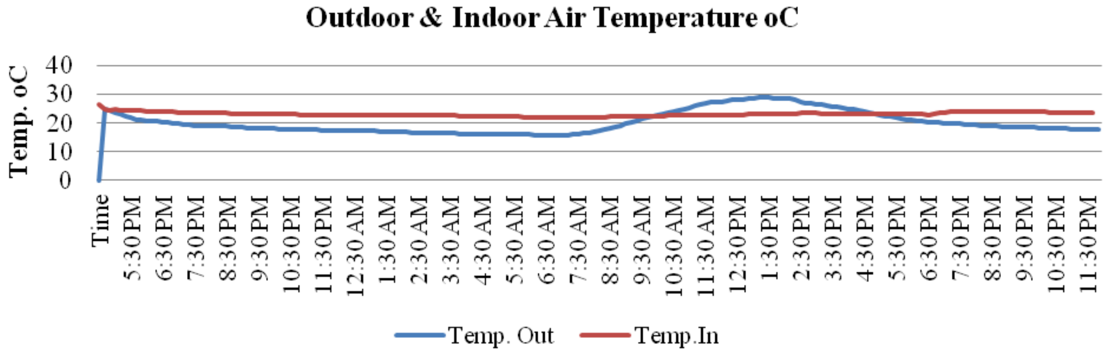


Figure 4-4: The measured indoor and outdoor temperature ^{0}C

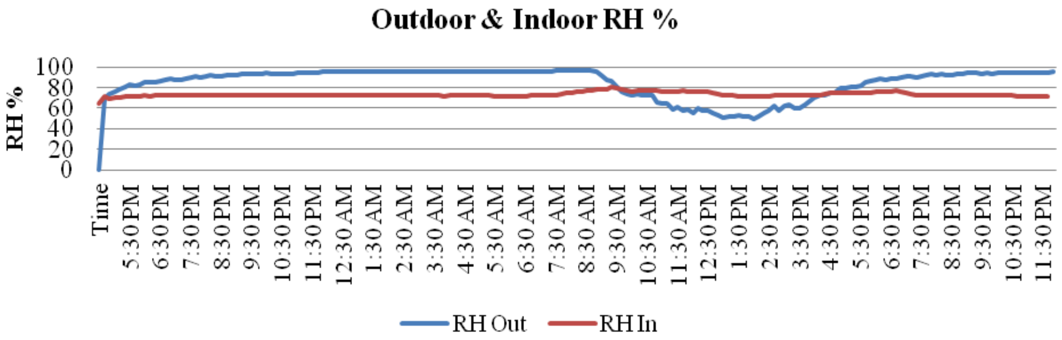


Figure 4-5: The measured indoor and outdoor RH

4.5 Questionnaire Survey Result Analysis

4.5.1 Introduction

The survey method used in this research is a cross-sectional survey in which the data or responses were collected at one point in time. This form of survey typically includes data that are quantifiable. A self-administered questionnaire was used to collect data, and the questionnaire was physically presented to potential respondents. Since the questionnaire is aimed at a specific group of healthcare workers who regularly work in multi-bed wards, this data collection method was chosen for convenience.

The survey was conducted within a selected hospital. The respondents, who are medical doctors, nurses, and other healthcare workers, were selected based on whether they worked in a multi-bed ward or not. Thus, the questionnaire was given to only those respondents that frequently work in the multi-bed wards within the studied hospital. The major objective of the questionnaire is to understand indoor air quality and ventilation within multi-bed hospitals from perceptions of the immediate users of the facility (see Appendix A). The responses from patients were not collected since their health condition might influence their perception of air quality and thermal comfort (Mohammed, 2015). The total number of healthcare workers (HCW) in the selected hospitals is 30, and a total of 20 people responded. Thus, the total response rate for the hospital is 67%, presented in Table 4-11.

Table 4-11: The Questionnaire response rates

Parameters	SHMH
Number of HCW the hospitals	30
Number of responses	20
Response rates	67%

The first step in the questionnaire design was identifying the survey's topics. These topics were deduced from the 'literature review' chapters, including indoor air quality, ventilation, thermal comfort, and infection, which are the significant factors of consideration when designing hospital wards. The second step in designing a questionnaire was the choice of open-ended or closed-ended questions. In this study, closed-ended questions have been used. The respondents used closed-ended questions such as 'Yes or No' to select precise options. Finally, the questions were written using simple and precise language to ease the respondents' understanding and comprehension. The questionnaire survey results were analyzed based on simple statistical techniques, including frequency of occurrence and percentages, and the results were presented using tables and graphs.

4.5.1.1 Age distribution

Figure 4-6 illustrates the age distribution of the entire data sample. The largest percentage of responses (45 %) was represented by the age group of 20-29 years, whereas the smallest percent of respondents (10 %) was from the age group of 50-up years. The rest of the 30-39 years and 40-49 years accounted for 25% and 20%, respectively.

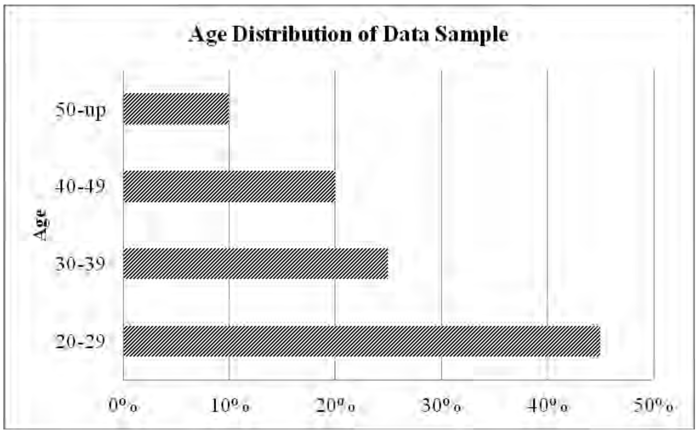


Figure 4-6: Age distribution of data sample

4.5.1.2 Gender distribution:

Figure 4-7 shows the gender distribution of the entire data sample where 80% (16 responses) and 20% (4 responses) responses were collected from female and male respondents, respectively.

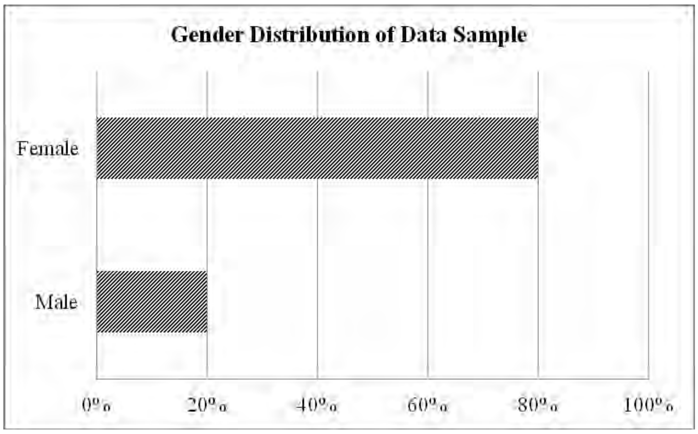


Figure 4-7: Gender distribution of entire data sample

4.5.1.3 Distribution according to Departments:

Among the wards under different departments, only multi-bed wards of the studied hospital were surveyed. Among the 20 responses, 8 (40%) were from the general ward, 9 (45%) were from the female ward, while the rest of 3 (15%) were from ICU. the number of respondents from the female ward was higher than the other wards. Figure 4-8 exhibits a detailed distribution of respondents between these wards.

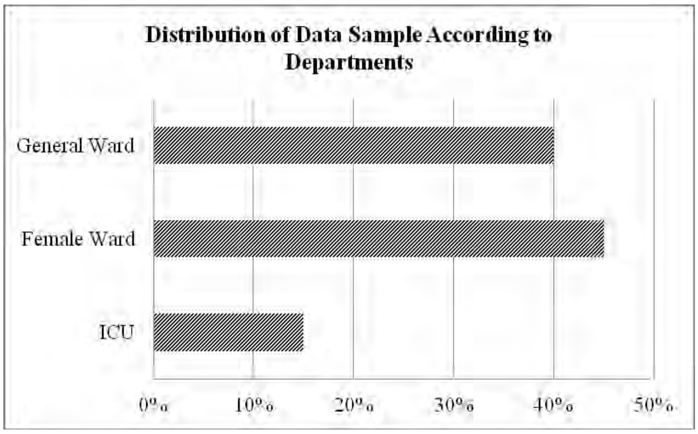


Figure 4-8: Distribution according to departments

4.5.1.4 Distribution according to rank:

The total number of health care workers (HCW) in the chosen hospital is 20. Doctors are 20% (4 respondents), nurses are 70% (14 respondents), and staff is 10% (2 respondents), as shown in Figure 4-9.

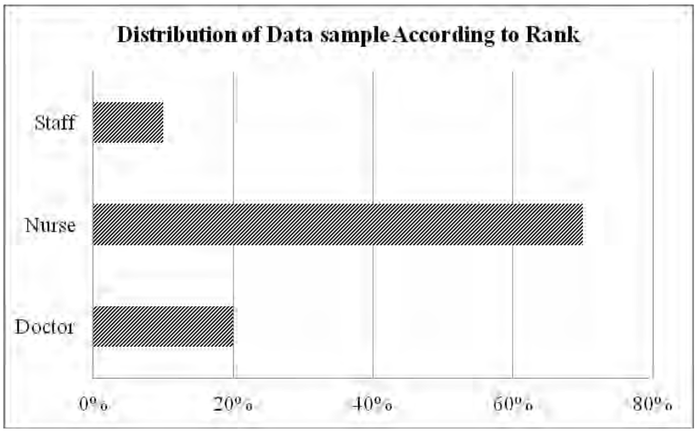


Figure 4-9: Distribution according to rank

4.5.2 SBS (Sick Building Syndrome) Consideration:

SBS (Sick Building Syndrome) is a condition where the inhabitants of the concerned buildings repeatedly express a complex range of unclear and often subjective health complaints, which are often linked with poor indoor air quality. When the medical doctors, nurses, and other healthcare workers in the selected hospital surveyed were asked, ***"Do you often experience the following symptoms inside the ward?"*** about 88% responded that they had any symptoms related to Sick Building in the Ward shown in Figure 4-10.

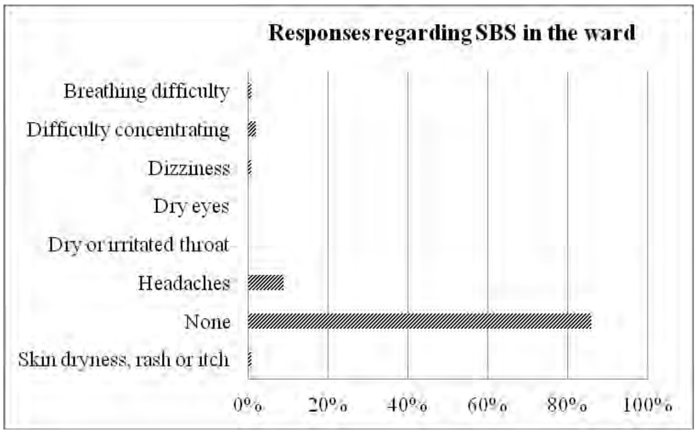


Figure 4-10: Responses regarding SBS in the ward

4.5.3 Indoor Air Quality (IAQ) Consideration

The level of air quality in the hospital environment has a substantial effect on the concentration of pathogens in the air. Subsequently, it dictates the rate of airborne infectious diseases obtainable indoors (Ulrich et al., 2008).

When the medical doctors, nurses, and other healthcare workers in the selected hospital surveyed were asked, ***"Have you ever considered indoor air quality as a***

problem in the wards?" about 85% responded that they do consider indoor air quality as a problem, and the remaining 15% said they do not consider IAQ as illustrated in Figure 4-11.

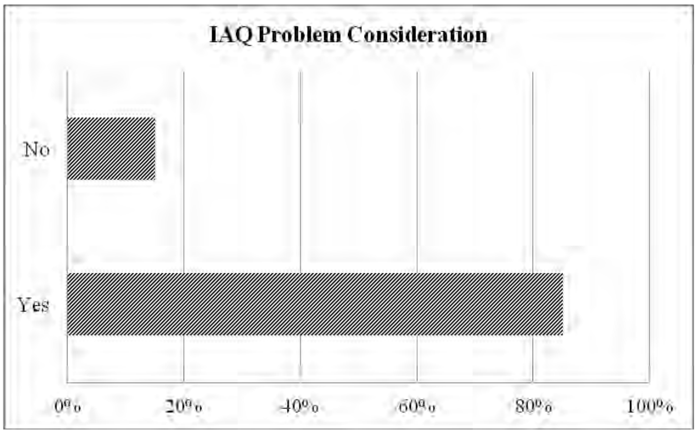


Figure 4-11: IAQ problem consideration in works

The consideration of indoor air quality in hospital wards in warm-humid climates results from so many factors as deduced from the outcome of the survey.

Table 4-12: Frequency of responses for IAQ considerations in a hospital ward

S/N		Frequency of responses
	Reasons for IAQ Consideration	
1.	Inadequate Ventilation (High temperature, stuffiness, discomfort, CO2 concentration)	6
2.	Congestion and overcrowding, e.g., Inadequate bed spacing	3
3.	Odour/smell/ Stinking due to infected wounds, patient properties, toilets	11
4.	Spread of pathogens in the form of airborne disease or respiratory droplets and HCAI	1
5.	Affects patients' health, especially respiratory conditions (Asthma, Hypothermic consequences, Delay healing)	2
6.	Lack of stable electricity	4

4.5.3.1 Experience of Smell and Odour in the Wards

Smell or odor in a shared environment like that of multi-bed hospital wards is usually a result of many factors. When the respondents were asked, ***"Do you usually experience some smell or odor in the wards?"*** about 83% said they usually experience some smells or odor in the hospital wards. The remaining 17% said they do not (Figure 4-12).

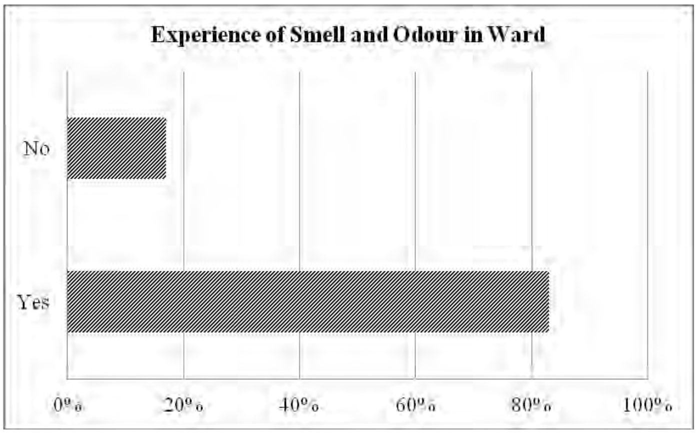


Figure 4-12: Experience of smell and odour in ward

Generally, smell and odors in a hospital environment and especially multi-bed wards result from many reasons, either from the building fabric, patient body, disinfectants, or inadequate ventilation. Apart from the accumulated patients' properties, dustbins, disposed waste, and food remnants in the wards also constitute another odor source. Moreover, the smell from dirty toilets and odors from various chemicals used in the wards contribute immensely to indoor air contamination. Table 4-13 shows various factors responsible for the smell/odor in the hospital wards studied.

Table 4-13: Reasons for smell and odors in the hospital multi-bed wards

S/N		Frequency of responses
Reasons for Smell and Odors		
1.	Toilet odors	7
2.	Wounds (Infected, septic, offensive, Burns, traumas, cancers, Infected operations, orthopedic cases, Debilitating ailments, Ulcers, and Bedsores)	2
3.	Chemicals (Disinfectants, Antiseptic, Medications)	8
4.	Dustbins/disposed waste /Food Remnants	8
5.	Congestion and Overcrowd (Patient bed spacing)	5
6.	Human Waste (Patient body, secretions, Spilling of blood, blood products, body fluids)	2

4.5.3.2 Indoor air contaminants sources within and around wards

Airborne pathogens in healthcare environments originate from diverse sources, mainly from staff, patients, and visitors within the hospital building (Ulrich et al., 2008). When the respondents were asked, ***"Do you recognize some indoor air contaminants sources within/around the wards?"*** about 78% said that they usually see some contaminants source within and around the hospital wards, and the remaining 22% do not recognize any contaminant sources (Figure 4-13).

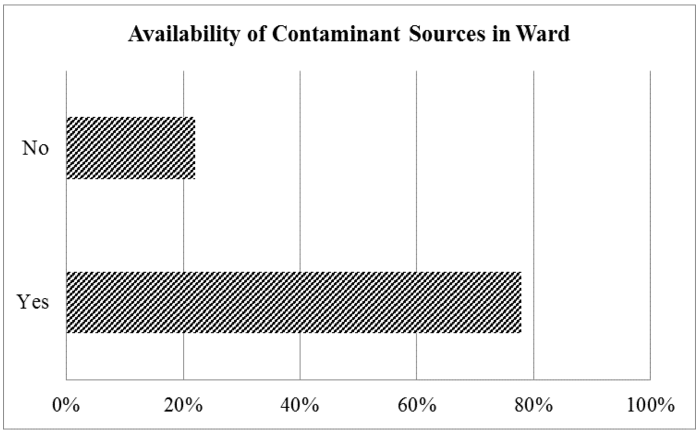


Figure 4-13: Availability of contaminant sources in ward

According to Ulrich et al. (2008), significant among the contaminant sources are environment-related factors, including toilets, pollutants in the surrounding environment, and waste disposal areas such as dustbins and incinerators when un-emptied. The smell and odor from patients' leftover food in the studied ward, mainly due to the lack of enough storage within the hospital wards, also contribute to the contamination of the indoor environment. Sources of contaminants in the hospital multi-bed ward in the study area are presented in Table 4-14.

Table 4-14: Sources of contaminants in multi-bed wards in the study area

S/N		Frequency of responses
Sources of Contaminants		
1.	Toilets	8
2.	Contaminants around the wards (Improper disposal of waste Within and Around the wards, poor sewage/drainage system, soak-away, and Patients Foods remnants)	6
3.	Dustbins/Waste Bins/incinerators	7
4.	Wounds (Dirty/undressed, infectious, septic, Uncasing Masses, Soiled Linen)	1
5.	Direct body smells and Human waste such as Bloods/body fluids/Un-emptied blood cloths, e.g., secretions	3
7.	Patients' bedsides and food leftovers (properties due to lack of enough storage)	6

4.5.4 Thermal Comfort in The Wards

The level of thermal comfort in indoor spaces in the study area has been an issue of concern due to the high temperatures in summer and the climatic context of the area. When multi-bed health care workers were asked about their thermal comfort satisfaction, ***"Are you comfortable with thermal comfort (temperature and humidity) in the ward?"*** More than 75% were not satisfied with thermal comfort in the hospital ward surveyed, as shown in Figure 4-14.

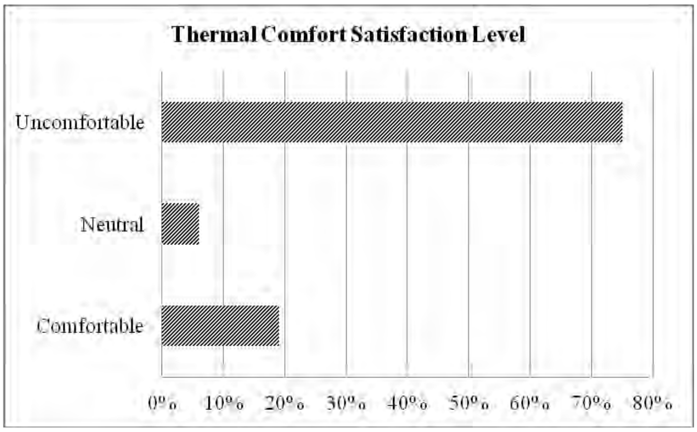


Figure 4-14: Thermal comfort satisfaction level in the ward

4.5.4.1 Draughtiness

The intensity of draughtiness in any space is determined by wind speed, temperature, and humidity level. The level of draughtiness in the hospital wards of the study area depends mainly on the season of the year. When the respondents were asked, ***"Is the ward draughty?"*** 30% said they feel draughtiness in the multi-bed wards, while the other 65% said they are not Figure 4-15.

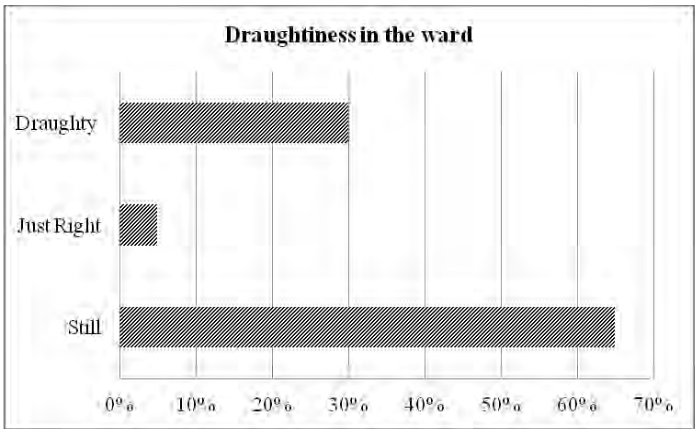


Figure 4-15: Draughtiness in the ward

4.5.4.2 Humidity

Relative humidity is the quantity of water vapor obtainable in the air at any given time in an environment. However, the survey outcome was conducted to ascertain the perception of hospital ward users about the level of relative humidity when the respondents were asked, ***"Is the ward humid?"*** The result shows that about 55% of the respondents said the wards are humid, while the other 35% said the wards are not humid, as illustrated in Figure 4-16.

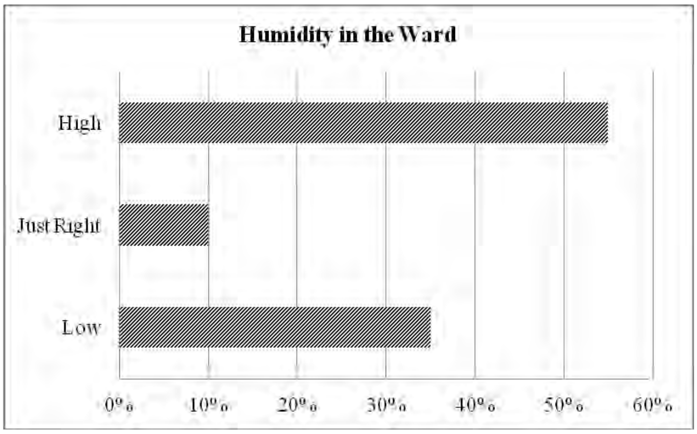


Figure 4-16: Humidity in the Ward

4.5.5 Ventilation in the Wards

The ventilation system in the studied multi-bed ward was hybrid, a combination of natural ventilation through the windows and ceiling fans. When the respondent to the questionnaire survey conducted in the hospital of the study area was asked, ***"What is the nature of the airflow in the ward space?"*** about 60% said the airflow is fairly good, 25% said not so good, and the remaining 15% said the airflow in the wards is good (Figure 4-17).

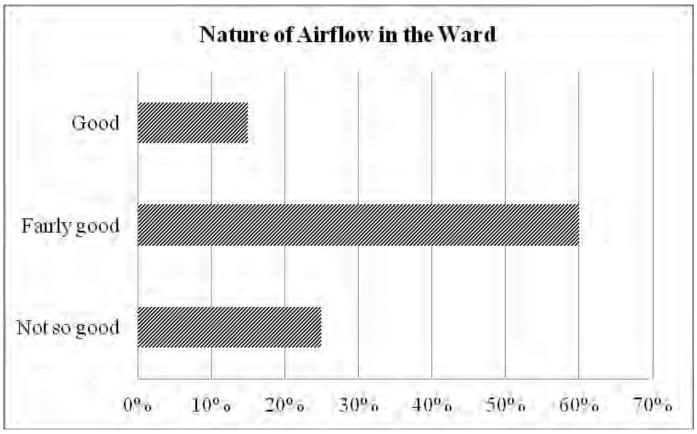


Figure 4-17: Nature of airflow in the ward

The level of air pollution in an environment is associated with various health concerns. When the respondents to the survey, including medical doctors, nurses, and other healthcare workers, were asked, ***"Have you experienced any cases of deterioration inpatient health due to indoor air quality problems in the wards?"*** About 90% said they had experienced such a situation Figure 4-18.

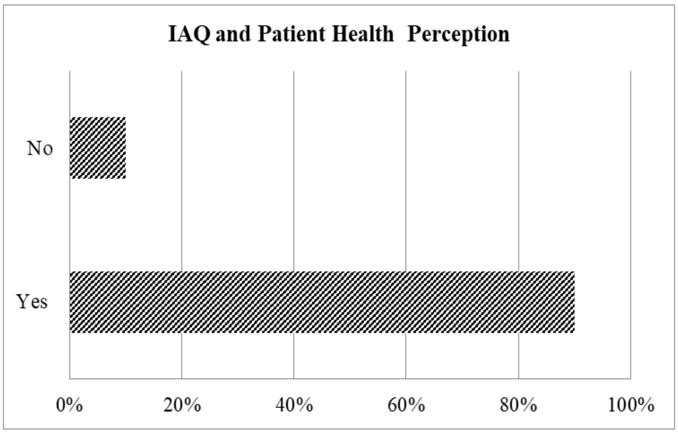


Figure 4-18: IAQ and patient health deterioration perception

4.5.6 Infection Control Measures in the wards

Cleaning is one of the most basic measures for infection control and is particularly important in the hospital environment. The principal aim of cleaning is to remove visible dirt. When asked the survey respondents, including doctors, nurses, and other healthcare staff, ***"How would you describe the cleanliness of the ward?"*** About 55% responded that they were satisfied with the cleanliness of the ward (Figure 4-19).

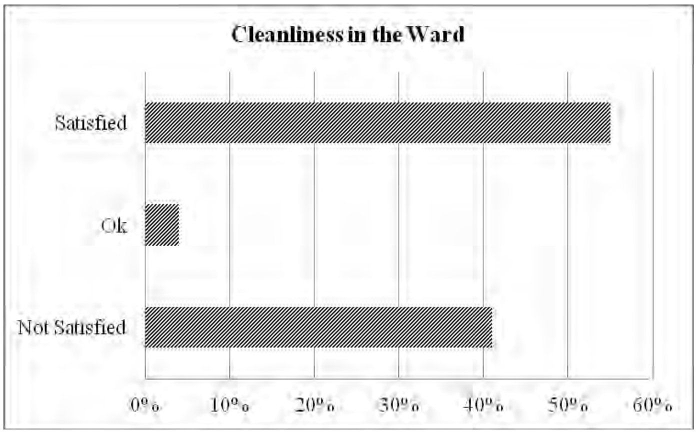


Figure 4-19: Satisfaction level of cleanliness in the ward

Opening windows and doors maximizes natural ventilation so that the risk of airborne contagion is much lower (Escombe et al., 2007). When asked the survey respondents, ***"What are ward's window conditions for most of the time?"*** In response to the inquiry, 90 percent of windows were closed at night, and 60 percent were open during the day. (Figure 4-20).

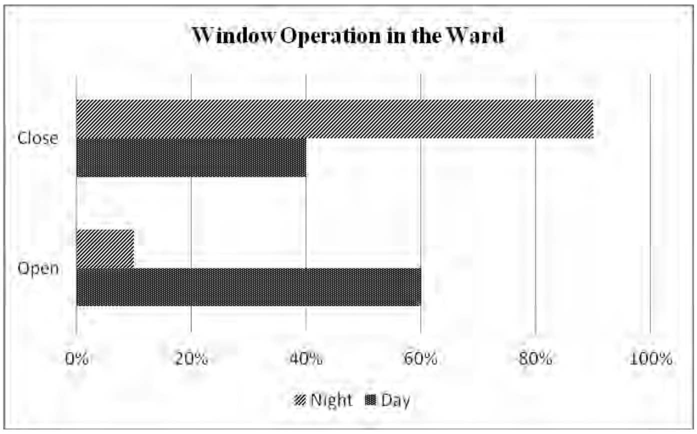


Figure 4-20: Window operation in the ward

Ward overcrowding is associated with a higher prevalence of infectious diseases among patients (Virtanen et al., 2011). Ward overcrowding is determined by bed occupancy for each ward with their attendants and staff. The study found a significant interaction between overcrowding and the overall rate of infectious diseases. When asked the survey respondents, ***"What is the average number of attendances per patient in the ward?"*** about 90% responded that the average attendant per bed is one, where 10% said two or more attendants per bed (Figure 4-21).

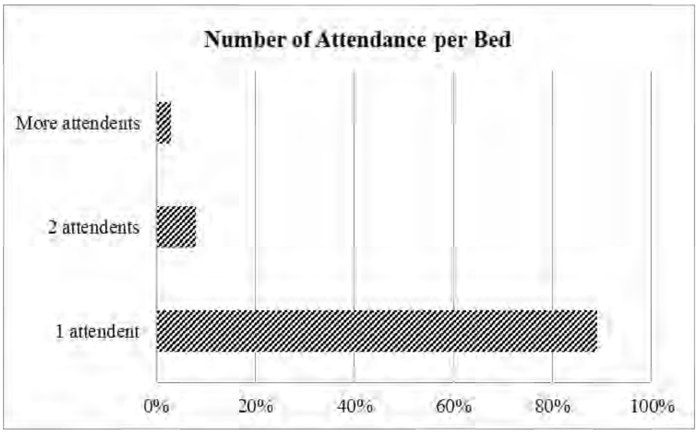


Figure 4-21: Number of attendances per patient in the ward

4.5.7 Indoor Air Quality and Patients Health

When the respondents to the survey, including medical doctors, nurses, and other healthcare workers, were asked, ***"Do you think the overall indoor ward condition has an impact on patient smooth recovery?"*** about 70% responded that they had perceived a direct relationship between improved indoor air quality and patients' smooth recovery. In comparison, about 10 percent said there were no effects of the overall ward condition on patient recovery smoothly Figure 4-22.

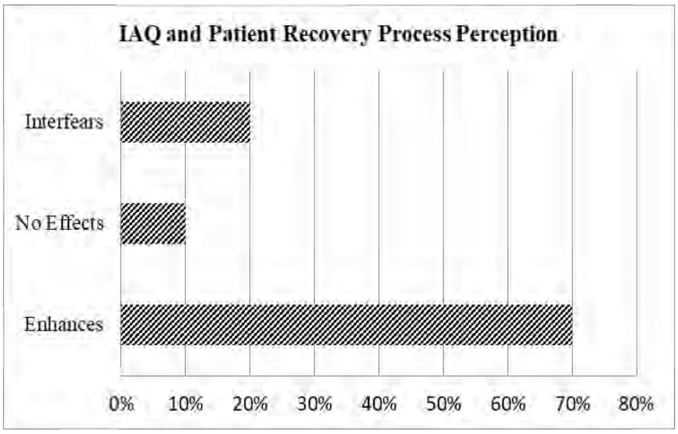


Figure 4-22: IAQ and patient health deterioration perception

4.6 Discussion

The questionnaire survey considered five (5) different indoor environmental conditions, including indoor air quality consideration, thermal comfort, ventilation efficiency, infection prevention measures, and the effect of indoor air quality on health. The result shows that 85% of the respondents consider indoor air quality problems in hospital wards. Moreover, due to the poor indoor air quality in the studied hospital ward, 83% of the respondents experienced odor problems with the hospital wards. This constraint is likely caused by inadequate ventilation and will be solved by optimizing the ventilation system by increasing the amount of air change per hour. According to the survey, the major consequences of this inadequate ventilation include; high temperature, stuffiness, discomfort, and CO2 concentration, mainly due to inadequate fans, lack of doors, and windows in the wards. From the survey outcome, the third motive for IAQ consideration is a lack of stable electricity in the study area, which leads to reliance on natural means for ventilation and IAQ control. The fourth prominent factor for IAQ consideration was congestion and overcrowding of patients and their relatives in the multi-bed wards. Congestion problems will be solved by adopting existing codes and standards regarding the relationship between the ward floor areas and allowing the number of beds. The fourth likely motivator for indoor air quality consideration among medical doctors, nurses, and other healthcare workers is the fear of the spread of pathogens in the form of airborne disease or respiratory droplets and Healthcare-Associated Infections (HCAI) within the multi-bed wards. This problem will be solved by providing enough ventilation in the multi-bed wards.

In terms of thermal comfort and ventilation, 75% of the respondents are not satisfied with the thermal comfort in the hospital wards. However, 15% of the respondents said the ventilation is good, 60% said the ventilation is fairly good, and the remaining 15% are not satisfied with the ventilation in the hospital wards. Besides, 55% of respondents found the problem of closing windows during the daytime, which increased the risk of infection. Finally, 20% of the respondents have experienced deteriorating patients' health due to an indoor air quality problem, while the remaining 70% did not experience it. Thus, the above conclusions confirmed the existence of ventilation and indoor air quality problems in the studied hospital wards.

4.7 Chapter Conclusion

This chapter presents the existing hospital wards' physical, environmental, and social assessments. The chapter also assessed and analyzed the physical properties of the studied hospital ward and provided the required information to be used as input in the subsequent part of this study. The chapter also presents the environmental parameters of the existing ward, including temperature and relative humidity measurement in the existing hospital ward, to underpin subsequent assessment steps of natural ventilation inwards, including full-scale measurements and CFD modeling.

The survey results show that the respondents are not satisfied with the wards' indoor air quality and ventilation. Only 15% of the respondents were well satisfied with the ventilation levels, while 83% of the respondents usually experience odor/smell in the investigated hospital wards. Thus, the existing ventilation system needs to be optimized to provide the required ventilation rates and improve indoor air quality.

The use of multiple data collection methods makes triangulation possible, and this provides for stronger substantiation of the theory (Koskosas & Asimopoulos, 2011). The present study used methodological triangulation among different types of triangulations, as shown in Figure 4-23.

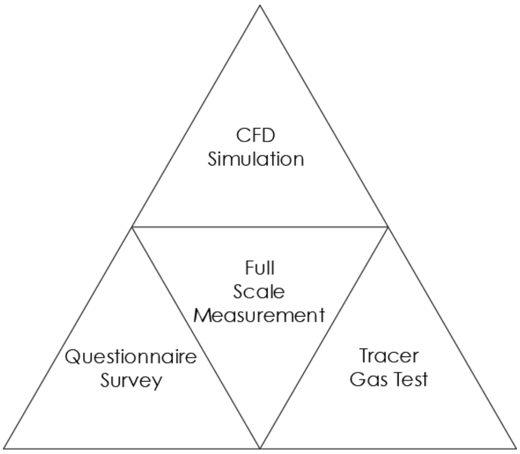


Figure 4-23: Methodological triangulation validation method used in this research

Thus, the outcome of this chapter has assisted in establishing and identifying the research problem and the existing knowledge gap regarding indoor air quality and ventilation beyond the literature assertions.

CHAPTER FIVE

MEASUREMENT OF ENVIRONMENTAL CONDITION AND VENTILATION RATES USING TRACER GAS TECHNIQUES

Chapter Structure

5 CHAPTER FIVE: MEASUREMENT OF ENVIRONMENTAL CONDITION AND VENTILATION RATES USING TRACER GAS TECHNIQUES

5.1 Introduction

The previous chapter (chapter 4), based on social understanding, demonstrated the problems of indoor air quality in the case study hospital wards. The psychosocial assumptions are correlated with a scientific approach to link ventilation levels to the design of wards. Therefore, in the present study, full-scale ventilation measurements have been conducted using tracer gas techniques and air temperature and relative humidity. Chapter (chapter 5) presents the results of the tracer gas techniques showing the air change rates, indoor air temperatures, and relative humidity of the investigated hospital ward.

5.2 Measurement of Ventilation Rates using Tracer Gas Technique

The total airflow rate, including outdoor air infiltration to building indoor space, is mainly measured using tracer gas techniques. Tracer gas provides a direct method for measuring the total airflow rates in buildings (Zhang, W. et al., 2015). This is achieved by injecting a readily detectable tracer into a space/room and recording the history of its concentration (D. W. Etheridge & Sandberg, 1996). The physical measurements of ventilation rates in the existing hospital multi-bed ward of the study area were conducted to ascertain the actual ventilation rates in the study area's typical wards. The measurements were conducted in December 2020. This month's selection is mainly due to accessibility because patients need to be evacuated for tracer gas measurements to be carried out.

The measured hospital ward with its prevailing wind directions or angle of attacks and positions of the CO_2 measurement devices are presented in Figure 5-1. The CO2 detector was used for measurement and was placed 1.0 m above floor level. The interior view of the measured hospital wards describing the positions of instruments, fans, and CO_2 bottles are shown in Figure 5-2. Moreover, to assess other indoor air parameters in the selected hospital multi-bed wards, dry bulb indoor and outdoor temperature, indoor and outdoor relative humidity were measured. Outdoor air parameters were measured with the Davis weather station. Additionally, data on outdoor wind speed and direction were also collected from the nearby meteorological station.

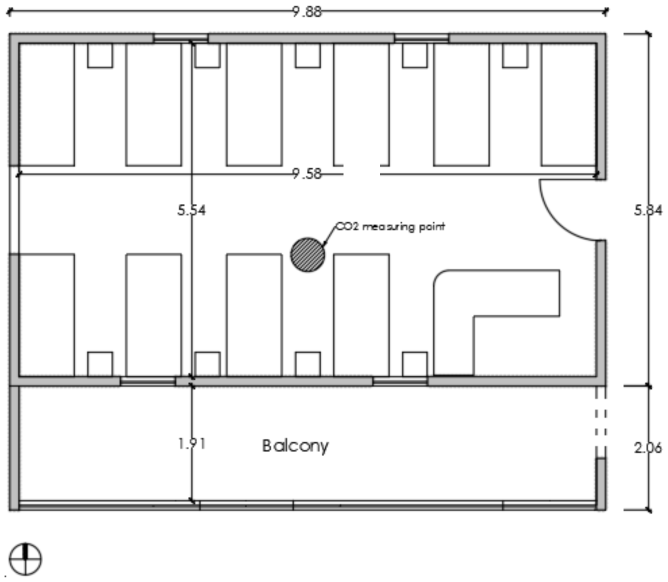


Figure 5-1: The measured hospital ward and its prevailing wind directions (angle of attack)

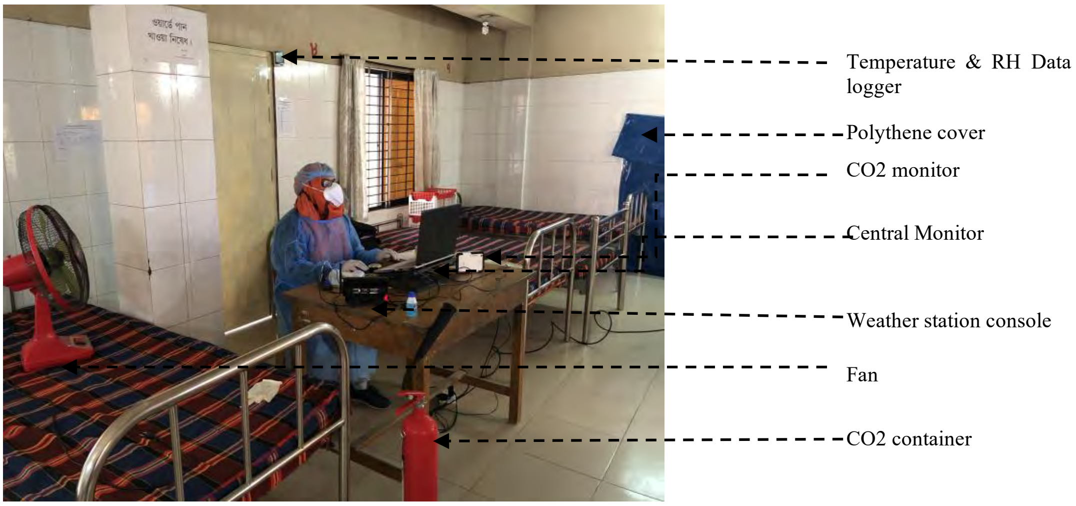


Figure 5-2: The interior view of the measured hospital ward showing fans, instruments, and CO_2 bottles

5.3 Tracer Gas Measurement Procedures

The measurement of air change rates, temperature, relative humidity, wind speed, and direction requires a systematic methodology and state-of-the-art equipment and materials. The onsite measurements were made to obtain air change rates, temperature, relative humidity, air velocity with the Davis weather station.

5.3.1 Measurement Equipment

Table 5-1: Instruments' specifications

Instrument (manufacturer)	NO.	Parameters	Picture of the instrument
CO_2 measurement Meter	1	CO_2 concentration, air temperature, and Relative Humidity Logger	
2D anemometer (ExTech)	1	Wind speed	
Thermo-Hygrometer (Zeal)	1	Air temperature and Relative Humidity	
Weather Station (Davis)	1	Air temperature, Relative Humidity, Wind speed, and direction	
Non-Contact Infrared Thermometer (Blunt Bird DN-997)	1	Measure the surface, room, water, food, etc., with clock function.	

5.3.2 Measurement Procedure

In this study, the measurements were conducted in an empty ward, and the measurement period was 40 minutes, with measuring intervals of 3 seconds. All openings in the studied hospital ward were closed before injecting the CO_2. Opening with built closure devices such as doors and windows were closed with such devices.

In contrast, openings without an installed closing tool, such as a toilet connecting to the ward, were closed using polythene sheet cover, as seen in Figure 5-3a. The polythene layer was chosen due to its benefit of blocking the gases from one zone to another. The injected CO_2 was allowed in the room for at least 10 minutes before the commencement of any measurement to allow proper mixing with indoor air. The mixing process was aided by portable fans placed in various positions of the room. The measurements were conducted for both closed and open windows scenarios to estimate infiltration and ventilation levels. The single measurement was performed in the examined hospital ward. In the case of opened windows, both the inlet and outlet openings were fully opened to achieve cross-ventilation in the measurement period. The sequence of events in the tracer gas measurement process is illustrated in Table 5-2.

Figure 5-3: (a) Corridor covered with polythene sheets, (b) instrument set up, (c) injecting CO_2

Table 5-2: Sequence of events in the tracer gas measurement process

S/N	Events	Descriptions
1	Hospital ward evacuation	The selected hospital ward was emptied before the tracer gas measurements.
2	Inspection of openings	All openings in the selected wards were inspected to check for damages and those without covers.

S/N	Events	Descriptions
3	Sealing of openings without covers	All openings without covers, such as the toilet linking the wards to other functions, were covered with polythene sheets
4	Equipment set-up	Measuring equipment, including CO_2 detectors, air temperature, relative humidity sensors, and mixing fans, were positioned accordingly.
5	Closed window measurement	The measurements were started with a closed window scenario to enable the same CO_2 in the opened window situation. The level of CO_2 escape with a closed window was infiltration.
6	CO_2 injection	CO_2 was injected into the empty ward simultaneously with the start of the mixing fans.
7	Mixing of the CO_2 in the ward	The injected CO_2 was allowed to mix for about 10 minutes before the commencement of the measurements.
8	Concentration records	The concentration readings were recorded at 3 seconds intervals
9	Opened window measurement	The opened window measurements commence immediately after completing the closed window scenario without injecting more CO2 into the ward. All the openings in the ward were opened, and measurement started immediately at 3 seconds interval
10	Measurement periods	The measurements lasted for 30 minutes

5.3.3 Carbon Dioxide (CO_2) as Tracer Gas

Carbon Dioxide (CO2) is widely used for measuring indoor air quality in buildings. CO2 measurements are regularly used to determine the indoor Air Change Rate (ACR) because they can be easily quantified. (Cui et al., 2015) confirm that CO2 is the best among tracer gasses because of its less impact on the environment. It is non-reactive, non-flammable, environmentally friendly, and cost-effective.

5.3.4 The Estimation of Air Change Rates

The tracer gas concentration was analyzed and recorded with the aid of CO_2 analyzer and data loggers. The results obtained from these measurements were used to estimate the air change rates of the hospital wards.

The ventilation rate can be estimated by multiplying the air change rate and room volume (Kiwan et al., 2013). For this study, the hospital ward's air change rates were calculated using the mathematical expression in Eq. 5-1.

$$N = \frac{\ln C(0) - \ln C(t)}{t}$$ ***Eq. 5-1***

Where,

N = Air Change Rate

C = Tracer Gas Concentration in Room

t = Time (h)

ln = natural logarithm

5.4 Full-scale Measurement Results and Discussion

5.4.1 Measurement of Air Change Rates

Air change rates were measured in conjunction with other parameters, including outdoor and indoor dry bulb temperature and outdoor and indoor relative humidity. Wind speed and direction data were collected from the on-site and nearest weather stations. The air change rates and other essential boundary conditions, including temperature and relative humidity for closed and opened windows, were also collected and presented in Table 5-3, Table 5-4, and Figure 5-4.

The first measurement instance was the air change rates assessed when the hospital ward openings were closed, which are infiltration rates due to cracks in the envelope and gaps along the window and door frames' perimeters. However, in naturally ventilated buildings like the ones under investigation, the effect of infiltration is uncontrolled. The infiltration of 0.21-ach-1 was recorded in SHMH hospital, as illustrated in figure 6.4[a].

Table 5-3: Infiltration rates and other climatic parameters for the closed window during the measurement period

Test date	CO_2 Injection	Close Window							
		Time	Infiltration rate	Wind (m/s)	Direction	T out °C	T in °C	RH out %	RH in %
03/12/2020	12:30 pm	12:40 pm	0.21	.4	WSW	28.1	22.8	57	76

It could be observed from Figure 5-4 that the infiltration rate is negligible. The orientation of wind flow direction with the inlet openings is WSW in SHMH. The outdoor prevailing wind speed is in SHMH was .4m/s.

Measurements of air change were also conducted in open window situations to determine the hospital ward's ventilation rate. The measurement was made by completely opening all inlet and outlet openings. The results obtained for air change rates, indoor and outdoor air temperature, and relative humidity are shown in Table 5-4. The air change rates in the ward measured with open windows indicate that it has not satisfied the ASHRAE requirements 6-ach$_{-1}$ inpatient rooms (Table 3-23), as illustrated in Figure 5-4.

Table 5-4: Air change rates and other climatic parameters for the opened window during the measurement period

Test date	CO_2 Injection	Open Window							
		Time	ACH	Wind (m/s)	Direction	T out °C	T in °C	RH out %	RH in %
15/07/2020	12:30 pm	13:00 pm	4.9	.4	WSW	28.6	22.9	51	74

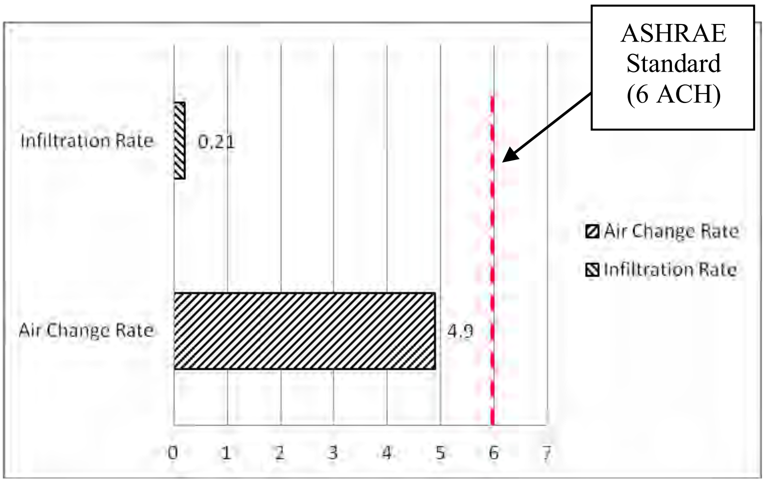


Figure 5-4: Infiltration rates and air change rates in closed and opened windows

5.4.2 Air Temperature Measurements

The indoor and outdoor air temperature measurements have been carried out simultaneously with the air infiltration rate measurement in the closed window. The temperatures outdoors are higher than indoors for the studied ward, as illustrated in Figure 5-5. The measurement indicates that the outdoor air temperature ranges from 27.9°C to 28.1°C, and the indoor air temperature falls between 22.7°C to 22.8°C during the measurement period. In both the close and open window scenario, the indoor temperatures were lower than the outdoor. The result indicates that the temperature met the study area's comfort requirements based on the estimated temperature of thermal neutrality.

The similarity between the temperatures in the two cases of opened and closed windows could be due to the moderate wind speed (0.4 m/s) at the time of the measurement. However, the indoor air temperature was lower in the opened window situation than the closed window, as observed in Figure 5-5. On the other hand, the difference between the outdoor and indoor temperatures is higher in closed window situations (Table 5-5 and Figure 5-6); this is because of the trapping of heat from various indoor sources due to little contact between indoor and outdoor air.

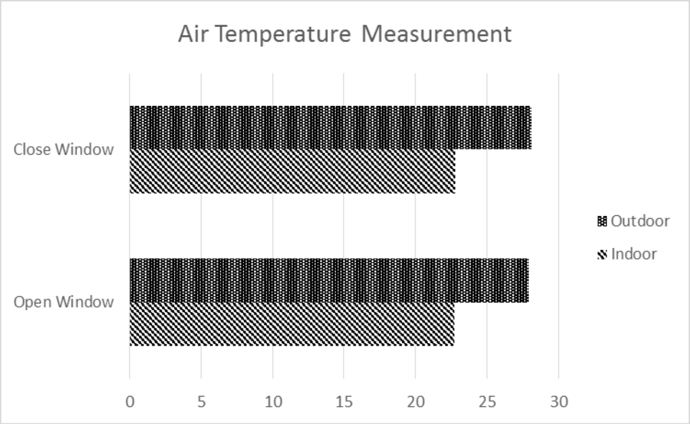


Figure 5-5: Air temperature measured in closed and opened window situations

Table 5-5: The difference in Indoor & Outdoor air temperature

	Close window	open window
SHMH	5.3 ºC	5.2 ºC

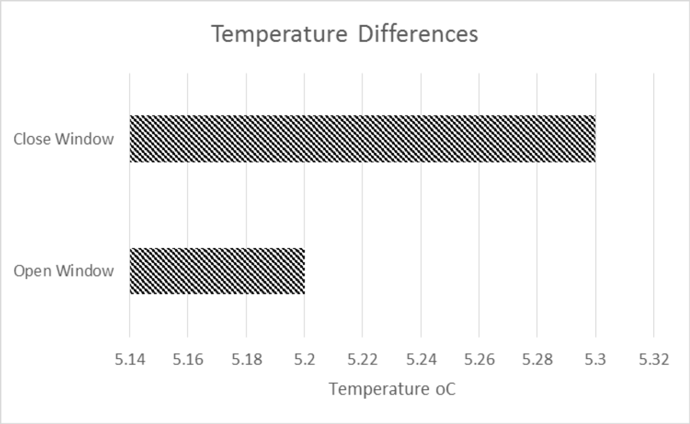


Figure 5-6: The difference in temperature between the closed and opened window

5.4.3 Relative Humidity Measurements

Air acceptability decreases considerably with increasing air temperature and relative humidity (Fang, 1998). In this study, the relative humidity measurements were made simultaneously with the air change rates. The result indicates that the relative humidity is higher indoors in a closed and open window situation than outdoors, as illustrated in Figure 5-7. This is because relative humidity in the ambient air was low in the study area. The Relative Humidity met the comfort requirement of the study area based on the literature study.

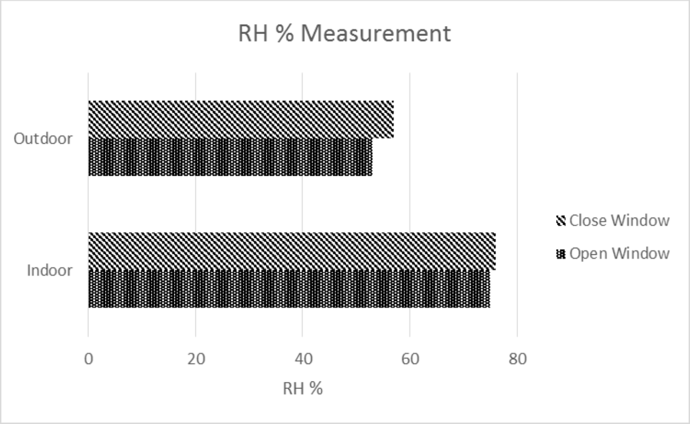


Figure 5-7: RH (%) of the measured ward in closed and opened window situation

Furthermore, the relative humidity difference between outdoor and indoor environments was higher in opened-door (20%) situations than in closed-door (19%) cases, as illustrated in Figure 5-8.

Table 5-6: The difference in indoor & outdoor relative humidity

	Closed Window	Open Window
SHMH	19%	22%

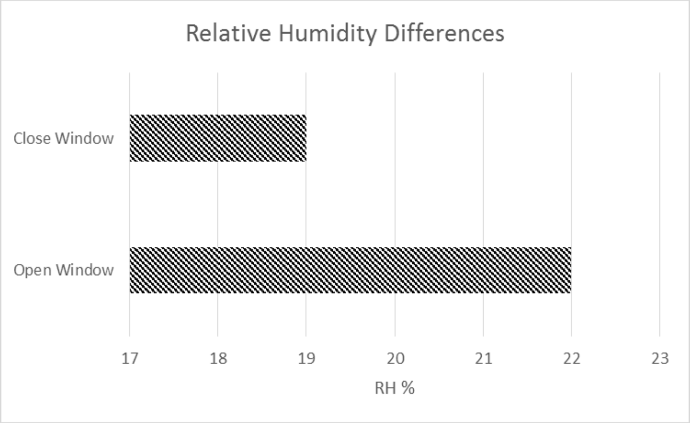


Figure 5-8: The difference in RH (%) between closed and opened window wards

5.5 The Logarithmic CO_2 Concentration Decay Curve

The CO2 concentration (ppm) decay curve for the studied case for the close and open window is shown in Figure 5-10. In contrast, the complete CO_2 decay curve in ppm showing data points used to calculate air change rates is illustrated in Figure 5-11 and Figure 5-12. The difference in gradients between the opened and closed window scenarios has been clearly demonstrated with continuous and dotted lines. The level of decay in the wards with opened windows is faster than in those with closed windows. The minor decay in the closed window situations results from infiltration through cracks and gaps on the envelope and openings. Moreover, the significance level in the regression coefficient (R^2) computed for all the cases is above 92%, showing a strong correlation and reliability.

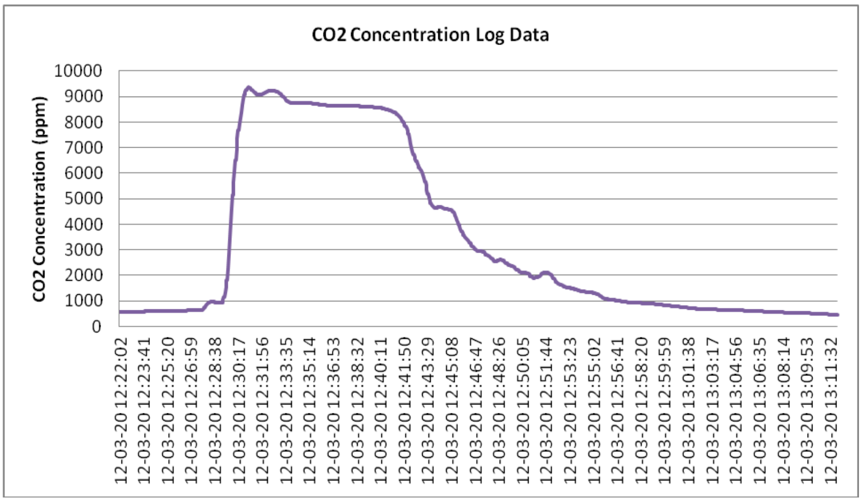


Figure 5-9: Log Data for CO_2 Measurement (PPM)

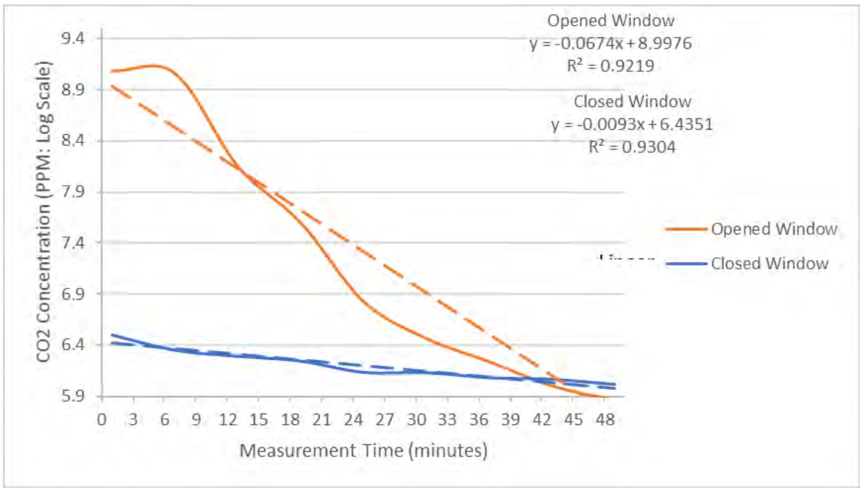


Figure 5-10: The logarithmic CO_2 concentration (ppm) decay curve for closed & opened window

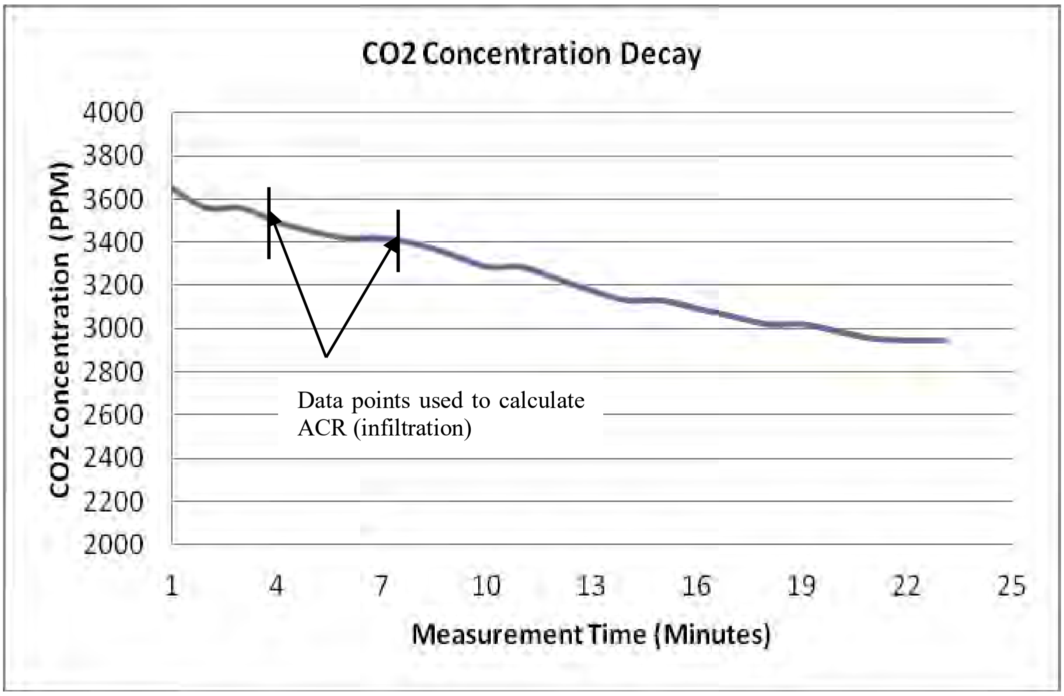


Figure 5-11: The CO₂ concentration (ppm) decay curve for showing data points used for infiltration

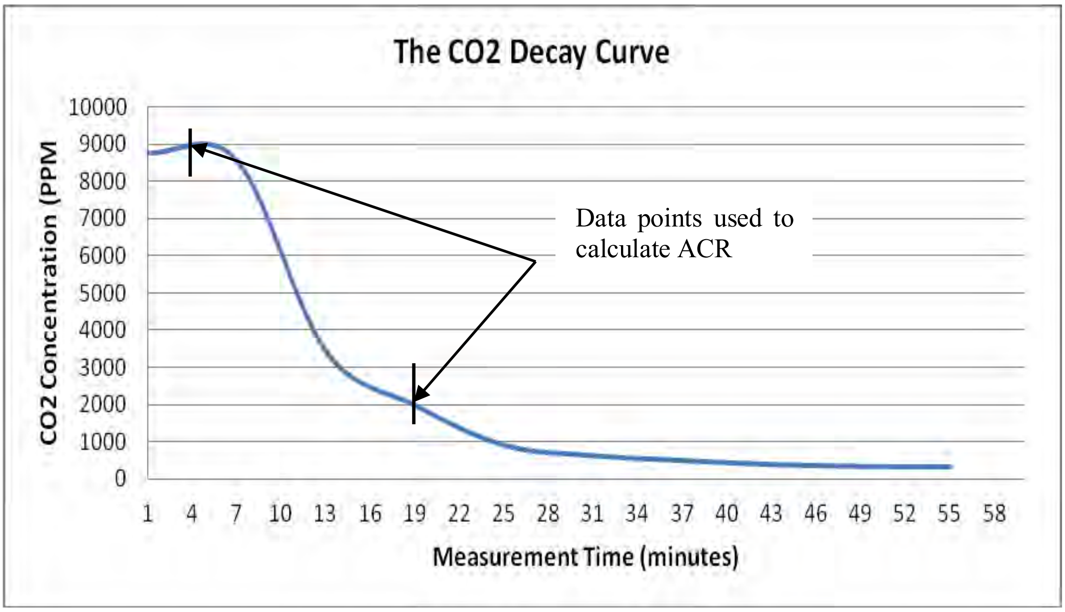


Figure 5-12: The CO₂ concentration (ppm) decay curve for showing data points used for ACH

5.6 Chapter Conclusion

The psychosocial perception of the hospital wards' occupants has been presented in the first section of this chapter (chapter 5). Based on the occupants' perception, the hospital ward's occupants were generally not satisfied with the indoor air quality and ventilation. The ventilation rate measurements taken during the test periods show relatively low airflow rates. This would confirm the assertion that ventilation rates were too low in the SHMH ward, which would account for the low indoor air quality highlighted by the ward's regular occupants.

In this chapter, the ventilation rate in the studied ward was calculated using the tracer gas decay method. The result showed that the ward's rate of air change was 4.9 ach^{-1}, which was below the 6-ach^{-1} ASHRAE standard for hospital wards during the measurement periods;

The tracer gas measurements' results further affirm the occupants' response, showing dissatisfaction with the indoor air quality and ventilation in hospital wards. The measurement results will be validated by replicating the hospital ward using CFD simulation, and it is the condition of measurement in the virtual environment. In chapters 7 and 8, the hospital ward in the SHMH was selected as the base case for further CFD analysis.

Thus, based on psychosocial and full-scale measurements, the indoor air quality and ventilation rates in the studied hospital ward were insufficient and needed to be improved to meet the minimum requirements and provide the occupants with the comfort they need.

CHAPTER SIX

THE CFD SIMULATION PROCESS AND VALIDATION OF SOFTWARE

Chapter Structure

6 CHAPTER SIX: THE CFD SIMULATION PROCESS AND VALIDATION OF SOFTWARE

6.1 Introduction

The accurate prediction of ventilation systems requires a reliable, cost-effective, easy to use, and readily available state-of-the-art tool. The simulation of hospital ward models using the selected Computational Fluid Dynamics (CFD) simulation software Fluent 18.1 requires validation. In this study, the accuracy of the CFD simulated hospital wards was validated against the full-scale measurement results of ventilation rates using tracer gas techniques presented in the previous chapter (Chapter 5). Moreover, apart from the validation results, this chapter (Chapter 6) also presents the processes and guidelines for conducting the CFD simulation and the boundary conditions employed. The guidelines include the processes right from model construction, computational mesh, atmospheric boundary layer profile, turbulence model, and convergence criteria.

6.2 Prediction of Ventilation Efficiency Using Computational Fluid Dynamics

It is generally acknowledged that earlier predictions and analyses of future building behavior are far more efficient and cost-effective than resolving problems when the building is in its occupancy period (Mohammed, 2015). CFD is a tool for predicting airflow in buildings right from the design stages. Other prediction tools, such as wind tunnels and full-scale measurements, are costly and difficult for comparative studies.

The Fluent 18.1 CFD model usually splits the interior space into several cells. The conservation of mass is satisfied for each cell to balance the sum of mass flows into or out of a cell from its neighbors to zero. The momentum exchange must be balanced in each direction with pressure, gravity, viscous shear, and energy transport by turbulent eddies. The Fluent 18.1 CFD code was used in the present study by implementing the pressure-based solver with absolute velocity formulation and steady-state simulation time. The typical process implemented in using CFD Fluent is illustrated in Figure 6-1.

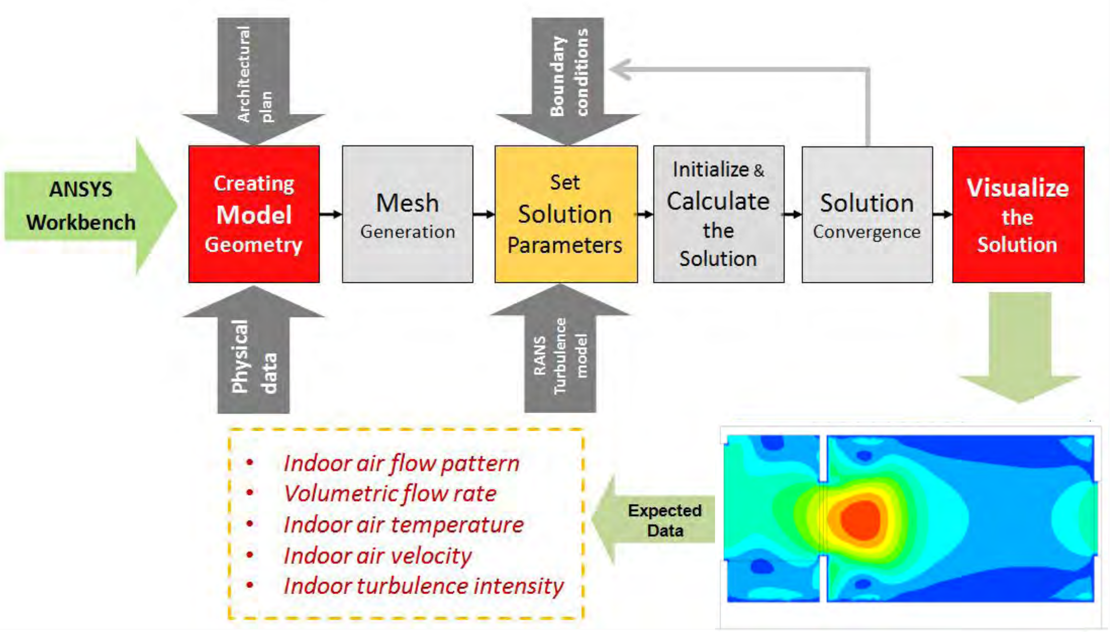


Figure 6-1: The typical process implemented in using CFD Fluent

6.2.1 Model Geometry Creation

Model creation is the first stage of the simulation, which involves building the geometry to be simulated. The model was created using the ANSYS Designer Modeler software in this study. This is because the model created from ANSYS Designer Modeler is more compatible with Fluent 18.1 simulation software than other modeling programs.

6.2.2 Computational Mesh Creation

This study generated the computational grids using Ansys built-in mechanical meshing software. The mesh generation process divides the entire simulation area into small triangular meshes. Owing to the considerable influence of cell size on the solution, careful selection of cell sizes in meshing is essential. The number of cells used in this work is 2.78 million.

6.3 Computational Domain With Solution Boundaries

This study designed the computational domain based on the recommendation (Franke et al., 2007) for a single building. A computational domain of dimension 67.9m x 39.88m x 18m was used to avoid domain size interference on the numerical simulation results. The distance between the inlet boundary and the building is recommended to be at least 5H if the approach flow profile is well-known. A reproduction of the domain used by Franke et al.(2007) is presented in Figure 6-2

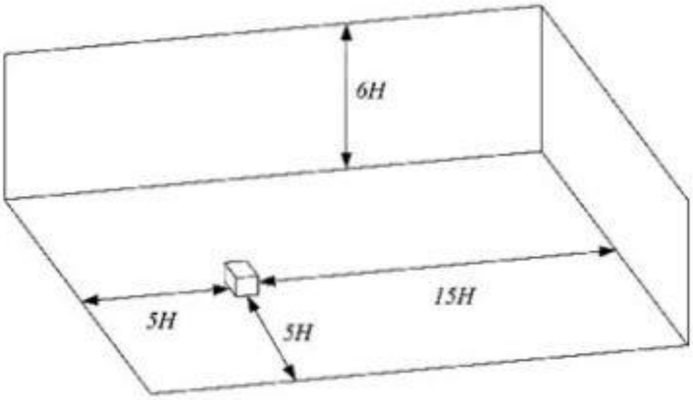


Figure 6-2: A reproduction of the domain used by Franke (2007)

CFD commercial code, ANSYS Fluent 18.1, was employed to perform the simulations. The 3D steady RANS equations were solved with the stress transport (Realizable) k- ϵ turbulence model. Second-order was used for both pressure interpolation and discretization schemes. Simulation convergence was achieved when the scaled residuals reached the specified limits of 10-6 for x, y, and z momentums, 10-5 for k, epsilon, and continuity.

6.4 Atmospheric Boundary Layer (ABL)

Atmospheric Boundary Layer (ABL) is the lowest part of the earth's atmosphere, with characteristics directly influenced by the contact with the earth's surface (X. Zhang, 2009). In order to achieve accurate and reliable predictions of the atmospheric processes in the lower part of the atmosphere, accurate simulation of the ABL flow in a computational domain is essential (Blocken et al., 2007).

Wind moving across the earth's surface is slowed by obstructions like buildings, trees, and similar, and the wind velocity increases with altitude. Wind speed at different heights with the wind speed at a reference height can be expressed by power-law equation (Feustel, 1999):

$v / v_{ref} = (h / h_{ref})^{\alpha}$ …………………… Eq. 6-1

Where, v = the velocity at height h (m/s), v_{ref} = the velocity at height h_{ref} (m/s), and α= exponent represents the terrain roughness. A greater value indicates a rougher terrain (Awbi, 2003). The terrain coefficient for wind speed, as deduced from (S. Omrani et al., 2017), is illustrated in Table 6-1

Table 6-1: Terrain coefficients for wind speed

S/N	Terrain	α
1.	Open, flat country	0.17
2.	Country with scattered windbreaks	0.20
3.	Urban	0.25
4.	City	0.33

In order to use meteorological data for natural ventilation design, knowing the relation between the reference wind speed and the wind speed at the openings is an essential factor that can help in a more realistic prediction of natural ventilation. The lack of such a relation in the literature was the motivation of the current study. The corrected wind speeds at the building positions estimated using Eq. 6-1 have been presented in Table 6-2 for the monthly differences.

Table 6-2:The corrected velocities at the building positions for the 12 months investigated

Months	Velocity at the meteorological station (m/s)	Corrected velocity at the building position (m/s)
January	1.21	0.77
February	1.24	0.78
March	1.21	0.77
April	1.44	0.91
May	1.53	0.97
June	1.38	0.87
July	1.30	0.82
August	1.41	0.89
September	1.31	0.82
October	1.30	0.82
November	1.31	0.82
December	1.23	0.78

6.5 Turbulence Model -Reynolds-Averaged Navier-Stokes (RANS) Equations

Navier-Stokes equations are the governing equations of CFD, which is based on the conservation law of the physical properties of the fluid. In the present study, the 3D steady RANS equations were solved using the realizable k–ε turbulence model by

Shih et al. (1995) using the commercial CFD code ANSYS Fluent 18.1. The k–ε model was selected for its generally good performance in predicting indoor air flows in buildings (Kosutova et al., 2019). Moreover, the realizable k-ε turbulence model was chosen for its excellent performance in predicting wind flows around buildings (M.A. Mohammed, 2015).

6.6 The Selected Hospital Wards Building Materials and Indoor Air Properties

6.6.1 Building Envelope (Wall)

The material used for constructing the building envelope (Wall) in the existing multi-bed ward studied was a brick wall of thickness .127m for external walls. The properties of the brick wall were required as input to the simulation of the thermal characteristic of the multi-bed ward, including thermal conductivity, density, absorptivity, specific heat emissivity, and heat transfer coefficient. The properties of the parameters mentioned earlier are presented in Table 6-3.

Table 6-3: Properties of bricks and plaster

S/N	Parameters	Brick Wall	Plaster
1	Thickness	.127m	.0063m
2	Density	1789 kg/m3	2374.417 kg/m3
3	Thermal Conductivity	0.55 W/m-k	0.43 W/m-k
4	Specific Heat	1171.52 J/kg-k	753.12 J/kg-k
5	Absorptivity	0.9	.9
6	Emissivity	0.94	-
7	Heat Transfer Coefficient	2.46	-

6.6.2 Concrete Slab

The properties of the concrete slab required as input to the simulation of the thermal characteristic of the multi-bed wards, including thermal conductivity, density, and specific heat, are presented in Table 6-4.

Table 6-4: Properties of concrete slab

S/N	Parameters	Concrete Slab .1016 m
1	Density	2487.667 kg/m3
2	Thermal Conductivity	1.34 W/m-K
3	Specific Heat	669.44 J/kg-K

6.6.3 Indoor Air Properties

Air is the most crucial element in ventilation studies. Comprehensive air quality is required to set up a simulation case for natural ventilation and indoor air quality studies. Parameters such as density, thermal expansion coefficient, specific heat capacity, and gravitation force of attraction were considered for setting up the computational model. The values for the parameters mentioned above are shown in Table 6-5.

Table 6-5: Properties of air

S/N	Parameters (Air)	Properties
1	Density	1.1672 kg/m3
2	Thermal Expansion Coefficient	3.32 x 10_{-3} (t = 27.4_{o}C)
3	Specific Heat Capacity	1006 J/kg-K
4	Gravitation Force	-9.81m/s_{2}

6.7 The CFD Validation Results

The air change rates (ACR) were estimated in site measurement. The model was a duplication of the existing ward, simulated in a virtual environment of CFD to validate the CFD models of the base-case. Moreover, the results of the full-scale measurement and the simulations were compared. The wind speed data was collected from the installed weather data station. The results obtained have been analyzed to provide an acceptable ventilation rate to achieve the ASHREA standard of 6-ach_{-1} (ASHRAE 2011; Ninomura & Bartley, 2001). The summary of the various boundary conditions used in the CFD simulation process is presented in Table 6-6.

Table 6-6: Summary of boundary conditions used for the simulations

S/N	Boundary	Settings
1	Inlet profiles (U, u*, k and ε)	used as user-defined functions (Appendix H)
2	outlet	Relative static pressure is zero
3	ground	No-slip rough wall
4	Building surfaces	No-slip rough wall with zero roughness
5	Domain size	67.9m x 39.88m x 18m (l x w x h)
6	Mesh type	Tetrahedral
7	Turbulence model	k-ε Realizable
8	Discretization schemes	Second-order upwind
9	Algorithm (pressure velocity coupling)	Standard
10	Time	Steady state simulation

S/N	Boundary	Settings
11	Near wall treatment	Standard wall functions
12	Total number of cells (Average)	2.78 million
13	Reference height	10m
14	Reference mean wind speed inlet	.4 m/s (See Table 6-2; for other wind speed values)
15	Gravity	-9.81
16	Air density	1.1672 kg/m3
17	Air temperature	28.6 oC
18	Ground roughness constant (Cs)	.5
19	Ground roughness height (Ks)	0.98
20	Wall motion	Stationary wall
21	Heat transfer through walls/roof	adiabatic

6.8 Acceptable Error Limits Between CFD Simulation and Full-Scale Measurements

According to (Yang et al., 2006), the error range obtainable with full-scale measurement could reach 10 – 15%, while Willemsen and Wisse (2002) believe that errors implanted in full-scale measurements can reach up to 20%. The difference between full-scale measurement and CFD simulation measurements was 4%, which is below the acceptable error margin. Table 6-7 shows the volumetric airflow patterns and air transition rates of the wards.

Table 6-7: The validation of the measured volumetric flow rates with cfd simulation

Cases	Ward Location	Air Change Rates (ACH)		Difference between CFD & Full Scale
		Full-Scale Measurement	CFD Simulation	
Base-Case	SHMH	4.94	5.12	4%

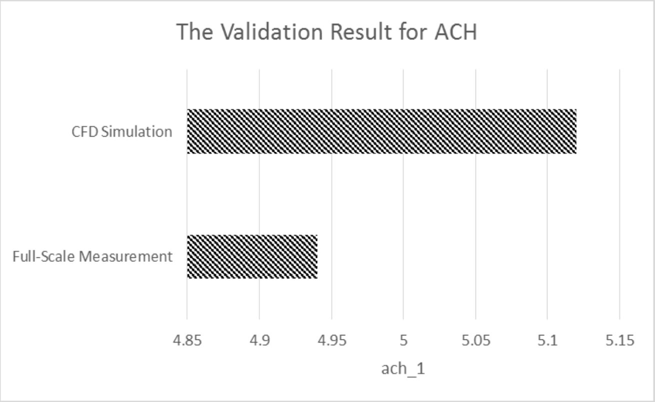


Figure 6-3: The validation results comparing air change rates

6.9 Grid Independence Test

A grid independence test is essential to ensure that the simulation results are not sensitive to grids. Three different grid alternatives were used, ranging from about 2.6 million cells to 2.8 million cells (Table 6-8). The result indicates that the difference between the three volumetric airflow rates is insignificant. This result suggests that the solutions are independent of the grids.

Table 6-8: Mesh properties

Grid alternatives	Mesh Properties			
	Total No of Cells	Total No of Nodes	No of Iterations	Volumetric Flow rates (m3/s)
Coarse Mesh	26,97,623	36,90,360	1000	0.220
Fine Mesh	27,80,846	38,13,212	1000	0.227
Finer Mesh	28,82,248	39,69,265	1000	0.219

6.10 Air Temperature Variation Between Dhaka City and Manikganj

Since the study area is rural, a brief 7-day temperature comparison (1 April 2021 to 7 April 2021) was conducted to better understand the temperature pattern between Dhaka and Manikganj. The analysis clearly shows that there are temperature variations between these two areas.

Table 6-9: Variation in air temperature between Dhaka city and Manikganj

	Mean Minimum Temperature (°C.)		Mean Maximum Temperature (°C.)		Mean Avg. Temperature (°C.)	
	Temperature	Difference	Temperature	Difference	Temperature	Difference
Dhaka City	25.29	0.43	39.57	0.14	32.43	0.14
Manikganj	24.86		39.71		32.29	

6.11 Chapter Conclusion

This CFD model was conducted using computational fluid dynamic software Fluent 18.1. The outcome of the validation study indicates that the difference between the CFD simulation and the full-scale measurement is 4% which is within the acceptable error margin. The following research phase uses the model to develop and improve sustainable ventilation design for the hospital wards in the tropics.

CHAPTER SEVEN

CFD SIMULATION RESULTS

Chapter Structure

7 CHAPTER SEVEN: CFD SIMULATION RESULTS

7.1 Introduction

The previous chapter (chapter 6) provided the procedures and guidelines for performing the CFD simulations, along with all relevant boundary conditions. This chapter explores the effect of different opening locations on ventilation rates in multi-bed hospitals, considering ten (10) different configurations, including the existing ward (SHMH). The existing hospital ward SHMH has been adopted as the base-case model in the study. This hospital was chosen because its architecture and opening configurations are similar to those of the other primary-level hospital wards in the study area. However, the investigations were all conducted assuming that the wards were empty.

In addition, the study also analyzed the impact of building orientation on ventilation rates in the hospital wards of the study area. The best opening layout has been established and presented in terms of ventilation rates and airflow distribution at occupancy (bed) levels. Since this study aims to increase ventilation rates to provide acceptable indoor thermal comfort, the level of dissatisfaction with ventilation in the investigated configurations has been estimated. This chapter (Chapter 7) was intended to satisfy objective 2 (two), ***"To articulate a relationship between ventilation, openings, and thermal comfort."***

7.2 Changing Opening Configuration on Walls

The study analyzed the ventilation efficiency of ten (10) different opening configurations/cases. This was conducted to determine the case with the highest air flow and air change rates while considering other environmental parameters such as indoor air velocity, indoor air temperature, and turbulent intensity. Table 7-1 contains a description of these cases. These arrangements were generally considered only to be openings located on the wall.

Among ten (10) cases, starting with the SHMH ward as the base case, eight (8) of them were classified as windward inlets and leeward outlets. The remaining two (2) cases were examined at windward-side inlets and adjacent-wall outlets. The existing case featured four openings, two inlets, and two non-aligned outlets for cross ventilation of the occupants. The remaining nine cases had two identical inlets and two identical outlets. At 1.0 m above floor level, the horizontal section was intended to represent patient relatives and other healthcare workers seated in a chair. By contrast, the horizontal section 0.6 m above the floor was proposed to represent a patient lying on a bed. Figure 7-2 and Figure 7-3 Figures represent the opening locations adopted in simulation in various cases.

7.3 Comparative Analysis of All the 10 Cases Simulated

7.3.1 Volume Flow Rates and Air Change Rate

The comparative analysis of the 10 cases studied has been presented in a tabular form in Table 7-1 to Table 7-5. All cases were simulated using prevailing wind speeds at a 35-degree angle to the openings determined by physical measurement. The air change rates for each of the ten cases are shown in Figure 7-1, with case 1 having the highest rate followed by case 5. The volumetric airflow rate and air change rate obtained from the base case was 0.22 m3/s and 5.12 ach-1, respectively, which were less than the ASHREA (2011) recommended standard air change rate 6 ach-1 for hospital wards. Cases 3, 8, and 9 could not meet the standard air change rates mentioned previously.

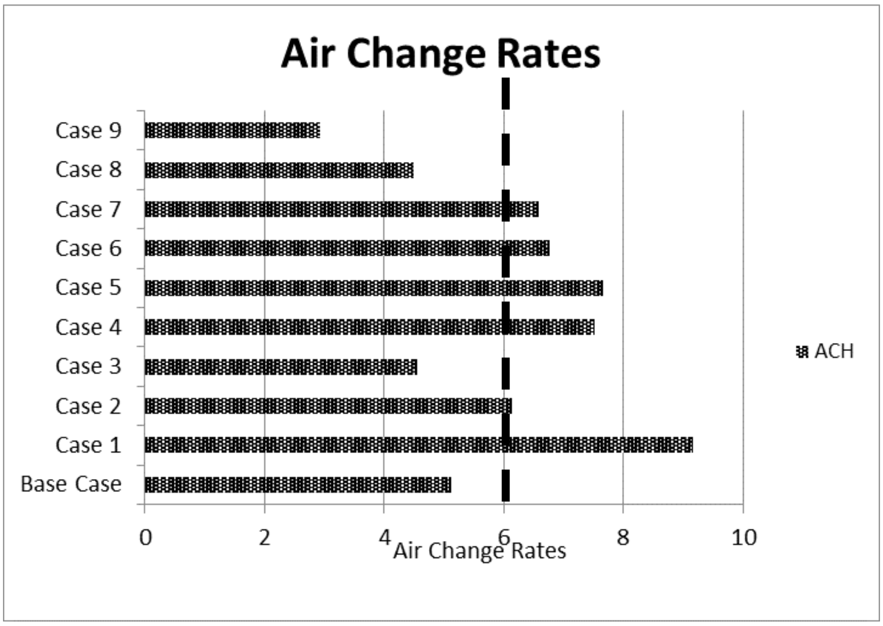


Figure 7-1: Air change rates of different simulated cases

The ten simulated cases are presented in Table 7-1, including diagrams, airflow rates, air change rates, average indoor air velocity, turbulence intensity, and air temperature. Horizontal sections of velocity vectors are shown in Table 7-2 and Table 7-3 to confirm the airflow distribution in the ward's center. However, as shown in the vertical section of all the cases (& Table 7-5), the airflow distribution is strong near the inlets but low in the center of the ward at the occupancy level.

7.3.2 Thermal Comfort

This section compares the results of comfort modeling at the occupant level to CFD simulations for all cases. Results indicate that the average indoor air temperature trend has a similar pattern among the cases having windward side inlets and leeward side outlets (case 1-case 7). The temperature is within the range of 27.26 oC to 27.72 oC. In contrast, windward side inlets and single adjacent side outlets (case 8) show a lower temperature (25.98 oC) than previous cases. It is due to the poor air circulation within the wards. For all the cases, the outside air temperature was 28.6 oC.

The sedentary activity was assumed in this investigation, and the metabolic rate was adjusted to 1.2 met (ASHRAE, 2013). For clothing insulation, light standard summer clothes with a value of 0.5 clo was employed (S. Omrani et al., 2018).

The average PMV index was within $0.23 < PMV < 0.33$ for case 1 to case 7 (Table 7-1), suggesting a comfortable occupancy level with a neutral thermal sensation. However, for case 8, the PMV is 0.1, which indicates a cooler feeling inside the ward. According to the PPD index, the number of people dissatisfied with their thermal environment was between 5.22% and 7.35%. The finding suggests that most people are satisfied with their indoor environment.

As a result, the indoor environment is considered comfortable for all cases in terms of thermal comfort. The PMV and PPD indexes for the wards of the studied hospital are shown in Table 7-6and Table 7-7. The result indicates that people will feel comfortable in an occupied zone.

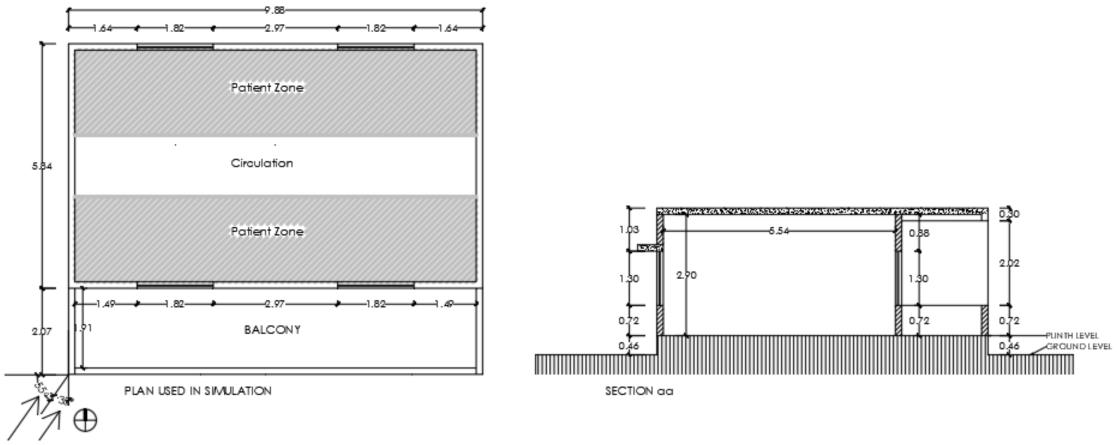


Figure 7-2: Plan & section showing opening position for simulation

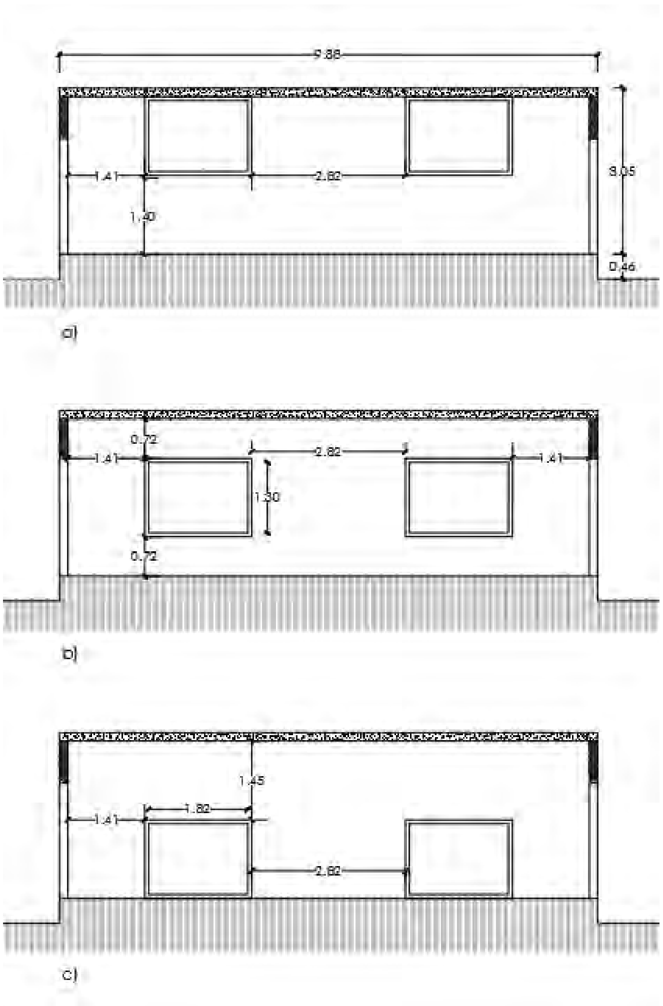


Figure 7-3: a) Up b) Centre and c) Down opening position for simulation

Table 7-1: Indoor airflow rates characteristics various ventilation strategies in the multi-bed wards

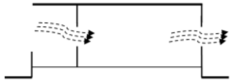
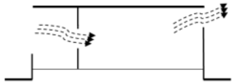
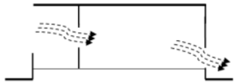
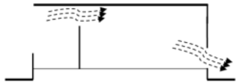
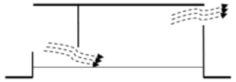
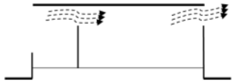
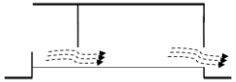
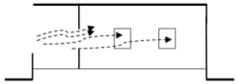
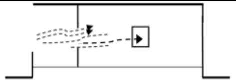
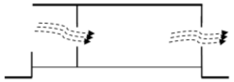
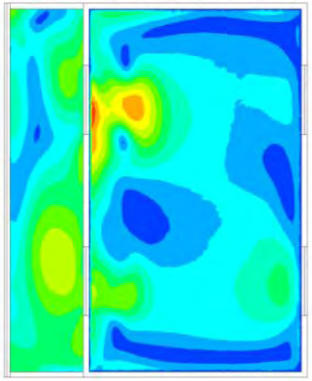
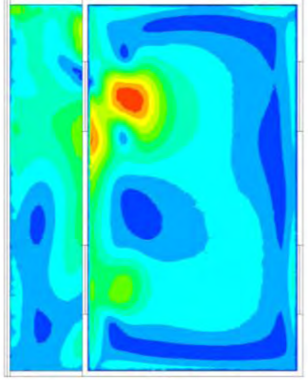
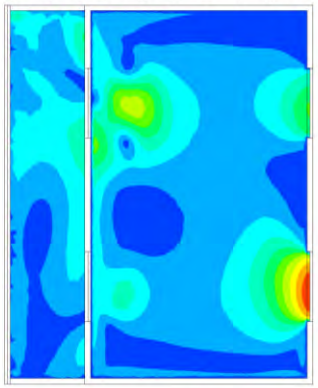
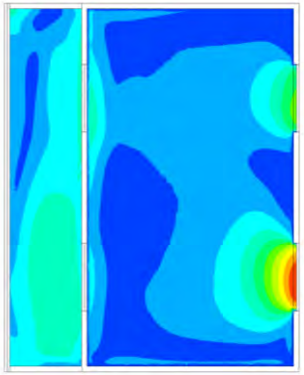
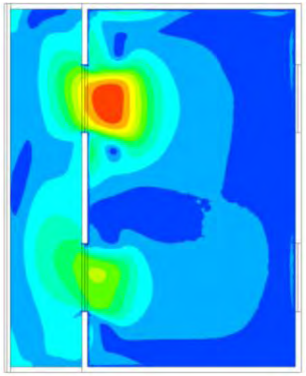
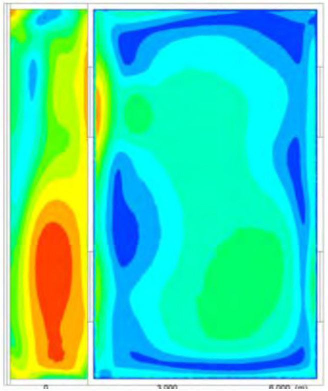
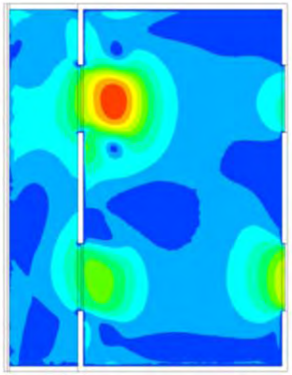
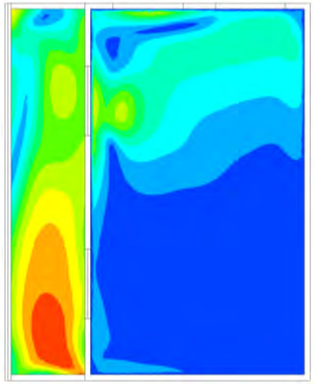
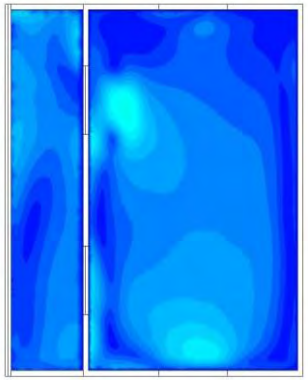
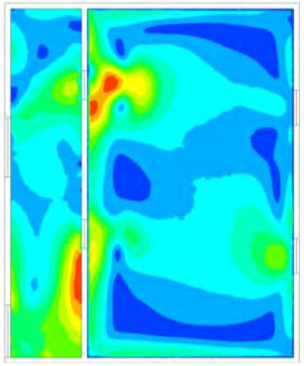
Cases	Description	Diagram	Volume Flow Rate(m3/s)	ACH	Avg.Air velocity (m/s)	TI (%)	Avg.Temp (oC.)	Avg. PPD (%)	Avg. PMV
Case 1	Inlets center & Outlets center		0.392	9.16	0.103	.36	27.44	7.13	0.320
Case 2	Inlets center & Outlets up		0.263	6.13	0.095	.36	27.28	6.90	0.302
Case 3	Inlets center & Outlets down		0.196	4.56	0.088	.38	27.31	7.20	0.325
Case 4	Inlets up & Outlets down		0.323	7.52	0.100	.39	27.47	7.32	0.334
Case 5	Inlets down & Outlets up		0.329	7.67	0.099	.39	27.42	7.17	0.323
Case 6	Inlets up & Outlets up		0.290	6.76	0.104	.39	27.45	7.21	0.326
Case 7	Inlets down & Outlets down		0.283	6.59	0.096	.37	27.26	6.76	0.291
Case 8	Inlets center & Outlets side wall single		0.193	4.50	0.037	.46	25.98	5.22	0.103
Case 9	Inlets center & Outlets side wall both		0.126	2.93	0.085	.28	27.65	7.80	0.505
Base Case	Inlets center & Outlets center (not-aligned)		0.221	5.12	0.057	.37	26.66	6.16	0.236

Table 7-2: Contours showing velocity magnitudes at occupancy level (.6 m) plan

Case 1	Case 2	Case 3	Case 4	Case 5
				
Case 6	Case 7	Case 8	Case 9	Base Case
				

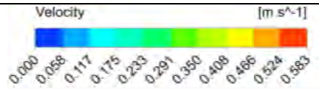
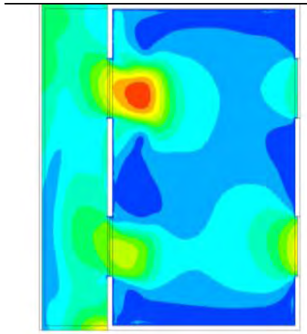
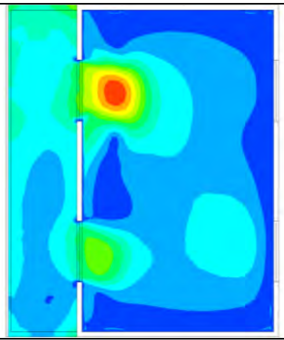
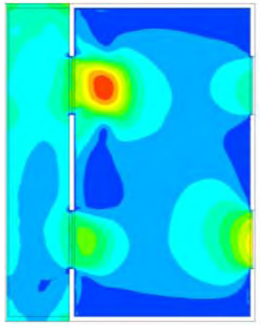
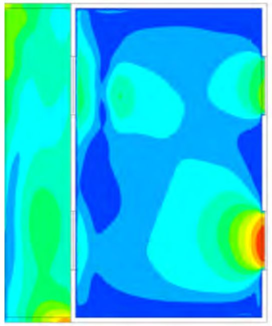
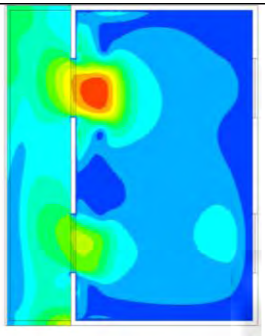
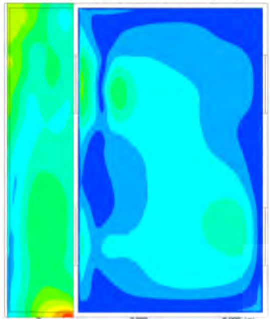
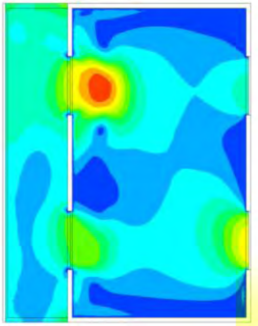
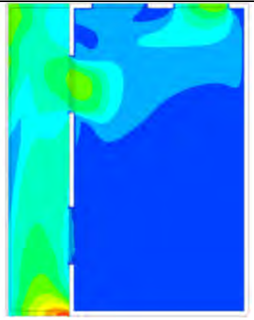
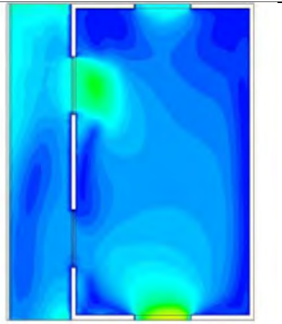
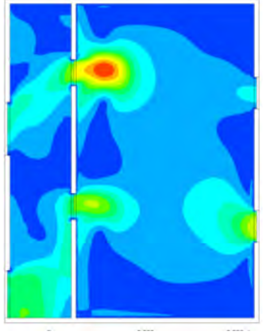


Table 7-3: Contours showing velocity magnitudes at occupancy level (1 m) plan

Case 1	Case 2	Case 3	Case 4	Case 5
				
Case 6	Case 7	Case 8	Case 9	Base Case
				

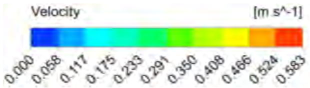


Table 7-4: Contours showing a vertical section of velocity magnitudes

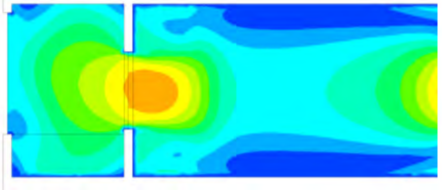
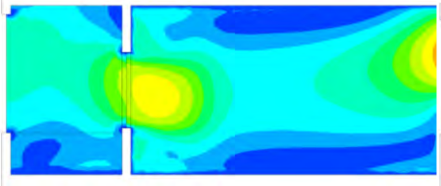
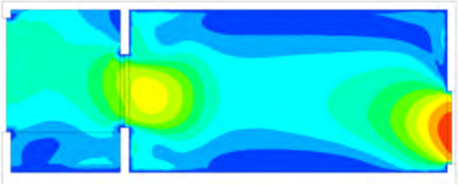
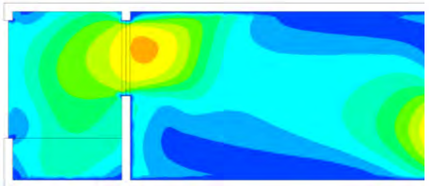
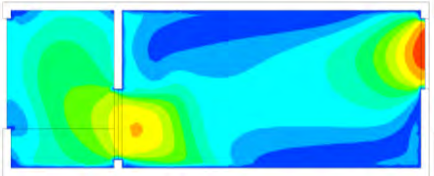
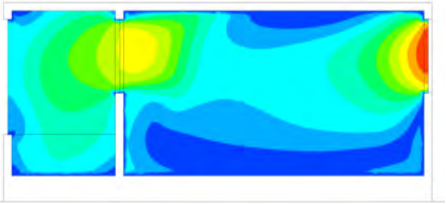
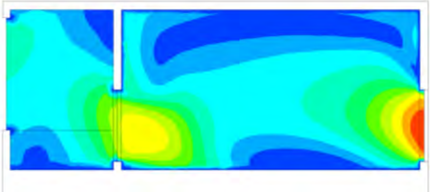
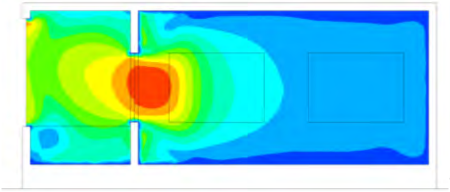
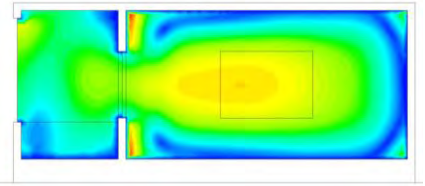
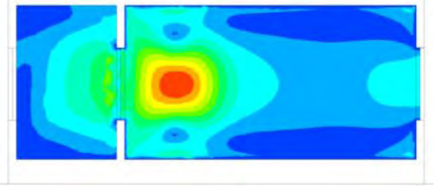
Case 1	Case 2	Case 3
		
Case 4	Case 5	Case 6
		
Case 7	Case 8	Case 9
		
Base Case		
		

Table 7-5: Contours showing a vertical section of vector

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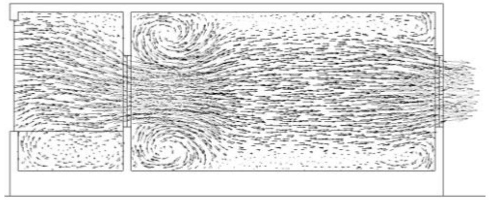
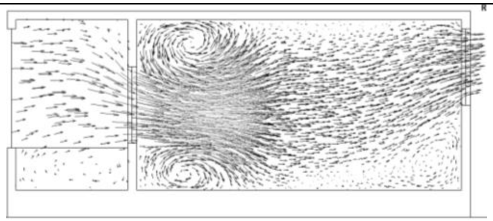
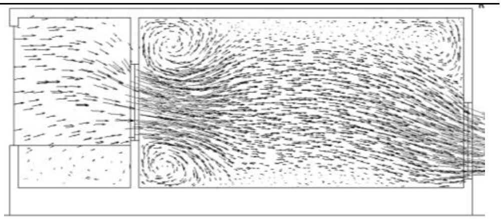
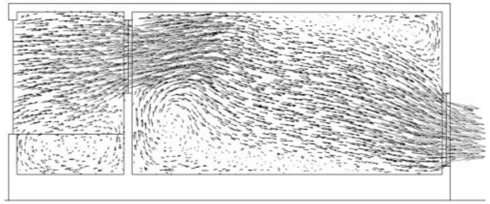
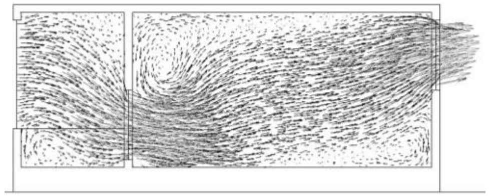
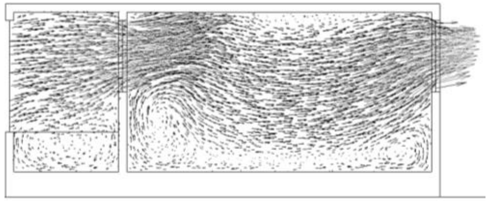
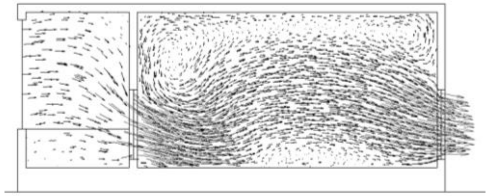
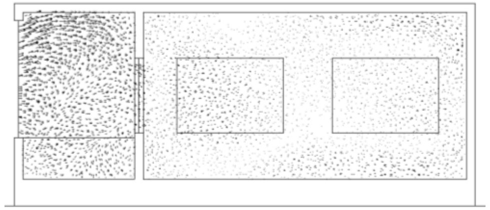
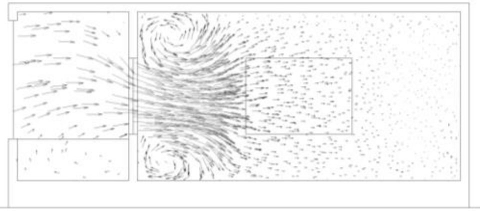
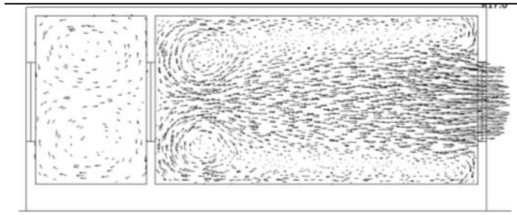
		
Case 4	Case 5	Case 6
		
Case 7	Case 8	Case 9
		
Base Case		
		

Table 7-6: Contours showing a vertical section of PMV of the ward

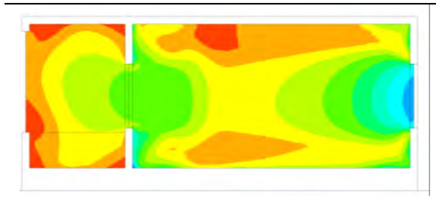
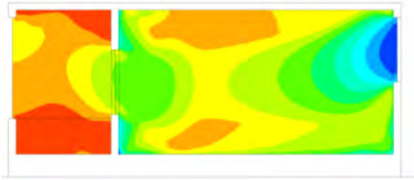
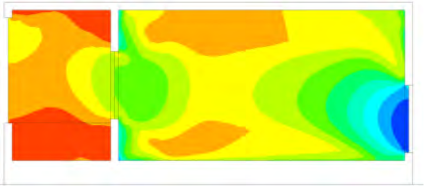
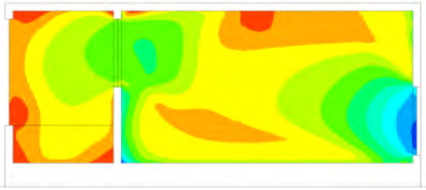
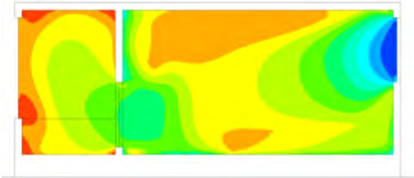
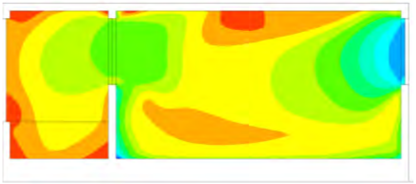
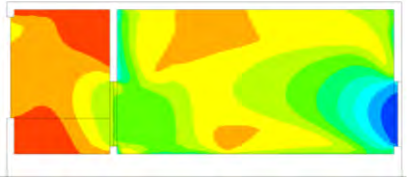
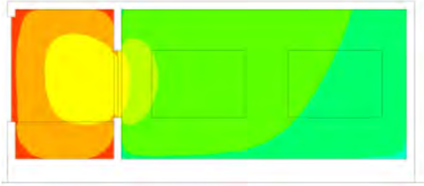
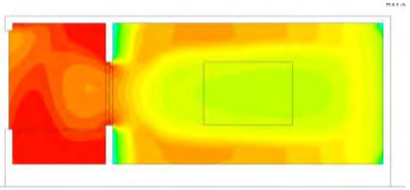
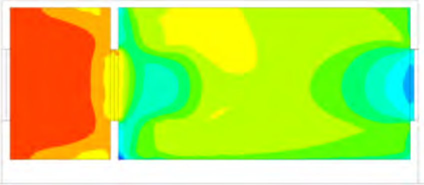
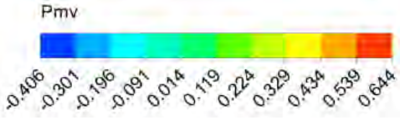
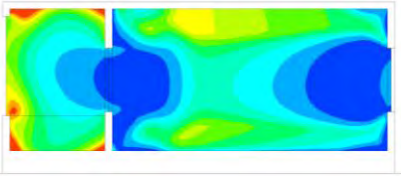
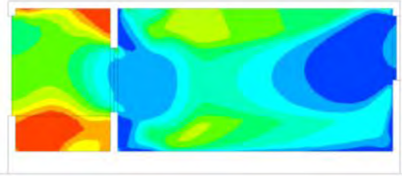
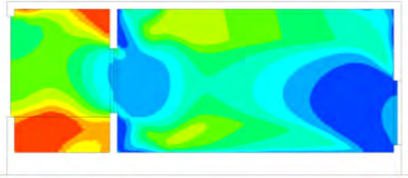
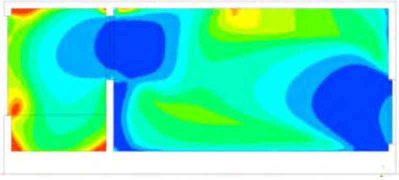
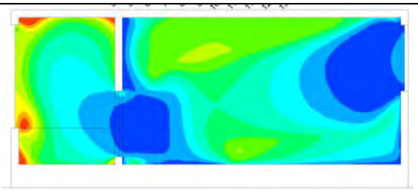
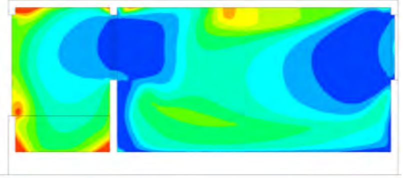
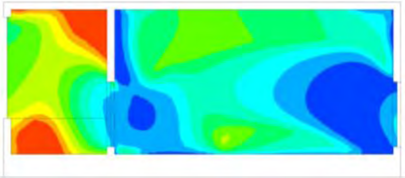
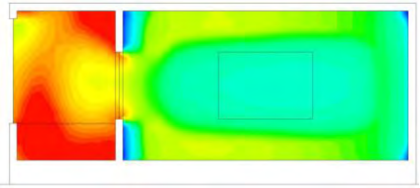
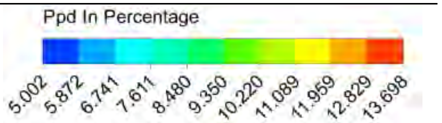
Case 1	Case 2	Case 3
		
Case 4	Case 5	Case 6
		
Case 7	Case 8	Case 9
		
Base Case		
		

Table 7-7: Contours showing a vertical section of PPD of the ward

Case 1	Case 2	Case 3
		
Case 4	Case 5	Case 6
		
Case 7	Case 8	Case 9
		
Base Case		
		

Surprisingly, all simulated results indicate that volumetric airflow and air change rates alone are insufficient to determine ventilation efficiency and effectiveness; instead, indoor air circulation and distribution at the occupancy level are also required. This is because of the consequences of the short-circuiting phenomenon, which results in inefficient yet high volumetric flow and air change rates. In case 1, the volumetric airflow rates are 0.392 m3/s, and the air change rate is 9.16 ach-1. Thus, in terms of volumetric airflow rate, air change rate, and airflow distribution, Case 1 is the best of the ten simulated and studied situations and chosen for additional ventilation study.

7.4 Percentage Dissatisfied (PD) and Ventilation Rate

The needed ventilation rates and air change per hour are commonly defined as acceptable indoor air quality (Bjarne W Olesen, 2011). Therefore, this part of the study deals with the Percentage Dissatisfied (PD) and ventilation rate of the hospital wards. ASHREA (2013) defines indoor air quality as *"Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction"*.

The percentage dissatisfied is used to establish ventilation requirements to obtain a specific level of air quality. Air change rates for different ventilation opening scenarios have been obtained through simulation. The corresponding percentages of dissatisfaction caused by a standard person at these ventilation rates were estimated using Figure 3-19. The air change rate in L/S per standard person was estimated for hospital multi-bed ward occupancy of 15, 25, and 35 standards person, and the results are presented in Figure 7-4. The percentage of dissatisfied per standards persons is obtained by dividing the ACR in L/S by the number of persons, as presented in

Table 7-8. The base-case ward was initially designed to accommodate ten beds. Hence, the 25 and 35 standards person was used to assume 10 patients with; 10/20 relatives and 5 HealthCare Workers (HCW)/nurses. In all the 10 cases, the result indicates that the highest percentage dissatisfied (PD) with indoor air quality for 15, 25, and 35 standard persons are 12%, 25%, and 32%, respectively.

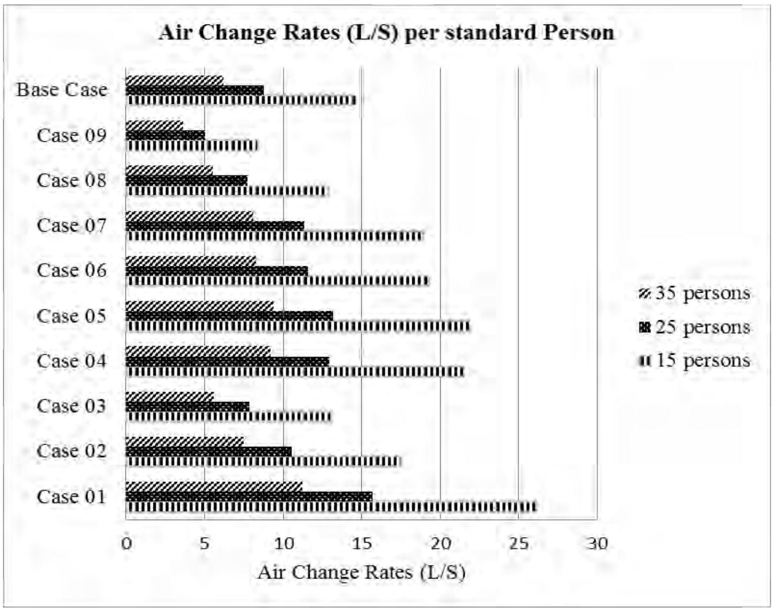


Figure 7-4: Air change rates (l/s) per standard person for different occupancy levels

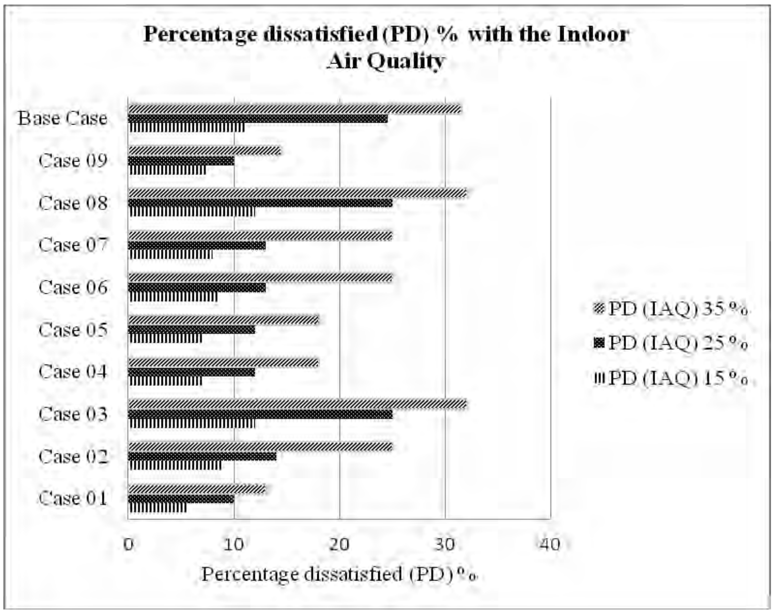


Figure 7-5: Percentage Dissatisfaction (PD) % with the indoor air quality

The CIBSE recommends a minimum ventilation rate of 60 l/s/patient in hospital wards. As a result, the studied ward can only accommodate four (4) people in the existing setup. However, in the improved case 1, seven (7) patients could accommodate. Thus, from the perspective of hospital infection control, either the volumetric flow rate of the rooms must be increased, or the patient population must be reduced.

Table 7-8: Air change rates per standard person for different occupancy levels and their corresponding percentage of dissatisfactions (PD)

Cases	Airflow rate (m3/s)	Volume (m3)	ACR (ach-1)	ACR (L/S)	15 Standard Persons	PD (IAQ) %	25 Standard Persons	PD (IAQ) %	35 Standard Persons	PD (IAQ) %
Case 01	.392		9.16	392	26.13	5.5	15.68	10	11.2	13
Case 02	.263		6.13	263	17.53	9	10.52	14	7.51	25
Case 03	.196		4.56	196	13.06	12	7.84	25	5.6	32
Case 04	.323		7.52	323	21.50	7	12.92	12	9.22	18
Case 05	.329	154.62	7.67	329	21.90	7	13.16	12	9.40	18
Case 06	.290		6.76	290	19.33	8.5	11.60	13	8.28	25
Case 07	.283		6.59	283	18.86	8	11.32	13	8.08	25
Case 08	.193		4.50	193	12.86	12	7.72	25	5.51	32
Case 09	.126		2.93	126	8.40	17.1	5.04	30	3.6	42
Base Case	.220		5.12	220	14.66	11	8.80	24.5	6.28	31.5

7.5 Local Indoor Air velocity, Turbulent Intensity, and Local Air Temperature

The local indoor air parameters such as velocity, turbulent intensity, and air temperature are necessary to better understand the airflow distribution and efficiency in the hospital wards. In this study, nine (09) different points were selected, three (3) each at the Windward side (W 1-3), Centre of the room (C 1-3), and Leeward side (L 1-3), to study the indoor local velocity, turbulent intensity, and air temperature. Points 1, and 3, in all the cases (W, C, L), are directly opposite the window openings, while point 2, the position is directly opposite the walls, as illustrated in Figure 7-6.

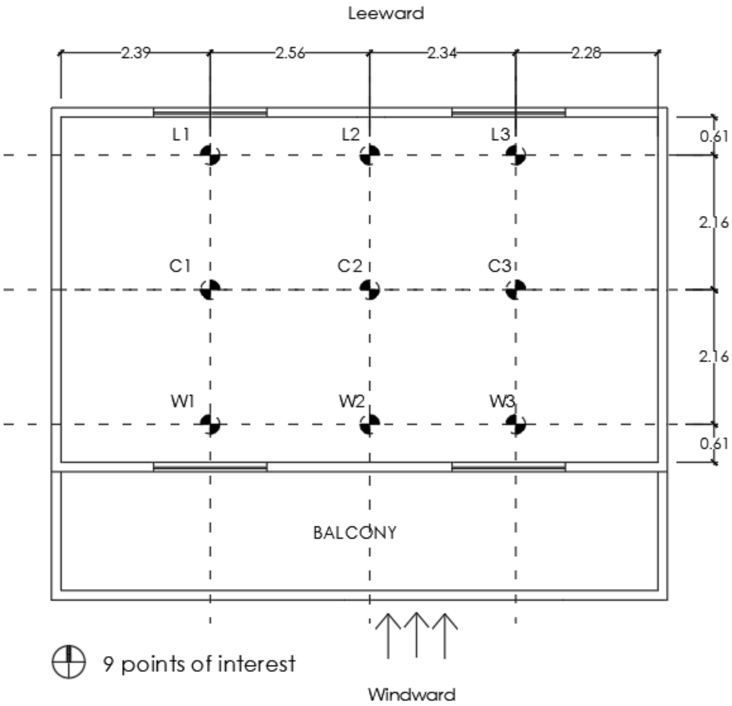


Figure 7-6: The measuring points for local indoor air parameters

7.5.1 Local Indoor Air Velocity

Compared to overall indoor air velocity, local indoor air velocity at different points of interest offers more precise knowledge about airflow distribution within an indoor environment. When evaluating ventilation effectiveness, the average airflow and the distribution of air velocities around the ventilated space should be considered. Furthermore, when concerned with ventilation in terms of its impact on comfort, airspeed over the human body is essential (Alwetaishi, 2016).

In this study, the local indoor air velocity at nine (09) points was measured at two occupancy heights of 1.0 m and 0.6 m above floor level to represent patient relatives seated on chairs and patients on beds. These measurements were conducted for both the Base-case and Case-1. The result indicates that the maximum local indoor airspeed is achieved at the points opposite the inlet openings (points 1 and 3) in both the 1.0 m and 0.6 m height cases., as illustrated in Figure 7-7 & Figure 7-8.

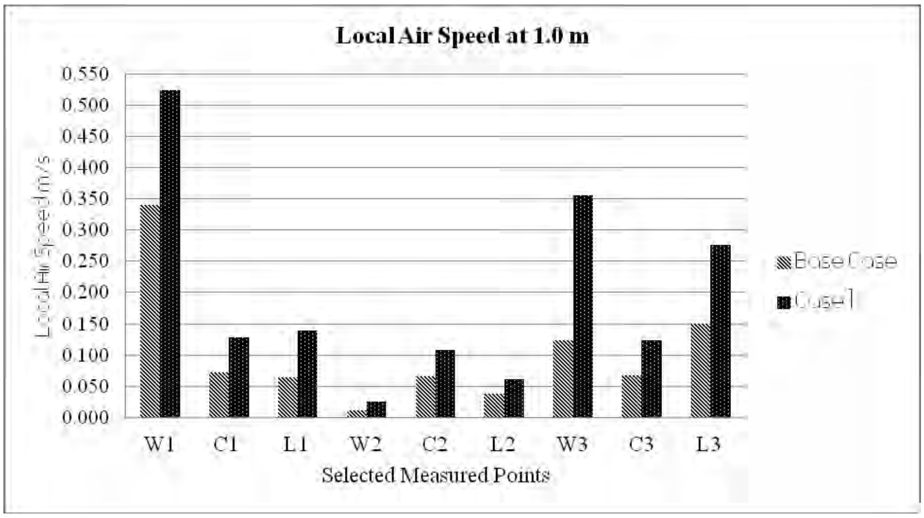


Figure 7-7: The comparative analysis of local indoor airspeed at 1.0 m above the floor level of the base case and case 1

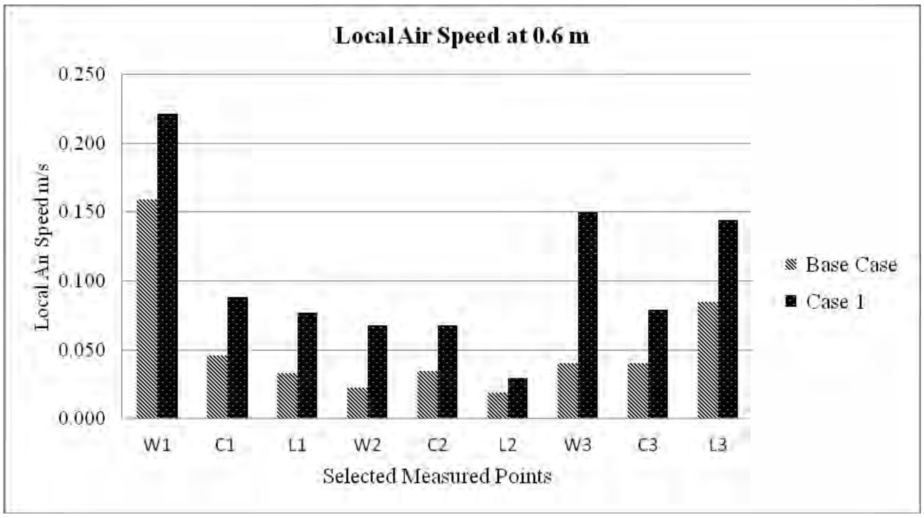


Figure 7-8: The comparative analysis of local indoor airspeed at 0.6 m above the floor level of the base case and case 1

Indoor air velocities are higher on the air inlet side of a ventilated space before decaying to a considerably lower value further downstream. The airspeeds are decaying at the points opposite the walls (Points 2). The airflow starts with a higher velocity opposite the windows in the windward location and significantly drops opposite the wall (L3). In the Centre, low air velocities are experienced with little variation in all the positions. Similarly, the velocities are higher on the leeward side adjacent to the windows and slightly lower adjacent to the wall. However, the variation is much lower than the windward side, as illustrated in Figure 7-7 & Figure 7-8.

The study clearly demonstrates that the highest indoor air velocities at the windward side of the ward near and opposite the inlet openings (W1) are 30% increased for 1.0 m levels. Similarly, the indoor air velocities at the windward side of the ward opposite the inlet openings (W1) are 45% decreased for a 0.6 m level. However, in their study, Yau et al. (2011) indicated that a local airspeed of 0.25 m/s or less is deemed comfortable for inhabitants in the tropics. Furthermore, variations in metabolic rates and clothing among patients and hospital staff would also result in different perceptions and requirements.

7.5.2 Local Indoor Turbulent Intensity

Local turbulent intensity is one of the major factors determining draught risk in building an indoor environment. In this study, the local turbulent intensity has been measured at nine (9) different points in the hospital ward, three (3) locations each at the windward, Centre, and leeward sides of the room. Interestingly, The results show that the higher the airspeed, the lower the turbulent intensity in the studied ward. This effect has also been observed by (Mohammed et al., 2013). This will be established by comparing Figure 7-9, Figure 7-10 below.

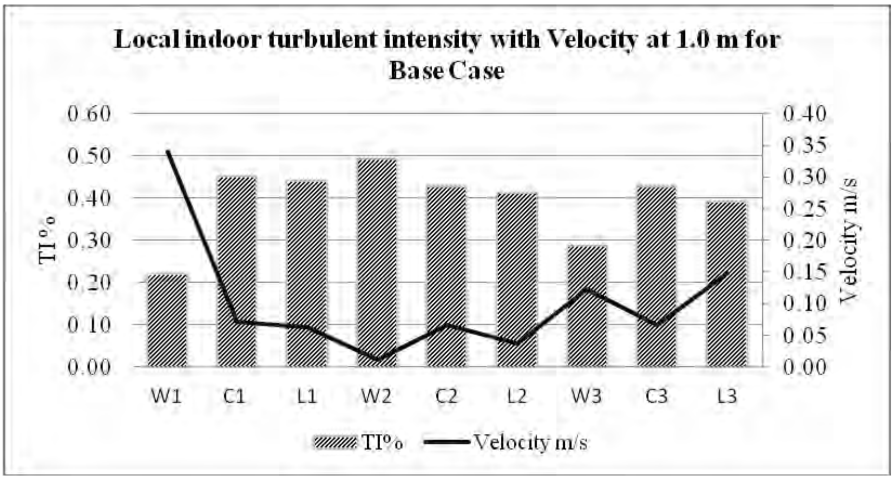


Figure 7-9: Local indoor turbulent intensity with velocity at 1.0 m for base case

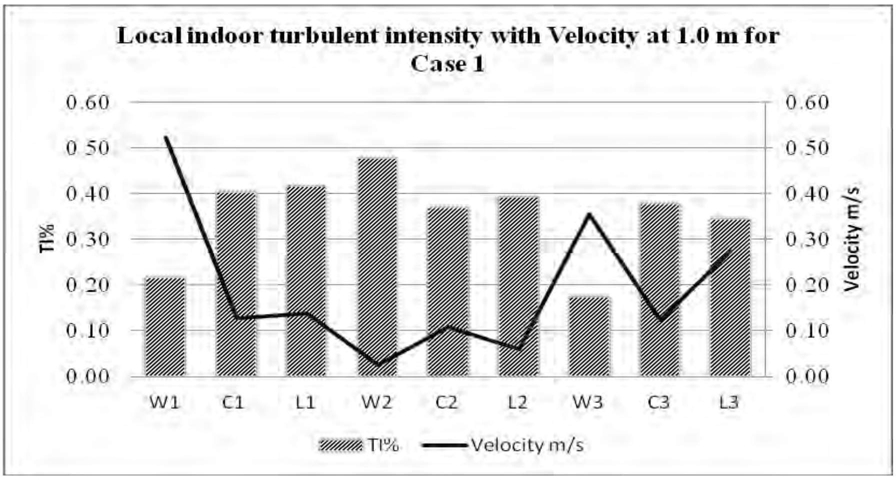


Figure 7-10: Local indoor turbulent intensity with velocity at 1 m for case 1

7.6 Local Draught Risk

Air temperature, air velocity, and turbulence intensity are the three main factors that determined the percentage of people complaining about draughts in the building. Hence, the 'percentage of dissatisfied' persons, PD, due to draughts, can be estimated from the empirical relationship published by Fanger et al. (1988) using Eq. 7-1.

$DR = (34 - t)\,(v - 0.05)^{0.62}(0.37vT_u + 3.14)$ Eq. 7-1

Where, t = Air temperature ($_o$C)

v = Local indoor mean air velocity (m/s)

T_u = Indoor turbulence intensity

In this study, the percentage of people dissatisfied due to draught in nine (9) points has been studied, and the result shows that all the points at the center and by the leeward side of the room have no risk of draught. The results indicate that the draught risk is higher in case 1 compared to the base case at both 1.0 m and 0.6 m occupancy heights. However, the highest draught risk at 0.6 m occupancy level is 7.09% and 5.88% for case 1 and base case, respectively, as illustrated in Figure 7-11. Moreover, the highest draught risk at 1.0 m occupancy height is about 11.72% and 10.02% for case 1 and base case, respectively, as illustrated in Figure 7-12.

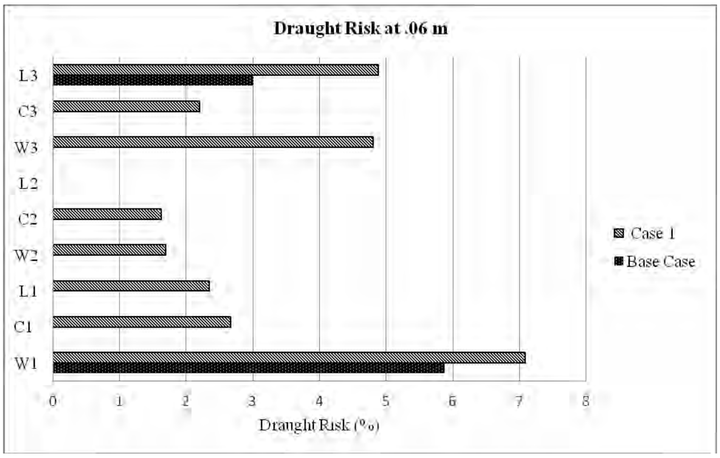


Figure 7-11: The comparative analysis of local draught risk at .6m height

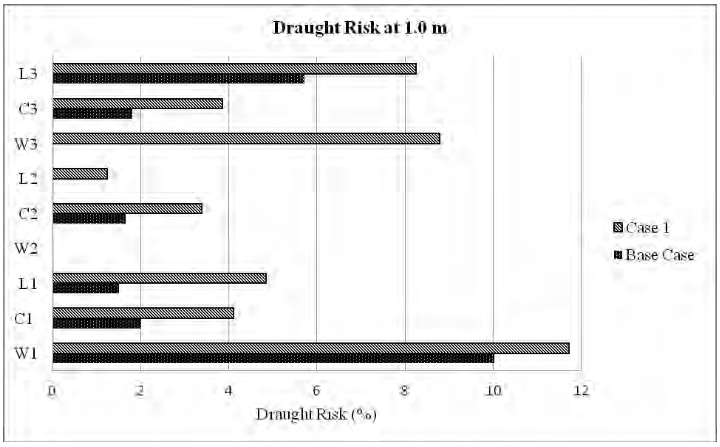


Figure 7-12: The comparative analysis of local draught risk at 1.0 m

The air velocity in a room can increase draught sensation; however, it may also improve comfort under warm conditions. The recommended air velocity of 0.15 m/s applies to the controlled environment in mild climates. However, in uncontrolled buildings with natural ventilation in hot climates, people can experience comfort with higher airspeeds. In heated environments, air velocities of up to 2 m/s may be comfortable (Cuaron et al., 2011). Several studies have shown that building inhabitants in tropical climates can tolerate higher draught rates while remaining comfortable. As a result, in the context of this analysis, the greater the draught chance, the better. Thus, the effect of draught is negligible in naturally ventilation buildings in hot climates like that of the study area.

7.7 Building Orientation and Natural Ventilation

The orientation of the building indicates the direction faced by the exterior elevation of the space. Various factors influence its selection. The major concern of this study is the nature of the climate because the study is mainly regarding outdoor wind speed and direction and their effects on indoor air flow rates and direction. Furthermore, it has been established that airflow rates in hospital wards must be implemented with predetermined patterns and directions to ensure proper ventilation in the wards (Li, Y. G. et al., 2008).

The orientation of building openings with the wind flow direction is one of the major factors determining indoor spaces' airflow rate. In this study, four (4) different orientations (Figure 7-13) were considered, including 0°, 30°, 60°, and 90° to the wind flow directions, and the wind velocity imposed on the computational domain's inlet was 0.4 m/s. These orientations were simulated to ascertain the difference in air change rates and the characteristics of indoor air distribution.

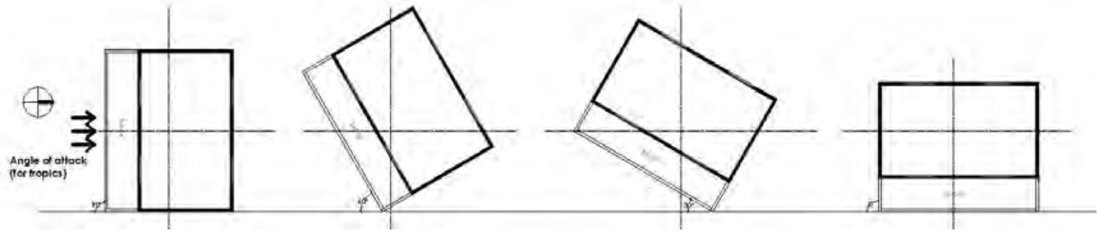


Figure 7-13: Different ward orientations studied

7.7.1 Volumetric Flow Rates and Orientations

The simulation was conducted to ascertain the influence of building orientation on volumetric airflow rates using a base-case and enhanced case 1, considering the four (4) selected wind directions. The result showing the volumetric/airflow rates of the multi-bed ward volume is presented in Table 7-9.

Table 7-9: Volumetric flow rates (m3/s) of different ward orientations for base case and case 1

Orientation	Volumetric Flow Rates (m3/s)	
	Base Case	Case-1
90 Degrees	0.34	0.44
60 Degrees	0.21	0.26
30 Degrees	0.18	0.20
0 Degrees	0.12	0.14

The volumetric airflow rates for cases with 90° orientation are the highest, followed by 60°, 30°, and 0°, respectively. Table 7-9 and Figure 7-14 illustrate the influence of orientation on volumetric airflow rates in the two simulated cases. The higher the angle of attack between the ward openings and the airflow direction, the higher the volumetric airflow rates in the wards.

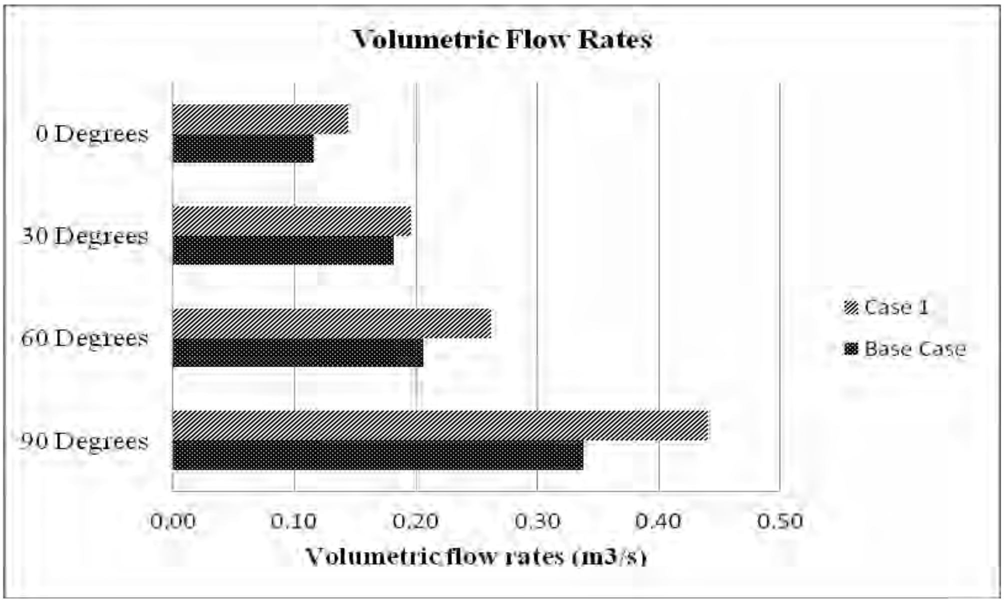


Figure 7-14: Volumetric flow rates of different ward orientations for the base case and case 1

7.7.2 Air Change Rates and Orientation

The simulation was performed to determine the effect of building orientation on air change rates using the base-case and case 1 for the four wind directions chosen. The results show that the maximum air change rate is obtained when the ward orientation with respect to the wind flow direction is 90°, followed by 60°, 30°, and 0°, respectively. Furthermore, air change rates in 90° and 60° orientations achieved the ASHREA standard of 6-ach-1 in hospital wards for case 1. As shown in Table 7-10, the remaining orientations (30^0 and 0^0) did not meet this criterion.

The comparative study of the two cases shows that case 1 has the highest air change rates in all four orientations, indicating its potential to eliminate pollutants in hospital multi-bed wards. The greater the air change volume, the greater a ventilation system can eliminate indoor air pollution by replacing polluted air with fresh air. Table 7-10 and Figure 7-15 demonstrate the comparative outcomes of the two situations of the four (4) separate orientation scenarios.

Table 7-10: Air change rates of different ward orientations for the base case and case 1

Orientation	Air Change Rates (ach-1)	
	Base Case	Case-1
90 Degrees	7.86	10.24
60 Degrees	4.80	6.10
30 Degrees	4.23	4.56
0 Degrees	2.70	3.35

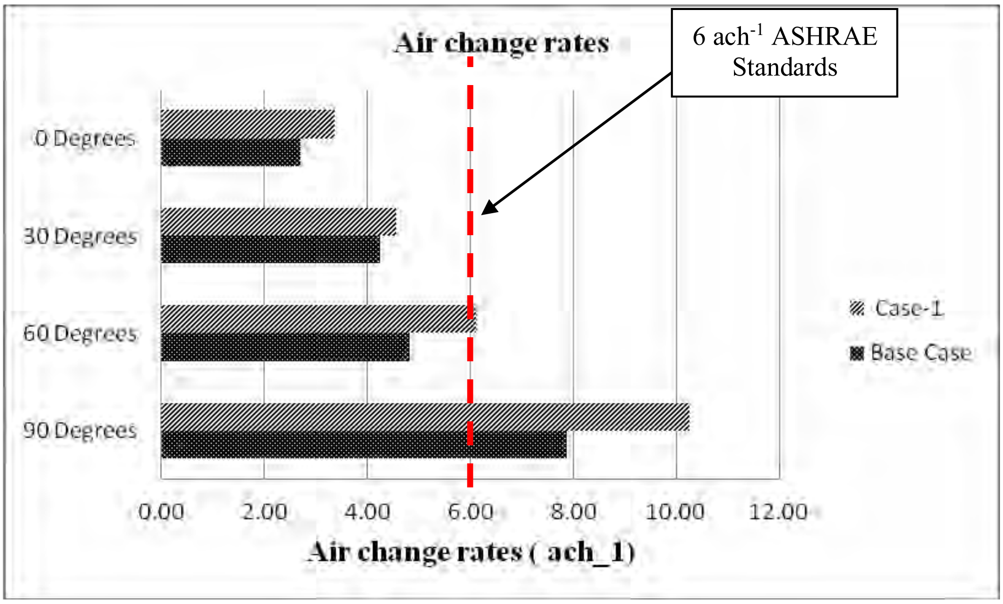


Figure 7-15: Air change rates of different ward orientations

7.7.3 Average Indoor Air Velocity and Orientation

The pattern and speed of the indoor air remain significant factors in determining indoor air quality and comfort in every indoor building space. Average indoor air velocity has been studied for the four (4) distinct orientations considered for base-case and case 1.

The result indicates that the average indoor airspeed for wind flows with oblique orientation (60°) to the inlet openings is higher than the average indoor velocity of wind flow normal (90°) to the inlet openings illustrated in Figure 7-16. Previous researchers have also obtained similar results. Therefore, oblique orientation provides better indoor space air distribution than the perpendicular orientation. Buildings subjected to oblique winds, with angles ranging between 30° and 60° away from the normal, can supply enhanced ventilation conditions in individual rooms and the entire ward. Moreover, the average indoor air velocity for the case with opening orientation parallel (0°) to the wind flow direction is the lowest among the four (4) cases considered, as shown in Figure 7-16 and Table 7-11.

Table 7-11: Indoor average air velocity of different ward orientations

Orientation	Average Indoor Air Velocity (m/s)	
	Base Case	Case-1
90 Degrees	0.03	0.07
60 Degrees	0.06	0.09
30 Degrees	0.05	0.08
0 Degrees	0.02	0.03

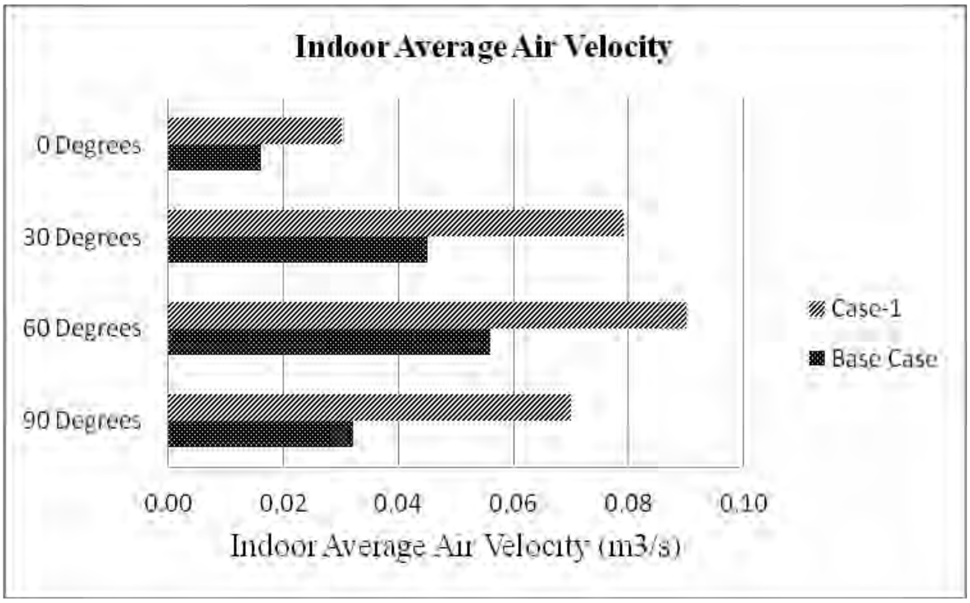


Figure 7-16: Indoor average air velocity of different ward orientations for the base case and case 1

However, airflow distribution and circulation in the two cases are improved in cases with oblique orientations (30o and 60o) than those with 90o orientation and poor 0° orientation. This is because the airflow in cases with oblique orientation travels greater distances due to the unpredictable positions of openings instead of cases with 90° orientation, where the air follows a defined pattern to exit.

The contours of velocity magnitudes in the four (4) orientations are presented in Table 7-10 and Table 7-11, at heights of 1.0 m and 0.6 m above floor levels. Table 7-14 shows the vertical section of the velocity magnitude.

Table 7-12: Indoor air distribution of different ward orientations at 1.0 m. (plan)

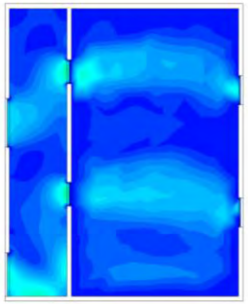
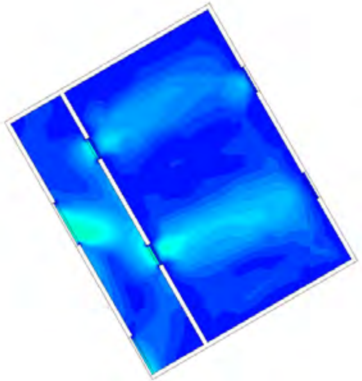
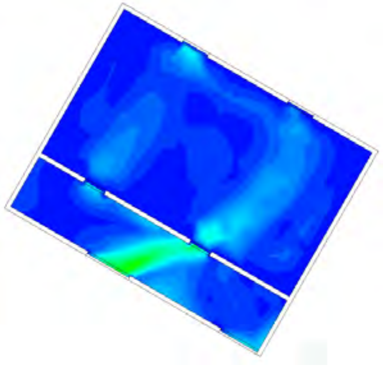
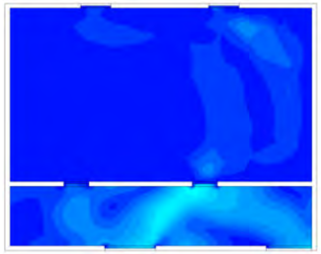
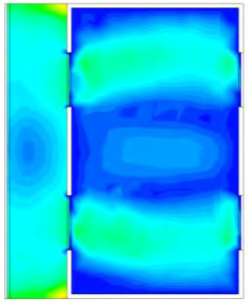
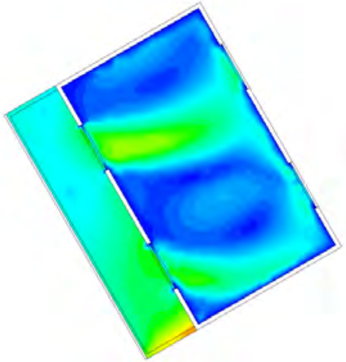
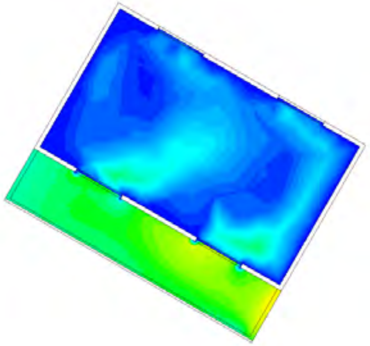
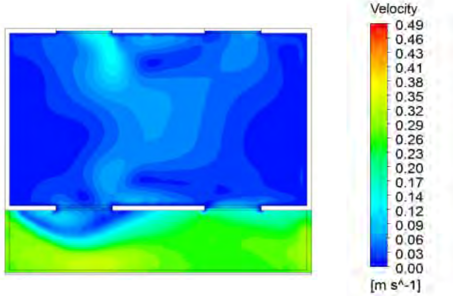
	Base Case (Angle- 90)	Base Case (Angle- 60)	Base Case (Angle-30)	Base Case (Angle- 0)
Wind Direction				
	Case1 (Angle- 90)	Case1 (Angle- 60)	Case1 (Angle-30)	Case1 (Angle- 0)
Wind Direction				

Table 7-13: Indoor air distribution of different ward orientations at 0.6 m. (plan)

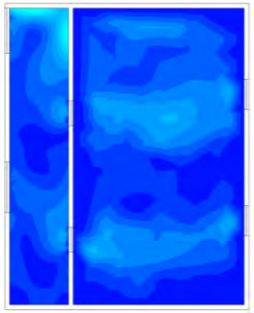
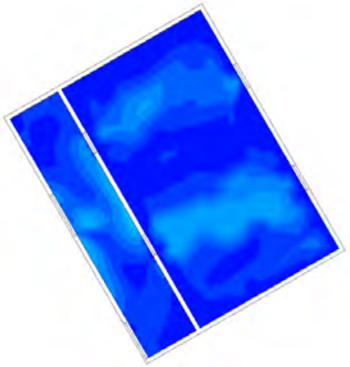
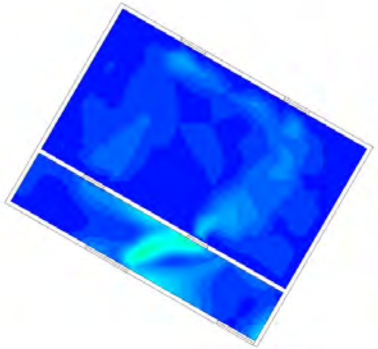
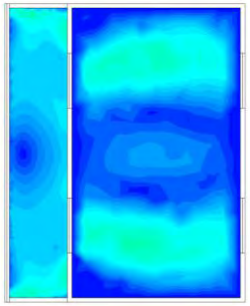
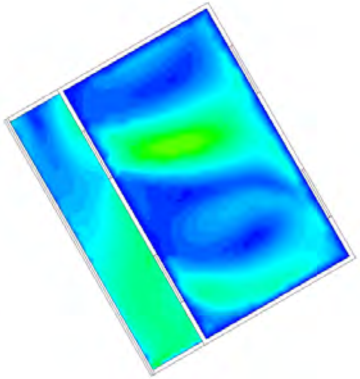
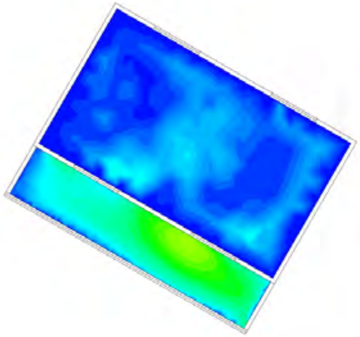
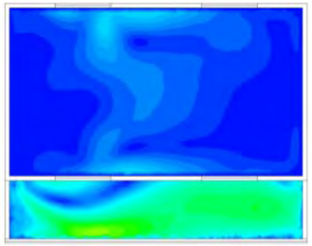
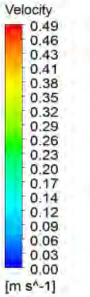
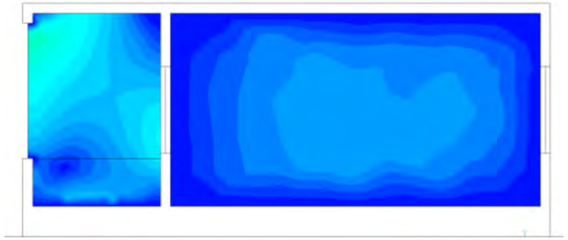
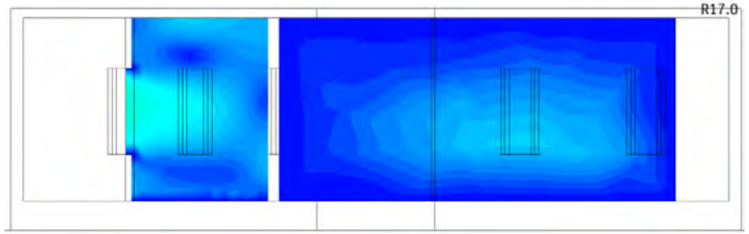
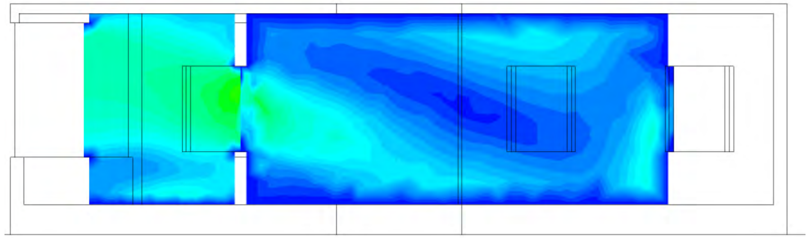
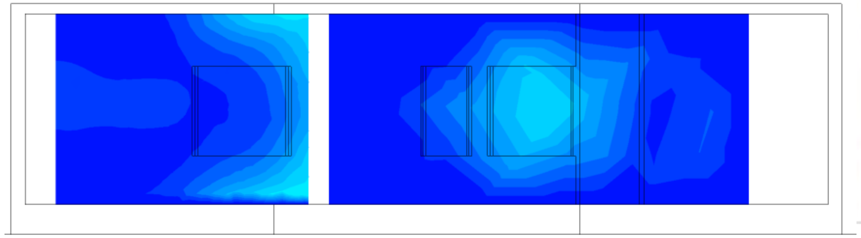
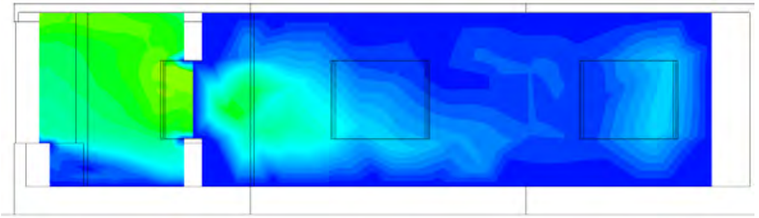
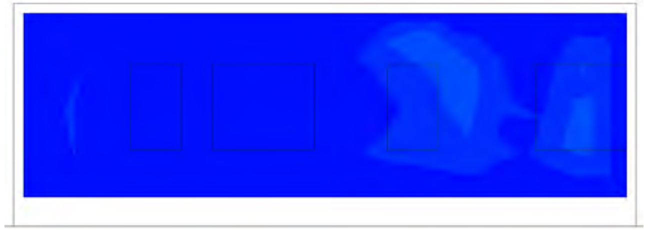
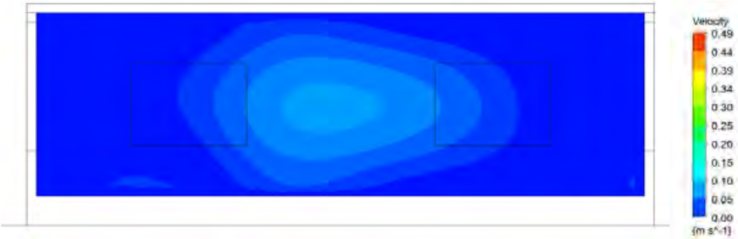
	Base Case (Angle- 90)	Base Case (Angle- 60)	Base Case (Angle-30)	Base Case (Angle- 0)	
Wind Direction					
	Case1 (Angle- 90)	Case1 (Angle- 60)	Case1 (Angle-30)	Case1 (Angle- 0)	
Wind Direction					

Table 7-14: Vertical indoor air distribution of different ward orientations at the centre of the ward (section)

	Base Case	Case 1
Angle- 90		
Angle- 60		
Angle-30		
Angle- 0		

7.7.4 Average Turbulence Intensity and Orientation

However, the variation of average indoor turbulence intensity to building opening orientation is less obvious, as illustrated in Table 7-15 and Figure 7-17, comparing the four (4) orientation cases simulated. However, the turbulent intensity is higher in case 1 compared to the other case considered. Since turbulent intensity increases with decreasing airspeeds, Case 1 has the lowest airspeed in 0-degree orientation, as shown in Figure 7-15, consequently raising the turbulent intensity.

Table 7-15: Indoor average turbulence intensity of different ward orientations

Orientation	Average Indoor Turbulence Intensity (%)	
	Base Case	Case-1
90 Degrees	0.070	0.083
60 Degrees	0.052	0.127
30 Degrees	0.050	0.090
0 Degrees	0.022	0.254

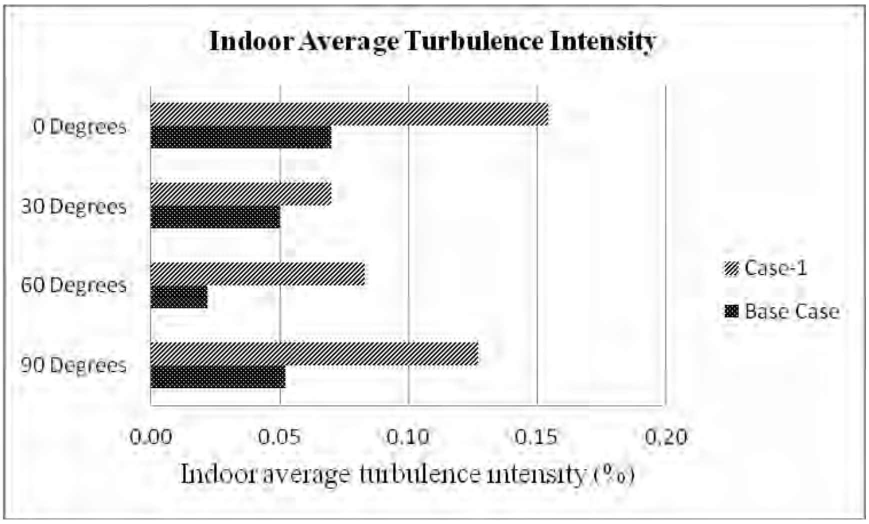


Figure 7-17: Indoor average turbulence intensity of different ward orientations the base case and the case 1

7.8 Monthly Evaluation Of Natural Ventilation In Hospital Wards

The base-case and case 1 were simulated using the study area's monthly average weather statistics to assess the ventilation rates at various times of the year, including monthly outdoor wind speeds and air temperature. The assessment of the monthly air change rates, indoor air velocity, and indoor air temperature is necessary for acquiring detailed information about the hospital ward's indoor air quality and ventilation. The simulations were conducted assuming that the prevailing wind angle to the inlet openings is perpendicular. The results indicate that the highest air flow rates and air change rates are experienced in May, and the lowest airflow rates and air change rates are experienced in March. The airflow and air change rates are higher in case 1 than in the base case. However, the air change rates in all 12 months have satisfied the 6-ach$_{-1}$ ASHRAE recommendation for hospital wards, as illustrated in Table 7-16, Figure 7-18, and Figure 7-19.

Table 7-16: The monthly volumetric flow rates and air change rates

Months	Volumetric Flow Rates m3/s		Air Change Rates ach_1	
	Base Case	Case 1	Base Case	Case 1
January	0.68	0.91	15.73	21.19
February	0.68	0.93	15.77	21.61
March	0.68	0.90	15.73	21.05
April	0.79	1.07	18.37	24.87
May	0.84	1.14	19.63	26.54
June	0.76	1.03	17.79	23.86
July	0.72	0.96	16.69	22.46
August	0.78	1.05	18.21	24.41
September	0.72	0.97	16.74	22.51
October	0.72	0.96	16.69	22.46
November	0.72	0.97	16.74	22.51
December	0.67	0.92	15.66	21.47

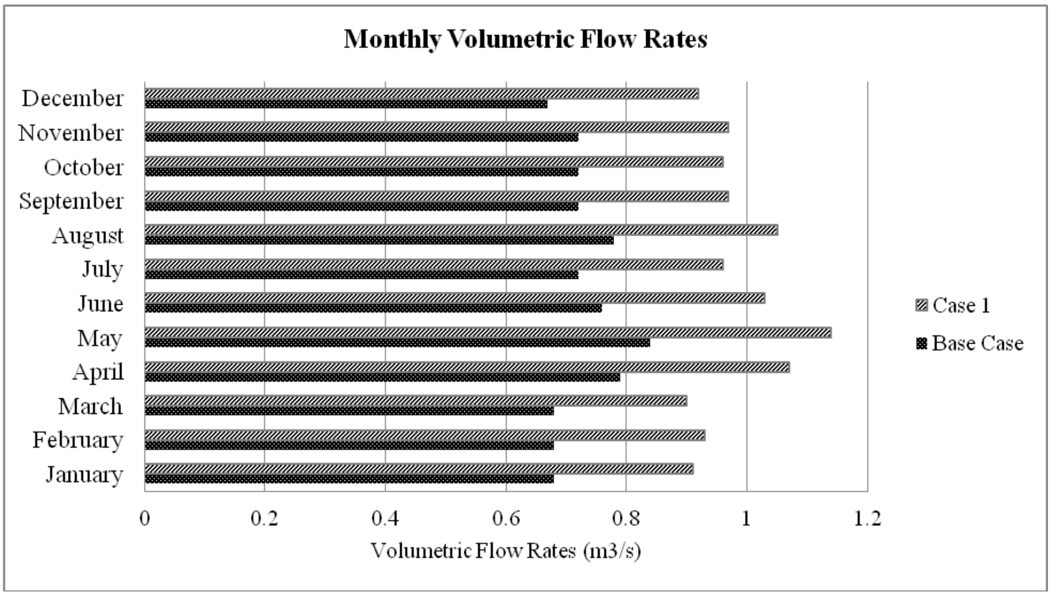


Figure 7-18: Monthly volumetric flow rates in the simulated hospital wards

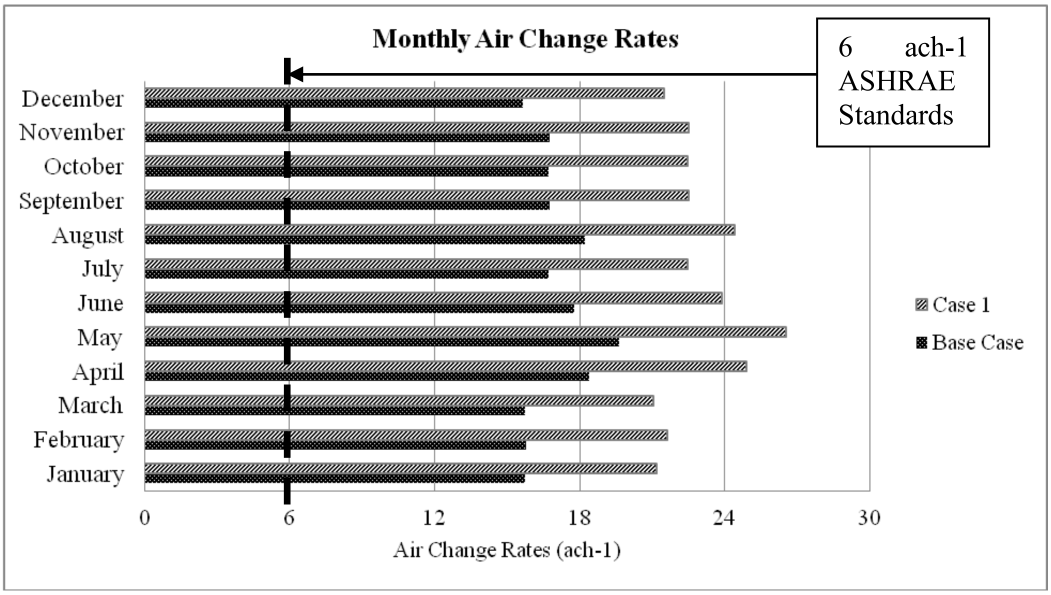


Figure 7-19: Monthly air change rates in the simulated hospital wards

This study studied the influence of monthly outdoor climate conditions on the average indoor air velocity, turbulent intensity, and air temperature. The results indicate that indoor air velocity is higher in case 1 than the base case, as illustrated in Table 7-17 and Figure 7-20. The monthly average indoor air velocity result is similar to the air change rates. The highest average indoor air velocities are experienced in April and May, and the lowest average indoor air velocities are experienced in March. Thus, higher indoor air velocity means the ventilation has greater efficiency in removing indoor air contaminants.

Table 7-17: The monthly average indoor air velocity and turbulent intensity

Months	Avg. indoor air velocity m/s		Avg. Turbulent Intensity %		Avg. Air Temperature ^{o}C	
	Base Case	Case 1	Base Case	Case 1	Base Case	Case 1
January	0.086	0.153	0.017	0.028	18.69	18.72
February	0.088	0.156	0.015	0.024	22.69	22.72
March	0.086	0.152	0.014	0.022	26.43	26.46
April	0.102	0.180	0.017	0.028	28.77	28.80
May	0.108	0.192	0.018	0.030	29.09	29.12
June	0.097	0.173	0.016	0.026	29.39	29.42
July	0.092	0.162	0.016	0.026	28.87	28.90
August	0.099	0.176	0.021	0.034	29.21	29.34
September	0.092	0.163	0.020	0.033	29.17	29.20
October	0.092	0.162	0.020	0.032	27.71	27.74
November	0.092	0.163	0.018	0.029	24.29	24.32
December	0.087	0.154	0.018	0.030	20.41	20.44

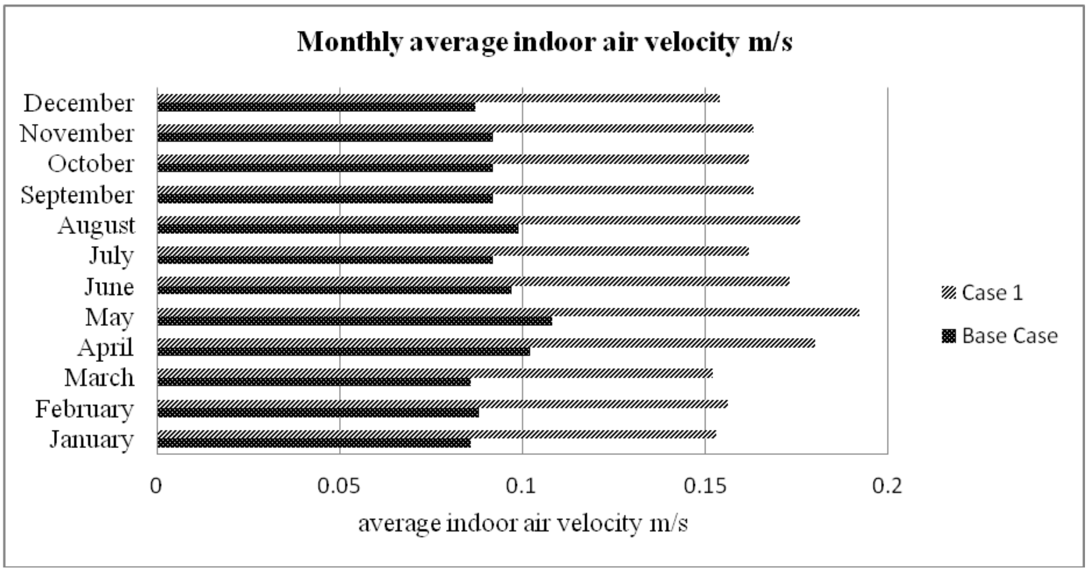


Figure 7-20: Monthly average indoor air velocity in the simulated hospital wards

The results about the turbulent indoor intensity indicate that the turbulent intensity is higher in case 1 compared to the base case. This is because case 1 has higher ventilation rates than the base case (see Figure 7-18). The findings show that the probability of draught risk in case 1 is greater than in the base case. There is a higher chance of draught risk from November to February, at 11.73 %. The rest of the months have low draught risk. In a naturally ventilated building in warm climates, people can experience comfort with higher airspeeds. Thus, the effect of draught caused by the turbulent intensity is negligible in the study area.

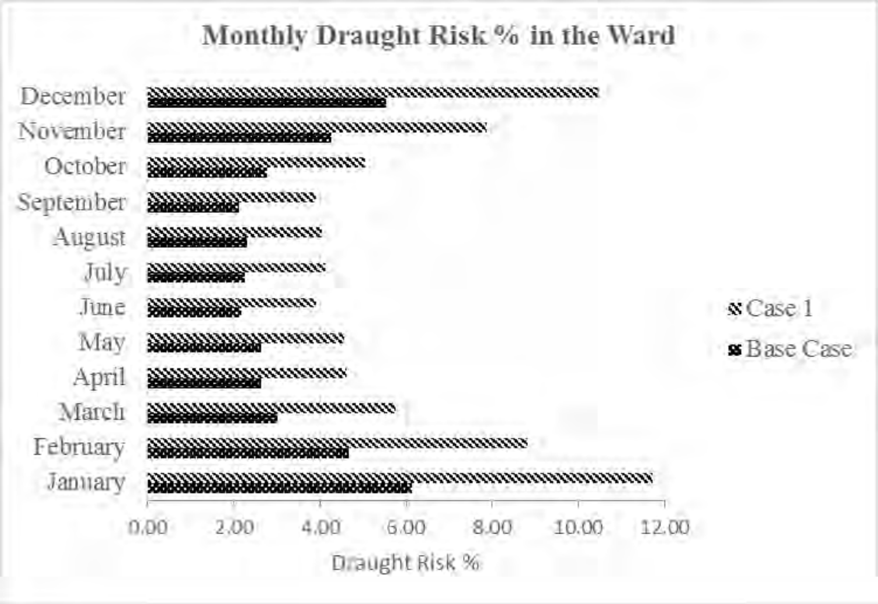


Figure 7-21: Monthly average indoor draught risk in the simulated hospital wards

The average indoor air temperature for different months of the year has been simulated and analyzed. The results indicate that the highest indoor air temperature is experienced in June, and the lowest is experienced in January, as illustrated in Figure 7-22. The adaptive temperature was calculated for the study area. The simulation outcome shows that the temperatures in April to September are slightly higher than the adaptive comfort temperature because the months are the hottest in the study area. On the other hand, temperatures in December, January, and February are lower, as seen in Figure 7-22.

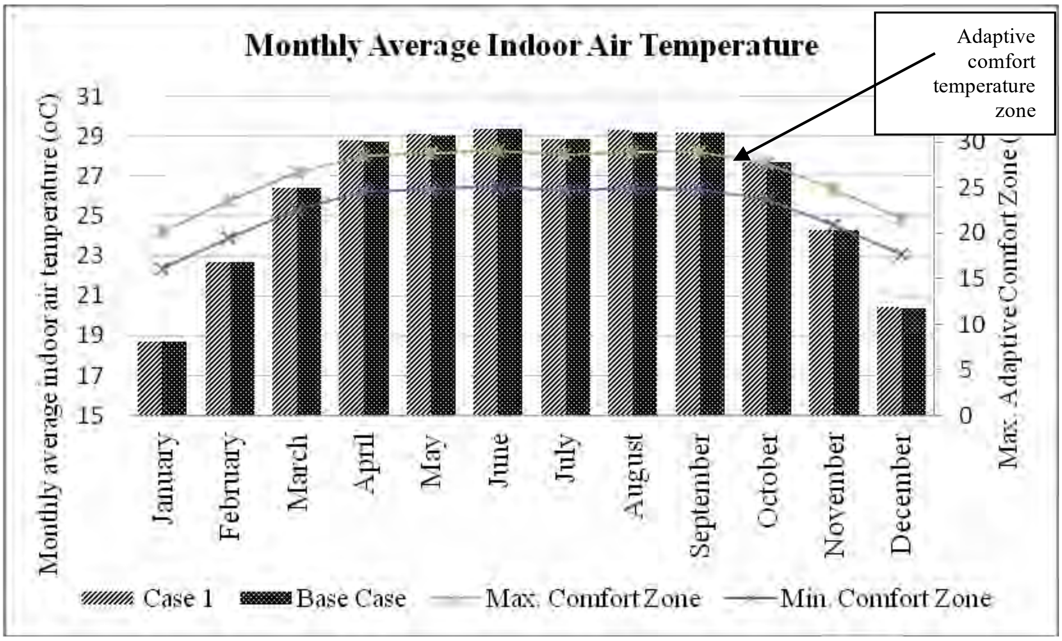


Figure 7-22: Monthly average indoor air temperature(oC) in the simulated hospital wards

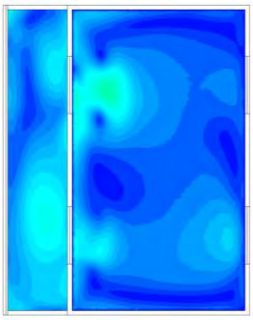
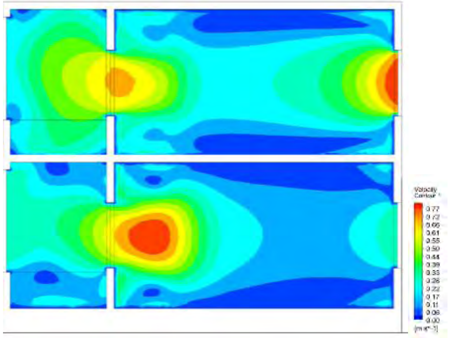
7.9 Evaluation of Multi Bed Ward at First Floor

Case 1 was simulated using the same parameters as the ground floor to estimate the ventilation rate on the first floor except for the floor height. The results show that the airflow rates were more than the ASHRAE standards of 6 ach 1. Nonetheless, it was evident that the temperature increased on the first floor (Table 7-18). As a result, thermal comfort indices increased. Table 7-19 shows the contour of various profiles of the Multi-bed Ward on the First Floor.

Table 7-18: Showing the various profiles of multi-bed ward at first floor

	Volume Flow Rate m3/s	ACH	Avg. Velocity m/s	Avg. Temp. oC	Avg. TI %	Avg. PPD %	Avg. PMV
First Floor	.370	8.614	.103	28.57	.138	20.12	.83

Table 7-19: Contour showing the various profiles of multi-bed ward at first floor

<table>
<tr><th>Horizontal Velocity profile @ .6m</th><th>Vertical Velocity Profile</th></tr>
<tr><td></td><td>
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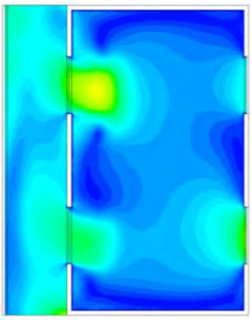
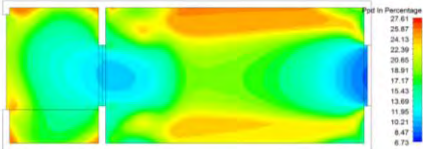
<tr><td rowspan="3"></td><td>
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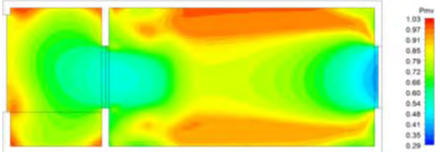
<tr><td>
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7.10 Chapter Conclusion

The analysis of the simulation results leads to conclusions on various issues investigated, including air change rates/airflow rates, air velocity, and turbulence intensity in the hospital wards of the study area. The inlet velocity of 0.4 m/s has been used to investigate the effect of various opening positions on ventilation rates, indoor airspeed, indoor air circulation patterns, and thermal comfort. The chapter also investigated the influence of different ward orientations, ventilation rates, and indoor airspeed in the hospital wards of the study area.

Case 1 is the best in terms of airflow rates, circulation, and distribution. The study also established that air change rates/volumetric airflow rates alone would not measure ventilation efficiency and effectiveness; instead, indoor air distribution and circulation are also essential due to the influence of short-circuiting. The effect of short-circuiting airflow, which results from the close proximity between the inlet and outlet openings, leads to a false estimation of air change rates and volumetric flow rates in an indoor environment.

The highest percentage of dissatisfaction (PD) due to indoor air quality for 15, 25, and 35 standard person occupancy levels are 12, 25, and 32%, respectively. However, Case 1 is among the cases with the lowest dissatisfaction rates.

The highest indoor local airspeeds in the multi-bed wards studied are obtainable opposite the inlet openings. Local indoor airspeeds are higher in the wards' windward sides, followed by the center and the leeward side close to the outlet openings. The highest draught risk estimated at 0.6 m for base-case and case 1 is 5.9% and 7.1 %, respectively. The highest indoor air velocities are 25.75% (0.103 m/s) of the external incident wind velocity for 1.0 m above floor level.

The volumetric airflow rates and the air change rates are higher in cases with external wind incidents typical to the inlet openings (90^{o}) and then followed by angles 60_{o}, $30_{o,}$ and $0_{o,}$ respectively. In case 1, the air change rates in wards with outdoor wind incident angles of 90^{o} and 60^{o} have satisfied the ASHREA standard of 6-ach$_{-1}$ in a patient room, while angles 30^{o} and 0_{o} did not. The study confirms that the average indoor airspeeds for wind flow with an oblique angle of attack to the openings (30^{o} and 60^{o}) are higher than those with a regular (90^{o}) angle of attack. Thus, the oblique orientations provide better airflow distributions than outdoor wind flow orientation normal to the inlet openings, where channel flow develops connecting the inlet and outlet.

For Case 1, the ASHRAE requirement was met based on monthly average wind speeds and temperatures. Moreover, the indoor air temperatures in 3 out of the 12 months in a year have satisfied the adaptive comfort requirements except for April to September, in which the temperatures are slightly higher than the adaptive comfort level.

To assess the various ventilation parameters, case 1 was simulated at first-floor height. The findings demonstrate that the airflow rates exceeded the ASHRAE standards of 6 ach 1. According to the findings, the indoor temperature rises on the first floor. As a result, the PPD increased to 20.12%, and the average PMV was .83. In conclusion, if multi-bed wards are located on the first floor, more attention should be given to ensure the thermal comfort of the occupants.

CHAPTER EIGHT

NATURAL VENTILATION AND INFECTION RISK ASSESSMENT

Chapter Structure

8 CHAPTER EIGHT: NATURAL VENTILATION AND INFECTION RISK ASSESSMENT

8.1 Introduction

The effects of different opening configurations, building orientation, and monthly outdoor wind speed on ventilation rates in hospital multi-bed wards have been analyzed and presented in the previous chapter (chapter 7). The chapter confirms the influence of the parameters mentioned above on ventilation efficiency in hospital wards. In this chapter, the effects of opening configuration, building orientation, and monthly outdoor wind speed on infection risk in multi-bed wards have been discussed and presented. This chapter (Chapter 8) has been intended to satisfy objective 3 (three), *"To **explore the potential of using natural ventilation strategies to reduce the risk of infection in the wards**."*

8.2 Natural Ventilation and Infection Risk Assessment of Influenza in Bangladesh

Respiratory infectious diseases are the third most common leading cause (12.6%) for hospitalization in Bangladesh rural healthcare hospitals (Ahmed, S. et al., 2010). In Bangladesh, short-term fever with flu-like symptoms is a significant public health concern, and it is often caused by viruses, the most common of which is the influenza virus.

Therefore, the current study investigated the effects of opening configuration, building orientation, and monthly outdoor wind speed for assessing the risk of influenza A virus. in the naturally ventilated multi-bed wards.

8.3 Wells-Riley's Model

The Wells–Riley model has been widely used to measure the quantitative transmission risk of respiratory infectious diseases in indoor environments. (Sze To & Chao, 2010). Moreover, the Wells- Riley equation can predict the spatial distribution of airborne pathogens and estimate the effect of ventilation rate on infection probability (Loomans et al., 2020). The probability of infection deduced by the Wells-Riley equation is an indicator for architectural/ventilation performance in preventing infection (Nardell et al., 1992). Therefore, this study's risk of infection is calculated using Eq. 8-1.

$$P = \frac{C}{S} = 1 - exp\left(-\frac{Iqpt}{Q} \right) \qquad \textit{Eq. 8-1}$$

Where P is the risk of cross-infection, C is the number of the case to develop an infection, S is the number of the susceptible, I is the number of infectors, p is the pulmonary ventilation rate of each susceptible (m3/h), Q is the room airflow rate (m3/h), q is the quanta produced by one infector (quanta/h), and t is the duration of exposure (h). Exposure periods can range from days for a patient to a few minutes for a staff member in the inpatient rooms. Thus, transmission risk is determined by the occurrences of chance (Beggs, Clive B. et al., 2003).

8.3.1 Input Parameters

The ventilation rate (Q) and air changes per hour (ACH) for the studied hospital ward of 154.62 m3 were measured for the base case and case 1. ASHRAE and the World Health Organization (WHO) recommend 6 ACH for health settings. Four values of ACH were therefore also studied: 3 ACH (poor ventilation), 6 ACH (minimum international recommended ventilation); 9 ACH (intermediate ventilation); and 12 ACH (optimal ventilation).

For this study, the mean quanta production rate for influenza is 100 quanta/h value used for a highly contagious case (Rudnick & Milton, 2003). However, to compare the low and high quanta values, 15q/h and high quanta values and 128q/h were used. The average breathing rate per patient (p) was estimated to be .45m^3/h (Hegazy et al., 2019) and for adults with a pulmonary ventilation rate of 0.48 m3/hr (approximately the average adult inhalation rate in U.S. EPA, 2011). For the study purpose, 0.48m3/hr has been used for the average breathing rate per patient (p).

The study assumes nine exposed susceptible patients and one infectious case among ten patients in the ward. The hypothetical time period ranges between 15 minutes and 1 hour. According to the mentioned variables, the estimated risk of infection can be calculated using Eq. 8-1.

8.4 Results and Analysis

8.4.1 Association Between Infection Probability and Ventilation Rate

The previous chapter (Chapter 7) presented the various window configurations of the case study wards. Only the base case and case 1 would be considered for the risk assessment. In this study, air change rates and airflow rates have been employed to determine the infection risk assessment of the investigated ward. The volumetric airflow rates obtained from the base case and case 1 are 0.22 m3/s and .39 m3/s, respectively. Table 8-1 and Figure 8-1 show the risk of infection (%) related to ventilation rate, exposure time, and infectivity for the base case and case 1.

A growing number of cases have proved the possibility of airborne transmission of the coronavirus disease 2019 (COVID-19). Ensuring an adequate ventilation rate is essential to reduce the risk of infection in confined spaces. This study estimated the association between the infection probability and ventilation rates with the Wells–Riley equation, where the q is the quanta produced by one infector (quanta/h) was calculated from 15-128 q/h. The various studies found that the quantum generation rate (q) by a COVID-19 infector is 15–48 q/h (Dai & Zhao, 2020).

Table 8-1: Probability of infection (%) related to ventilation rate, time of exposure and infectivity (q/h)

	15q/h				100q/h				128q/h			
Q (m3/s)	15m	30m	45m	1h	15m	30m	45m	1h	15m	30m	45m	1h
Base Case	0.22	0.45	0.68	0.9	1.5	2.98	4.44	5.88	1.91	3.8	5.64	7.46
Case 1	0.13	0.25	0.38	0.51	0.85	1.7	2.53	3.35	1.08	2.16	3.23	4.28

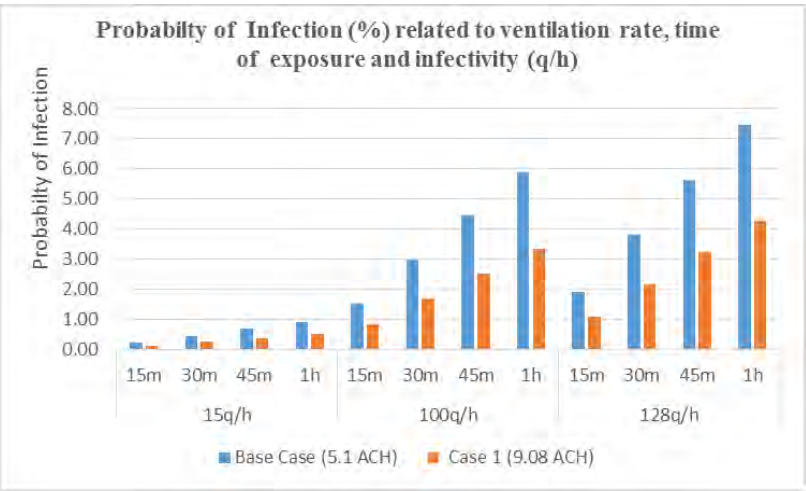


Figure 8-1: Probability of infection (%) of two different ventilation rates

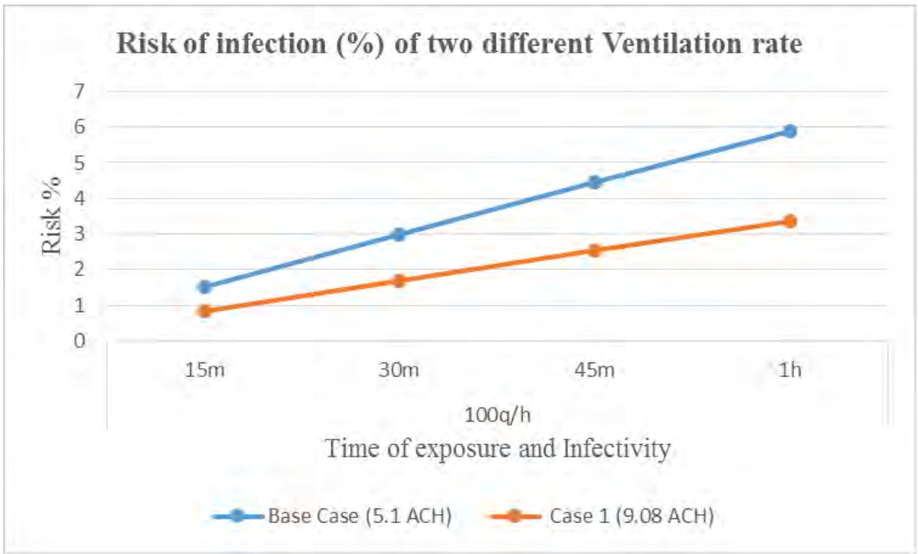


Figure 8-2: Risk of infection (%) of two different ventilation rates

Figure 8-2 compares the probabilities of infection risk (%) of two different Ventilation rates. It clearly shows that the risk of infection decreases with the increase of the ventilation rate. The risk of infection reduces 5.88% to 3.35% in an hour as the ventilation rate increases from 0.22m3/s to 0.39m3/s.

Based on the Wells-Riley model, Figure 8-3 illustrates the estimated probability of infection transmission in the ward when exposed to the three kinds of patients for a hypothetical time duration of 15 minutes.

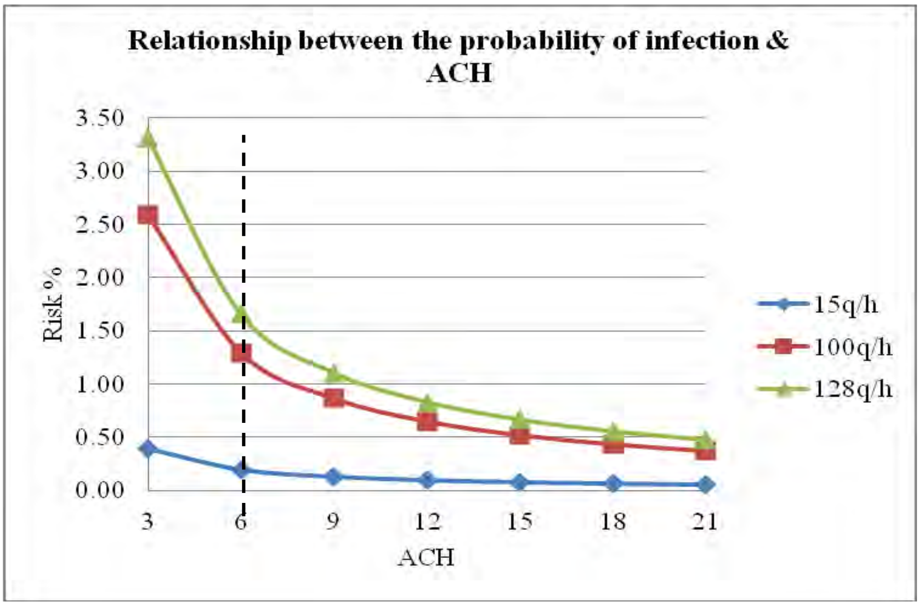


Figure 8-3: Shows the relationship between the probability of infection, ACH, and quanta generation rate using the Wells-Riley model (Exposure time 15m)

Wells-Riley equation gave a rough estimation for the probability of infection transmission inside the ward with different ACH. However, it cannot predict the spatial distribution of risk inside the ward.

When infectiousness is low (q=15q/h), improving the air supply flow rate results in minor improvements in the percentage of infected occupants (Figure 8-3). This implies that while infectiveness is minimal and exposure time is short, the disease would not spread across the community occupying the same indoor enclosure except at a low airflow rate; therefore, the air supply flow rate has marginal improvement in protective effectiveness. When infectiveness is high (100 qph or higher), increasing the air supply flow rate to 6 ACH induces a rapid decrease in infected individuals. These results indicate that the supply flow rate has an important role in occupant protection when the ward has higher infectiveness, with the exposure period of the susceptible population being short (t = 15m).

8.4.2 Ward-Orientation and Infection Risk for Influenza

The orientation of building openings with the wind flow direction is a significant factor determining the airflow rate in indoor spaces. This study considered four (4) different orientations (Figure 7-13 in chapter 7), including 0°, 30°, 60°, and 90° to the wind flow directions. The wind velocity imposed on the inlet of the computational domain is 0.4 m/s. These orientations were simulated to ascertain the difference in air change rates and the characteristics of indoor air distribution because the orientation of building openings with the prevailing wind flow direction has a significant impact on the indoor ventilation rates. Table 8-2 shows the volumetric flow rates (m3/s) with orientations and the risk for the base case and case 1, where infectivity was 100q/h and exposure hour were 1 hour.

Table 8-2: Volumetric flow rates (m3/s) with orientations & probability of risk (%)

Orientation	Volumetric flow rates (m3/s) with orientations & the risk (%)			
	Base Case	Risk %	Case-1	Risk %
90 Degrees	0.35	3.74	0.44	2.98
60 Degrees	0.21	6.15	0.22	5.88
30 Degrees	0.18	7.14	0.20	6.45
0 Degrees	0.11	11.42	0.14	9.08

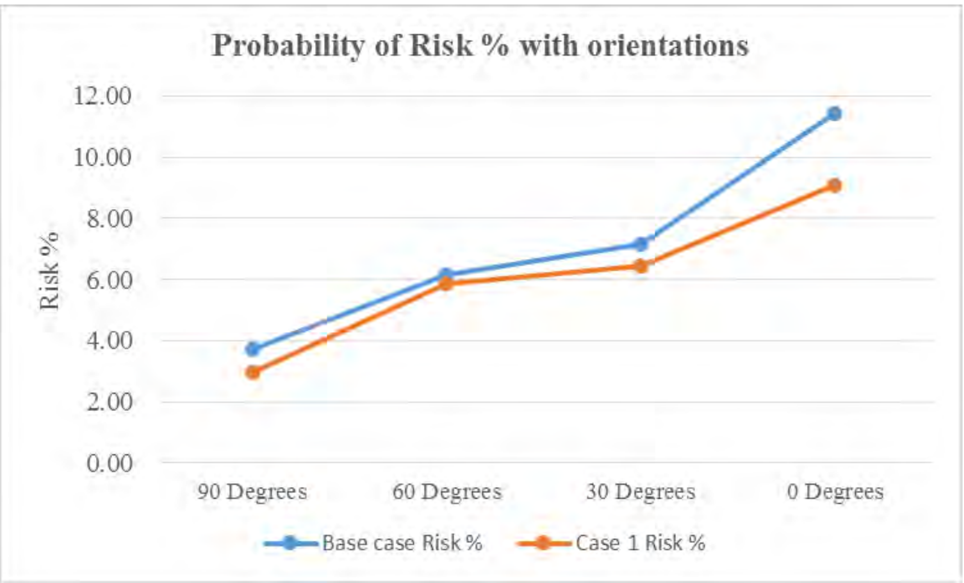


Figure 8-4: Risk of infection with orientations

Figure 8-4 indicates that the orientation of the ward to the predominant outdoor air contributes to a significant increase in the risk of infection. The figure clearly demonstrates that the external wind incidents perpendicular to the inlet openings (90°) result in higher volumetric airflow rates and air change rates, followed by angles 60°, 30°, and 0° help reduce the risk of infection in the ward.

8.4.3 Seasonal Airflow and Infection Risk for Influenza

Influenza, also known as the flu, is a viral infectious disease caused by influenza viruses that affect the nose, throat, and lungs. Seasonal influenza viruses are classified into A, B, and C. The current study only considers influenza A (H1N1), also known as the seasonal influenza virus, among several subtypes of influenza A viruses. Therefore, the infection risk assessment analysis with monthly air change rates, indoor air velocity, and indoor air temperature is necessary to acquire detailed information on the chances of the hospital wards being infected.

Table 8-3: The influenza season in Bangladesh

January	February	March	April	May	June	July	August	September	October	November	December
winter		Pre-monsoon			Monsoon				Post-monsoon		
			🟧	🟧	🟧	🟥	🟥	🟧			

The influenza season in Bangladesh starts from April and lasts up to September, with a peak in July and August (R. U. Zaman et al., 2009), as presented in Table 8-3.

Table 8-4: Monthly volumetric flow rates (m3/s) & the risk (%)

	Base Case			Case 1		
Months	Volumetric flow rates (m3/s)	ACH	Risk %	Volumetric flow rates (m3/s)	ACH	Risk %
January	0.68	15.73	0.493	0.910	21.19	0.366
February	0.68	15.77	0.492	0.928	21.61	0.359
March	0.68	15.73	0.493	0.904	21.05	0.369
April	0.79	18.37	0.422	1.068	24.87	0.312
May	0.84	19.63	0.395	1.140	26.54	0.292
June	0.76	17.79	0.436	1.025	23.86	0.325
July	0.72	16.69	0.465	0.965	22.46	0.346
August	0.78	18.21	0.426	1.049	24.41	0.318
September	0.72	16.74	0.464	0.967	22.51	0.345
October	0.72	16.69	0.465	0.965	22.46	0.346
November	0.72	16.74	0.464	0.967	22.51	0.345
December	0.67	15.66	0.495	0.922	21.47	0.362

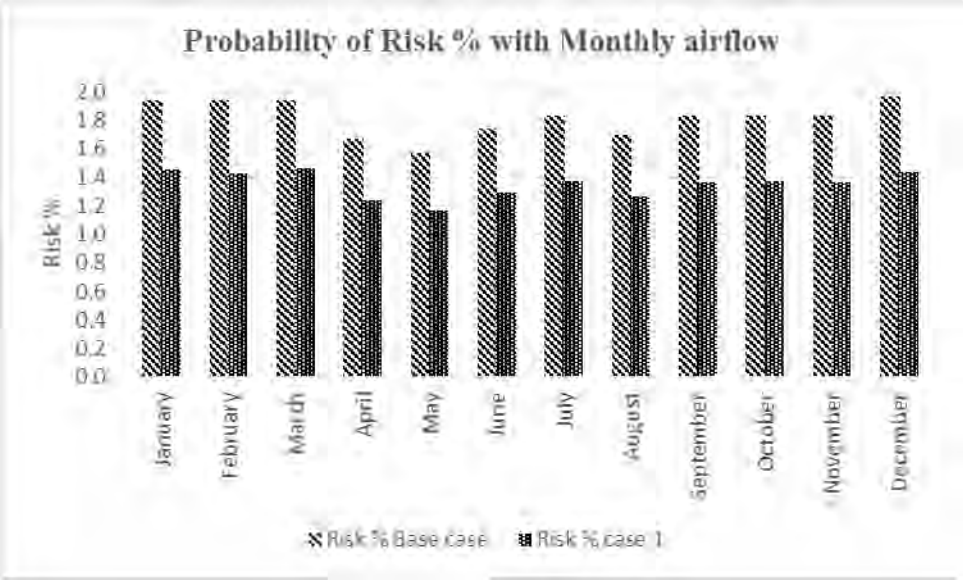


Figure 8-5: Risk % of infection with monthly airflow in Dhaka

The results indicate that the highest air flow rates and air change rates are experienced from April to August, with the risk of infection lower in these months. Conversely, the lowest airflow rates and air change rates are experienced in March, indicating the highest infection risk. The airflow rates and air change rates are higher in case 1 than in the base case. However, the volumetric flow rates of all the 12 months with the probability of risk % for case 1 are illustrated in Figure 8-6.

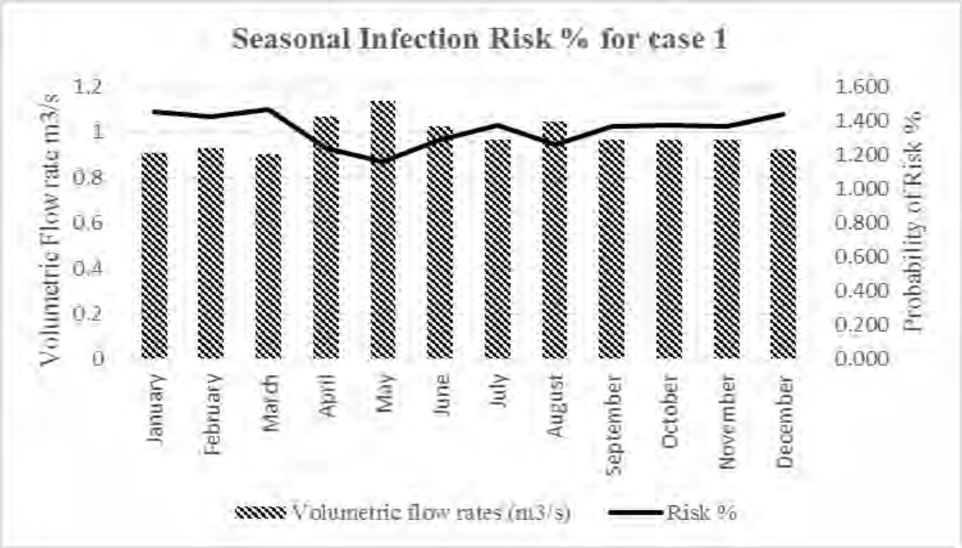


Figure 8-6: Risk % of infection with monthly airflow in Dhaka for case 1

Figure 8-6 shows that the case study ward could provide a higher airflow rate during the months of the influenza season. That reduces the risk of infection in the hospital wards of the case study. However, as airflow levels are lowest in July and September, additional steps should be taken to minimize infection transmission in the case study unit.

8.5 Chapter Conclusion

There is strong evidence that aerosol transmission plays a significant role in influenza spread (Smieszek et al., 2019). As a result, this study investigated the impact of airflow rate, infectiousness, and exposure time on ventilation efficiency in the study wards against the airborne model of influenza transmission. A higher degree of ventilation has been shown to reduce the risk of airborne infection.

The study shows that enhancing the supply flow rate up to 6 ACH significantly decreases the risk of infection. A rise of over 6 ACH, on the other hand, results in small change in infection control. Furthermore, while the infectiousness is low (15 qph), increases in the airflow rate result in negligible improvements in the ventilation's preventive effectiveness. In contrast, an increase in supply flow rate up to 6 ACH leads to a significant improvement in protective effectiveness for relatively moderate infectiousness (100 qph); but, for high infectiousness (128 qph), an increase in airflow rate gradually decreases the infection risk for the short exposure period. (t = 15m). Protection against airborne infection is improved by improving absolute ventilation per occupant, which can be accomplished by increasing the number of ACH or increasing the room volume per occupant for a given air exchange rate.

The volumetric airflow rates and the air change rates are higher in cases with external wind incidents perpendicular to the inlet openings (90^{o}) and then followed by angles 60^{o}, 30^{o}, and 0^{o}, respectively. In case 1, the air change rates inside wards with outdoor wind incident angles of 90^{o} and 60^{o} have satisfied the ASHREA standard of 6-ach-1 in a patient room, while angles 30^{o} and 0^{o} did not. The study confirms that wards to the prevailing wind with 90^{0} perform well in reducing the risk of infection. However, considering indoor distribution and direction with incident angles between 30^{0} and 60^{0}, the performance is better.

This study has also shown that monthly average wind speeds could reduce the study ward's transmission risk. A higher ventilation rate will have a higher capacity to dilute to reduce the cross-infection (Loomans et al., 2020). Since the volume flow rate is the lowest during the influenza season, additional steps must be taken in July to minimize the probability of risk during the peak influenza season.

CHAPTER NINE

CONCLUSIONS

Chapter Structure

9.1 Introduction

9.2 Discussion

9.3 Summary of Key Findings

9.4 The COVID-19 Pandemic and the Significance of the Study Findings

9.5 Limitations

9.6 Recommendations

9.7 Closing Remarks

9 CHAPTER NINE: CONCLUSIONS

9.1 Introduction

This study aimed to investigate natural ventilation strategies in primary health care hospital wards in the Dhaka region of Bangladesh. The preceding chapters (chapter 7 and chapter 8) discussed and analyzed the study results. This final chapter will analyze the research's overall findings and recommend guidelines to improve the indoor thermal environment in hospital wards while minimizing airborne infection risks. Finally, this research's contribution and recommendations for the future scope of work will be discussed.

9.2 Discussion

In the first chapter, it might be noted that most of the available building codes, including BNBC, are developed based on mechanically ventilated buildings. No specific guidelines were found related to natural ventilation in hospital multi-bed wards. ASHRAE requires air changes to ensure that fresh air enters spaces continuously. However, this guideline does not suggest effectively removing contaminated air that may be caught in dead zones or poorly circulated areas, depending on the room configuration.

Besides, overcrowding, inadequate facilities, lack of adequate infection control measures, and ineffective ventilation methods are reported as the primary cause of infection in hospital wards of Bangladesh (Begum et al., 2017). Despite these findings, very few studies have been carried out on natural ventilation strategies in hospital wards in Bangladesh; hardly any research focuses on the effect of architectural design on hospital wards' infection control.

Through a simulation study, natural ventilation strategies for primary health care wards were explored and applied for enhanced indoor air quality. This might be an effective method and approach for improving thermal comfort while reducing infection risks in Dhaka's primary hospital wards. The major conclusion drawn from the various aspects of this study is presented in the following sections.

9.2.1 The Occupants' Psychosocial Perception of The Existing Hospital Wards

The questionnaire survey considered five (5) different indoor environmental conditions, including indoor air quality consideration, thermal comfort, ventilation efficiency, infection prevention measures, and the effect of indoor air quality on health.

The results were discussed in Chapter 4, where it showed that 84% of respondents consider indoor air quality problems in hospital wards when discharging their duties. 93% of the respondents experienced odor problems with the hospital wards. 71% are not satisfied with the thermal comfort in the hospital ward in terms of thermal comfort and ventilation. About 70% responded that they had perceived a direct relationship between indoor air quality and deterioration/improvement in patients' smooth recovery. In comparison, about 20% said there were no effects of the overall ward condition on patient recovery smoothly. Besides, 55% of respondents found the problem of closing windows during the daytime, which increased the risk of infection.

Thus, the above conclusions confirmed ventilation and indoor air quality problems in the studied hospital wards.

9.2.2 The Measurement of Ventilation Rates in the Existing Hospital Wards

The ventilation rate in the studied ward was calculated using the tracer gas decay method. The result showed that the ward's air change rate was 4.9 ach^{-1}, below the 6-ach^{-1} ASHRAE standard for hospital wards during the measurement periods. The tracer gas measurements' results further affirm the occupants' response, showing dissatisfaction with the indoor air quality and ventilation in hospital wards.

Thus, the ventilation system in the hospital wards of the study area needed to be optimized to achieve the standard requirement.

9.2.3 The Opening Position and Ventilation Rates in Hospital Wards

In the present study, the influence of natural ventilation strategies with various opening positions on the ventilation rates and indoor airspeed and distribution has been investigated using ten (10) different cases in Chapter 7. The result shows that case 1 with inlet openings at the middle of the windward façade (Figure 7-3 b) provided the highest air change rates. The sizes of openings to ward floor area in this study were not considered further because the ratio of openings size to ward floor area in the hospital wards studied has satisfied the International Mechanical Code requirement of at least 8% and has achieved the acceptable ventilation rates.

9.2.4 The Influence of Building Orientation on Ventilation Rates

The highest indoor air velocities at the windward sides of the ward, near and opposite the inlet openings, are 30% and 10% of the external incident wind velocity for heights 1.0 m and 0.6 m above floor level, respectively. The simulation results show the highest draught risk estimated at 1.0 m occupancy level for base-case and best-case is 10.2% and 11.72%, respectively. However, the highest draught risk estimated at 0.6 m occupancy level for base-case and case 1 is 5.88% and 7.09%, respectively. These risks are significant in cooler regions, but they have less impact in hot climates, especially in naturally ventilated buildings. This is due to the ability of building occupants in hot climates to withstand higher airspeeds.

Volumetric air flow rates and air change rates are higher in cases with external wind incidents perpendicular to the inlet openings. Oblique orientations (60^o & 30^o) provide better airflow distributions compared to cases with outdoor wind flow orientation normal to the openings. The study confirms that the average indoor airspeeds for wind flow with an oblique angle of attack are higher than those with normal (90^o) angle attacks.

9.2.5 The Influence of Monthly Average Weather Condition on Ventilation Rates, Indoor Air Velocity, and Temperature

The study area's monthly ventilation rates in hospital wards have been simulated using Case1. The results indicated that the highest air change rates of 19.63 ach-1 (base case) and 26.54 ach-1 (Case 1) were experienced in May. The lowest air change rates of 15.66 ach-1 (base case) 21.19 ach-1 (Case 1) are experienced in December and January. However, the air change rates in all the 12 months simulations for both Cases have satisfied the ASHRAE standards of 6-ach-1 in hospital wards. The average indoor air temperatures of the 12 months in a year have satisfied the adaptive comfort requirements except for the months of May, June, August, and September, in which the temperatures are slightly higher than the adaptive comfort level. The highest indoor air temperatures of 29.39^o C (Base Case) and 29.42^o C (Case 1) are experienced in the month of June, while the lowest indoor air temperatures of 18.69° C (Base Case) and 18.72° C (Case 1) are experienced in the month of January.

9.2.6 The Influence of Ventilation Rates on Infection Risk

The Wells-Riley model has been used to analyze the influence of airflow rate, infectiousness, and exposure time against the airborne model of influenza transmission in the case study ward and presented in chapter 8. It is proven that a higher ventilation rate decreases the chance of transmission of viral diseases.

An increase in supply flow rate up to 3 ACH rapidly reduces the infection risk. Analysis indicates that wards to the dominant winds with 30^0 to 60^0 perform well in controlling the risk of infection. The study indicates that the prevailing wind with 90° provides a high air change rate. The oblique orientation provides improved indoor airflow distributions. Thus, the analysis indicates that wards to the dominant winds with 30^0 to 60^0 perform well in controlling the risk of infection.

Further, the studied hospital ward was designed to accommodate ten patients' beds. The WHO and ASHRAE recommend a minimum ventilation rate of 60 l/s/patient in hospital wards. The simulation showed that the studied ward could only accommodate four (4) people in the existing setup following the above codes. However, in the improved case 1, seven (7) patients could accommodate. Thus, from the perspective of hospital infection control, either the volumetric flow rate of the rooms must be increased, or the patient population must be reduced.

9.3 Summary of Key Findings

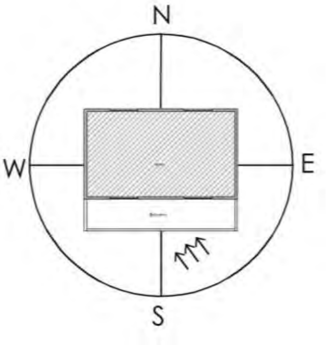
This study investigated six (6) primary-level hospitals of different places in Bangladesh. However, the tracer gas test was conducted at one of the six primary care hospitals studied. Table 4-1 clearly shows that most hospital wards are similar in design, size, height, and openings. All drawings were collected from HED (appendix L) and depicted typical ward features. The SHMH in Manikganj is an example of Bangladesh's typical primary-level hospital ward. Thus, the results of simulations based on SHMH wards could be generalizable.

9.3.1 Design Guidance for Architects’

This section provides recommendations for architects responsible for hospital ward planning and design in tropical climates such as Dhaka. This guidance will serve as feedback for the architects to feedforward for subsequent hospital ward design. These recommendations are based on the findings of the current investigation and are summarized below:

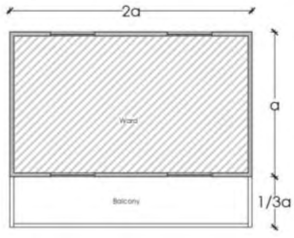
- Site Planning and orientation of the hospital ward

The positioning of hospital wards with wind flow direction is essential for adequate natural ventilation. The simulation results revealed that orienting buildings toward the prevailing wind play a crucial role in improving ventilation performance. Further revealed that hospital wards with oblique opening orientation (within 30 degrees to 60 degrees) to prevailing outdoor wind increase internal air velocity, reducing the infection risk inside the ward. In order to achieve this in the study area, the longer side of the hospital wards should be oriented facing the dominant prevailing wind direction.



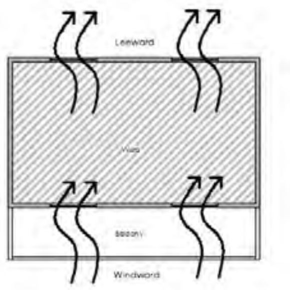
- The physical size of the hospital ward

The simulation of various ventilation alternatives was conducted using an existing hospital ward interior measuring 9.58m x 5.54m x 2.91m (L x W x H), with a floor area of 53.07 m2. It is a simple rectangular form with a length (2a) twice its width (a). An open balcony was used on the windward side. The depth of the balcony was 35% of the width of the ward. This simple rectangular size of the wards was maintained throughout the simulation while changing the opening positions. The results indicated that with these parameters, the minimum required ventilation rates ASHRAE 6 ach_1 for the hospital ward could be achieved while maintaining the occupants' thermal comfort.



- Arrangement of Fenestrations of the hospital ward

In this study, several fenestration configurations were investigated. The results indicated that by positioning equal and aligned inlet and outlet openings in the windward and leeward facades, the desired ventilation rates could be achieved by utilizing the outdoor wind speed (Figure 7-3).



- The ratio of opening sizes to ward floor area

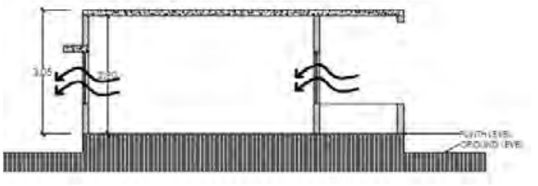
The hospital ward located at SHMH was adopted as the base case and used for the simulation. Table 9-1 shows that the base-case ward has not fulfilled the BNBC and International Mechanical Code requirement that openable areas through adjoining space should be more than 8% of the total ward floor areas. Due to sliding doors, the operable areas decrease around 50%, affecting the airflow rate. The opening area in this study was increased by removing the sliding door, which facilitated the provision of the required ventilation rate and airflow circulation at the occupancy level.

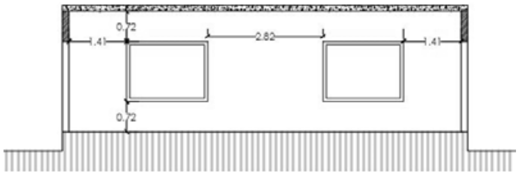
Table 9-1: The ratio of opening sizes to ward floor area

S/N	Hospital Wards	Floor Area	Opening Area	Effective Ventilation Area	Openable Area %
1	Base Case	9.88m X 5.84m = 57.7m2	0.91m X 1.30m X 2	2.37 m2	4.12%
2	Case 1	9.88m X 5.84m = 57.7m2	1.82m X 1.30m X 2	4.73 m2	8.19%

- Opening Position of the hospital ward:

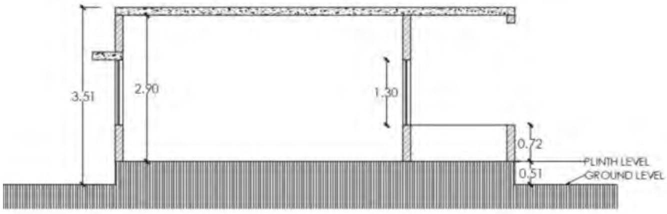
Openings should be located in the middle of the windward and leeward walls and aligned with each other to get the required average wind speed at occupancy level (at about 1 m above the floor) and to avoid airflow short-circuiting. There are three window positions: up, center, and down (Figure 7-3).





- Building height:

On the ground floor, the building height was 3.5m, with a .51m plinth and a .72m sill level for better instances. The indoor clear ward height of 2.91m (from finish floor level to ceiling) met the BNBC and ASHRAE standard requirements of a 6 ach_1 air change rate and could meet the thermal comfort parameters for the occupants.



- Outdoor prevailing wind speed

Different average outdoor wind speeds for 12 months ranging from .4m/s to 2.0 m/s have been simulated and analyzed. The results indicate that outdoor prevailing wind speeds ≥.4m/s, the air change rates have satisfied the ASHRAE standard requirements. Fans should supplement the ventilation when the outdoor local wind speed is ≤ .4 m/s.

9.4 The COVID-19 Pandemic and the Significance of the Study Findings

At the time of writing this report, the World Health Organization (WHO) had declared the novel coronavirus-2 (nCoV-2) outbreak a pandemic and an international public health emergency, and the entire world is working to address it. It is a rapidly evolving and emerging situation. This has emerged as a severe threat to human health and the whole world's economy. Bangladesh is one of the densely populated countries in the world, which also has come under attack by COVID-19. The first case of a COVID-19 patient was detected in Bangladesh on March 8, 2020. Since then, 30,205 people have been officially reported as COVID-19 infected with 432 deaths (Anwar et al., 2020).

However, the country's limited health care service facilities and public unawareness are the major problems for Bangladesh to tackle this situation effectively. Numerous measures are being put in place to try and reduce the spread of this deadly disease, with the most effective response to the outbreak being mass quarantines, a public health technique borrowed from the Middle Ages.

The widely accepted main transmission mechanism is through droplet-borne pathways. However, many researchers and studies consider that the COVID-19 virus can also spread via the airborne route and remain in the air for up to three hours (Dai & Zhao, 2020). This leads to questions as to whether enough is being done regarding ventilation to reduce the risk of the spread of COVID-19 or other diseases that may be airborne. Ventilation is the main focus when it comes to the transmission of such deadly pathogens and should be appropriately designed and operated. Current evidence suggests that the COVID-19 virus spreads in poorly ventilated and crowded indoor settings, where people spend more extended periods of time (WHO, 2021).

This study evaluates the current ventilation strategies used in buildings to assess if there is room for further development, especially for hospital wards, to reduce or eradicate the risk of pathogen transmission and adapt ventilation measures to new threats posed by pandemics like COVID-19. A growing number of cases have proved the possibility of airborne transmission of the coronavirus disease COVID-19. Ensuring an adequate ventilation rate is essential to reduce the risk of infection in confined spaces. In chapter 8, the association between the infection probability and ventilation rates with the Wells–Riley equation, where the q is the quanta produced by one infector (quanta/h), was calculated from 15-128 q/h. Various studies found that the quantum generation rate (q) by a COVID-19 infector is 15–50 q/h (Dai & Zhao, 2020).

Results showed that the inlet and outlet at the center of the facade and positioning face to face and having maximum natural air velocity, the maximum contamination will exhaust from the space and result in less COVID contamination dissemination through natural ventilation.

Further, when COVID-19 infectiousness was low (q=15q/h), improving the air supply flow rate resulted in minor improvements in the percentage of infected occupants (Figure 8-3). This implies that while infectiveness is minimal and exposure time is short, the disease would not spread across the community occupying the same indoor enclosure except at a low airflow rate; therefore, the air supply flow rate has marginal improvement in protective effectiveness. When infectiveness is high (50 q/h or higher), increasing the air supply flow rate by more than 6 ACH induces a rapid decrease in infected individuals. These results indicate that the supply flow rate has an important role in occupant protection when the ward has higher infectiveness, with the exposure period of the susceptible population being short (t = 15m).

Therefore, this study could establish a relation between covid-19 dissemination and natural ventilation in a hospital ward. As a result, architects and healthcare designers would be able to minimize the probability of COVID-19 infection in hospital wards in Dhaka during the design phase.

9.5 Limitations

There were some limitations associated with this study, as stated below:

- The tropical climates in this study refer to Dhaka, precisely, Manikganj
- Hospitals vary widely depending on their functions, but this study was limited to hospital multi-bed wards only.
- The study did not consider furniture and other indoor geometries.
- The research only took into account the open balcony on the windward side, which has a depth of 35% of the width of the ward.
- In the questionnaire survey, responses from patients were not collected because their health condition might influence their environmental perception.

9.6 Recommendations for Future Works

Due to computing capacity limitations when using CFD modeling techniques and practical issues when performing full-scale measurements, many simplifications and assumptions have been made. Hence, the study needs more precision, and the following recommendations are made.

Indoor parameters such as dwarf walls, furniture, and building inhabitants were not considered. These indoor parameters are likely to affect the study's outcome. As a result, it is recommended that when simulating natural airflow, furniture and other items accessible in the building's interior be taken into account in the future.

This study used cases with a rectangular floor plan and identical inlet and outlet for cross ventilation setups in terms of building form and layout. Since the findings and recommendations are based on this analysis, they do not extend to buildings with substantially different layouts and opening configurations.

This study was only focused on the multi-bed hospital wards. Thus, the transmission risk data may not be fully applicable in other resource-limited health care settings in the tropics.

This thesis focused on natural ventilation and some design-related parameters. However, the relative effect of all the design-related parameters on natural ventilation was not investigated. Ultimately, a tool that can optimize the natural ventilation design based on all the design-related parameters can be developed as future work.

9.7 Closing Remarks

This study aims to provide natural ventilation in the tropical Dhaka climate for effective ventilation and to reduce the risk of infection in hospital wards. Various research methods, including psychosocial perception, full-scale measurement, and CFD simulations, were employed to achieve the objectives. The findings of this study are significant for architects building system designers as a feed-forward for future projects and upgrades to existing buildings. The study will reduce the existing knowledge gap between tropical climates and the risk of infection by providing sustainable ventilation, considering factors such as the COVID-19 and influenza virus and the occupants' thermal comfort. Finally, this study established a relation between ventilation variables and infection risk, which will help health care designers evaluate various parameters throughout the design process.

REFERENCES

REFERENCES

Adamu, Z. A., & Price, A. (2015). The design and simulation of natural personalised ventilation (NPV) system for multi-bed hospital wards. *Buildings*, *5*(2), 381–404. https://doi.org/10.3390/buildings5020381

Adamu, Z. A., Price, A., & Cook, M. J. (2012). Performance evaluation of natural ventilation strategies for hospital wards - A case study of Great Ormond Street Hospital. *Building and Environment*, *56*, 211–222. https://doi.org/10.1016/j.buildenv.2012.03.011

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., & Baharum, M. R. (2015). A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings*, *101*, 153–162. https://doi.org/10.1016/j.enbuild.2015.04.033

Agarwal, K. M., Mohapatra, S., Sharma, P., Sharma, S., Bhatia, D., & Mishra, A. (2020). Study and overview of the novel corona virus disease (COVID-19). *Sensors International*, *1*(100037). https://doi.org/doi.org/10.1016/j.sintl.2020.100037

Ahmed, K. S. (1995). *Approach to Bio-climatic Urban Design for the Tropics with special reference to Dhaka, Bangladesh* [Unpublished Doctoral Thesis]. Architectural Association School of Architecture, London, UK.

Ahmed, K. S. (2003). Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environments. *Energy and Buildings*, *35*(1), 103–110. https://doi.org/DOI: 10.1016/S0378-7788(02)00085-3

Ahmed, S., Siddique, A. K., Iqbal, A., Nurur Rahman, F. K. M., Islam, M. N., & Sobhan, M. A. (2010). Causes for hospitalizations at upazila health complexes in Bangladesh. *Journal of Health, Population and Nutrition*, *28*(4), 399–404. https://doi.org/10.3329/jhpn.v28i4.6047

Ahmed, Z. N. (1987). The Effects of Climate on the Design and Location of Windows in Bangladesh. [Unpublished MPhil thesis]. In *Ph.D. Thesis*. Sheffield City Polytechnic.

Ahmed, Z. N. (1994). *Assesment of Residential Sites in Dhaka with respect to Solar Radiation gains,* [Unpublished Doctoral Thesis]. De Montfort University, UK.

Ahsan, M. (2018). *Frequent power cuts back again*. New Age. http://www.newagebd.net/article/38458/frequent-power-cuts-back-again

Alfano, D., Romana, F., Olesen, B. W., Palella, B. I., & Riccio, G. (2014). Thermal comfort: Design and assessment for energy saving. *Energy and Buildings*, *81*, 326–336. https://doi.org/10.1016/j.enbuild.2014.06.033

Allard, F., & Santamouris, M. (1998). Natural ventilation in buildings: a design handbook. In *James & James (Science Publishers) Ltd*.

Alwetaishi, M. (2016). Impact of Building Function on Thermal Comfort: A Review Paper. *Merican Journal of Engineering and Applied Sciences*, *9*(9), 928–945.

Ampt, A., Harris, P., & Maxwell, M. (2008). The Health Impacts of the Design of Hospital Facilities on Patient Recovery and Wellbeing, and Staff Wellbeing: A Review of the Literature. In *Research Studies*. University of New South Wales: Sydney.

Anwar, S., Nasrullah, M., & Hosen, M. J. (2020). COVID-19 and Bangladesh: Challenges and How to Address Them. *Frontiers in Public Health*, *8*. https://doi.org/DOI=10.3389/fpubh.2020.00154

Appah-Dankyi, J., & Koranteng, C. (2012). An assessment of thermal comfort in a warm and humid school building at Accra, Ghana. *Adv. Appl. Sci. Res.*, *3*(1), 535–547.

ASHRAE. (2013). Ventilation for acceptable indoor air quality. In *ASHRAE Standard* (pp. 1–70).

ASHRAE Standard 55. (2004). *American society of heating refrigeration and air-conditioning Engineers, Atlanta.*

ASHRAE Standard 55. (2013). Thermal Environmental Conditions for Human Occupancy. In *ASHRAE*.

Atkinson, G. A. (1953). An Introduction to Tropical Building Design. *Architectural Design*, *xxiii*(10), 268–271.

Atkinson, J. (2009). *Natural Ventilation for Infection Control in Health-Care Settings.* (James Atkinson, Y. Chartier, Pessoa-Silva, C. Lúcia, P. Jensen, Y. L. Set, & W. Hong (eds.)). WHO Publication.

Awbi, H. (1994). Design considerations for naturally ventilated buildings. *Renewable Energy*, *5*(5–8), 1081–1090. https://doi.org/10.1016/0960-1481(94)90135-X

Awbi, H. (2003). Ventilation of buildings. In *Ventilation of Buildings: Second Edition*. Taylor & Francis. https://doi.org/10.4324/9780203634479

Aynsley, R. (2014). Natural ventilation in passive design. *Environment Design Guide*, *80*(80), 1.

Azizpour, F., Moghimi, S., Salleh, E., Mat, S., Lim, C. H., & Sopian, K. (2013). Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan MalaysiaMedical Centre (UKMMC). *Energy and Buildings*, *64*, 317–322. https://doi.org/DOI: 10.1016/j.enbuild.2013.05.033

Balaras, C. A., Dascalaki, E., & Gaglia, A. (2007). HVAC and indoor thermal conditions in hospital operating rooms. *Energy and Buildings*, *39*(4), 454–470. https://doi.org/10.1016/j.enbuild.2006.09.004

Bangalee, M. Z. I., Lin, S. Y., & Miau, J. J. (2012). Wind driven natural ventilation through multiple windows of a building: A computational approach. *Energy and*

Buildings, *45*, 317–325. https://doi.org/10.1016/j.enbuild.2011.11.025

Bangalee, M. Z. I., Miau, J. J., Lin, S. Y., & Ferdows, M. (2014). Effects of Lateral Window Position and Wind Direction on Wind-Driven Natural Cross Ventilation of a Building: A Computational Approach. *Journal of Computational Engineering*, *2014*, 1–15. https://doi.org/10.1155/2014/310358

Beggs, C. B., Kevin, G., Catherine, J. ., Abigail, E. ., & Andrew, S. P. (2008). The ventilation of multiple-bed hospital wards: Review and analysis. Association for Professionals in Infection Control and Epidemiology,. *American Journal of Infection Control, 36*(4), 250–259.

Beggs, C. B., Noakes, C. J., Sleigh, P. A., Fletcher, L. A., & Siddiqi, K. (2003). The transmission of tuberculosis in confined spaces: An analytical review of alternative epidemiological models. *International Journal of Tuberculosis and Lung Disease*, *7*(11), 1015–1026.

Beggs, C. B., Shepherd, S. J., & Kerr, K. G. (2010). Potential for airborne transmission of infection in the waiting areas of healthcare premises: Stochastic analysis using a Monte Carlo model. *BMC Infectious Diseases*, *10*, 247. https://doi.org/10.1186/1471-2334-10-247

Begum, A., Bari, M. S., Azad, M. A. K., Hossain, M. I., & Saha, P. R. (2017). Prevention of Nosocomial Infection & role of Hand Hygiene Compliance in a Private Hospital of Bangladesh. *Bangladesh Critical Care Journal*, *5*(2), 83–87. https://doi.org/10.3329/bccj.v5i2.34382

Begum, B. A., Biswas, S. K., & Hopke, P. K. (2011). Key issues in controlling air pollutants in Dhaka, Bangladesh. *Atmospheric Environment*, *45*(40), 7705–7713. https://doi.org/10.1016/j.atmosenv.2010.10.022

BERC. (2018). *Annual Report* (Issue December).

Bernoulli, D., & Blower, S. (2004). An attempt at a new analysis of the mortality caused by smallpox and of the advantages of inoculation to prevent it. *Reviews in Medical Virology*, *14*(5), 275–288. https://doi.org/10.1002/rmv.443

Blocken, B., Stathopoulos, T., & Carmeliet, J. (2007). CFD simulation of the atmospheric boundary layer: wall function problems. *Atmospheric Environment*, *41*(2), 238–252. https://doi.org/10.1016/j.atmosenv.2006.08.019

Bradshaw, V. (2006). *The Building Environment: Active and Passive Control Systems* (Third). John Willey and Sons, Inc. https://books.google.com/books?hl=en&lr=&id=cS5tNV6sVDYC&pgis=1

Centre for Research and Information (CRI). (2018). *Bangladesh Towards Better Healthcare*. CRI; CRI. http://cri.org.bd/publication/pub_sep_2018/better-health/Bangladesh_Towards_Better_Healthcare_Sep_2018.pdf

Ceylan, A. (2011). *Negative Effects of Air Conditioning Systems on Internal Air Quality*. Yıldız Technical University Institute of Science, Master's Thesis,.

Chen, S. C., Liao, C. M., Li, S. S., & You, S. H. (2011). A Probabilistic Transmission Model to Assess Infection Risk from Mycobacterium Tuberculosis in Commercial Passenger Trains. *Risk Analysis*, *31*(6), 930–939. https://doi.org/10.1111/j.1539-6924.2010.01552.x

CIBSE. (1997). *Natural Ventilation in Non-domestic Buildings. Application Manual AM10: 1997.*

Cuaron, J. J., Hirsch, A. E., Medich, D. C., Hirsch, J. A., & Rosenstein, B. S. (2011). Introduction to radiation safety and monitoring. In *Journal of the American College of Radiology* (Vol. 8, Issue 4). Routledge. https://doi.org/10.1016/j.jacr.2010.08.020

Cui, S., Cohen, M., Stabat, P., & Marchio, D. (2015). CO2 tracer gas concentration decay method for measuring air change rate. *Building and Environment*, *84*(2015), 162–169. https://doi.org/10.1016/j.buildenv.2014.11.007

Dai, H., & Zhao, B. (2020). Association of the infection probability of COVID-19 with ventilation rates in confined spaces. *Build. Simul*, *13*, 321–1327. https://doi.org/doi.org/10.1007/s12273-020-0703-5

De Dear, R. (1998). Global database of thermal comfort field experiments. *ASHRAE Transactions*, *104*(Pt 1B), 1141–1152.

De Dear, R. (2004). Thermal comfort in practice. *Indoor Air, Supplement*, *14*(SUPPL. 7), 32–39. https://doi.org/10.1111/j.1600-0668.2004.00270.x

De Dear, R., & Brager, G. S. (2001). The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology*, *45*(2), 100–108. https://doi.org/10.1007/s004840100093

EECMP. (2015). *Energy Efficiency and Conservation Master Plan up to 2030* (Issue March). http://sreda.gov.bd/files/EEC_Master_Plan_SREDA.pdf

Eibach, D., Casalegno, J. S., Bouscambert, M., Bénet, T., Regis, C., & Comte, B. (2014). Routes of transmission during a nosocomial influenza A(H3N2) outbreak among geriatric patients and healthcare workers. *Journal of Hospital Infection*, *86*(3), 188–193. https://doi.org/10.1016/j.jhin.2013.11.009

Escombe, A. R., Oeser, C. C., Gilman, R. H., Navincopa, M., Ticona, E., & Pan, W. (2007). Natural ventilation for the prevention of airborne contagion. *PLoS Medicine*, *4*(2), 0309–0317. https://doi.org/10.1371/journal.pmed.0040068

Escombe, A. R., Oeser, C., Gilman, R. H., Navincopa, M., Ticona, E., & Martinez, C. (2007). The Detection of Airborne Transmission of Tuberculosis from HIV-Infected Patients, Using an In Vivo Air Sampling Model. *Clinical Infectious Diseases*, *44*(10), 1349–1357. https://doi.org/10.1086/515397

Etheridge, D. (2011). Natural Ventilation of Buildings: Theory, Measurement and Design. In *Natural Ventilation of Buildings: Theory, Measurement and Design* (illustrate, Issue 7242). John Wiley & Sons. https://doi.org/10.1002/9781119951773

Etheridge, D. W., & Sandberg, M. (1996). *Building Ventilation: Theory and Measurement.* John Wiley and Sons Ltd.

Evans, J., & Alam, M. I. (2017). *Primary Health Care Systems: Case study from Bangladesh*.

Evola, G., & Popov, V. (2006). Computational analysis of wind driven natural ventilation in buildings. *Energy and Buildings*, *38*(5), 491–501. https://doi.org/10.1016/j.enbuild.2005.08.008

Fang, L. (1998). Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*, *8*(2), 80–90. https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x

Fanger, P. O. (1972). Thermal comfort: Analysis and applications in environmental engineering. In *Applied Ergonomics* (Vol. 3, Issue 3). DANISH TECHNICAL PRESS. https://doi.org/10.1016/s0003-6870(72)80074-7

Fanger, P. O., Melikov, A. K., Hanzawa, H., & Ring, J. (1988). Air turbulence and sensation of draught. *Energy and Buildings*, *12*(1), 21–39. https://doi.org/10.1016/0378-7788(88)90053-9

Fanger, P. O., & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, *34*(6), 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8

Fernstrom, A., & Goldblatt, M. (2013). Aerobiology and Its Role in the Transmission of Infectious Diseases. *Journal of Pathogens*, *2013*, 1–13. https://doi.org/10.1155/2013/493960

Feustel, H. E. (1999). COMIS-an international multizone air-flow and contaminant transport model. In *Energy and Buildings* (Vol. 30, Issue 1). https://doi.org/10.1016/S0378-7788(98)00043-7

Franke, J., Hellsten, A., Schlünzen, H., & Carissimo, B. (2007). Best practice guideline for the CFD simulation of flows in the urban environment. In *COST action* (Vol. 44, Issue May). Meteorological Inst. http://cat.inist.fr/?aModele=afficheN&cpsidt=23892111%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Best+practice+guideline+for+the+CFD+simulation+of+flows+in+the+urban+environment#0

Fung, Y. W., & Lee, W. L. (2015). Identifying the most influential parameter affecting natural ventilation performance in high-rise high-density residential buildings. *Indoor and Built Environment*, *24*(6), 803–812. https://doi.org/10.1177/1420326X14536189

Ghiaus, C., & Allard, F. (2012). Natural ventilation in the urban environment: Assessment and design. In C. Ghiaus & F. Allard (Eds.), *Natural Ventilation in the Urban Environment: Assessment and Design* (Vol. 9781849772, pp. 1–241). Earthscan. https://doi.org/10.4324/9781849772068

Gilani, S. I. U. H., Khan, M. H., & Pao, W. (2015). Thermal Comfort Analysis of

PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings. *Energy Procedia*, *75*, 1373–1379. https://doi.org/10.1016/j.egypro.2015.07.218

Gilkeson, C. A., Camargo-Valero, M. A., Pickin, L. E., & Noakes, C. J. (2013). Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Building and Environment*, *65*, 35–48. https://doi.org/10.1016/j.buildenv.2013.03.006

Givoni, B. (1976). *Man Climate and Architecture* (Architectu). Applied Science Publishers Ltd. London, UK.

Givoni, B. (1995). Passive and low energy cooling of buildings. In *Choice Reviews Online* (Vol. 32, Issue 05). John Wiley and Sons. Inc. https://doi.org/10.5860/choice.32-2759

Gonzalo, R., & Habermann, K. J. (2006). *Energy-efficient architecture basics for planning and construction*. Birkhäuser-Publishers for Architecture.

Gough, H., King, M.-F., Nathan, P., Grimmond, C. S. B., Robins, A., Noakes, C. J., Luo, Z., & Barlow, J. F. (2019). Influence of neighbouring structures on building façade pressures: Comparison between full-scale, wind-tunnel, CFD and practitioner guidelines. *Journal of Wind Engineering & Industrial Aerodynamics*, *189*, 22–23. https://doi.org/doi.org/10.1016/j.jweia.2019.03.011

Green, F. H. W. (1977). Atlas of the Environment. Vol. 1. In *The Geographical Journal* (Vol. 143, Issue 3). Arrow books Ltd., London. https://doi.org/10.2307/634740

Gurley, E. S., Zaman, R. U., Sultana, R., Bell, M., Fry, A. M., & Srinivasan, A. (2010). Rates of Hospital-Acquired Respiratory Illness in Bangladeshi Tertiary Care Hospitals: Results from a Low-Cost Pilot Surveillance Strategy. *Clinical Infectious Diseases*, *50*(8), 1084–1090. https://doi.org/10.1086/651265

Hegazy, S., Amer, A., & Hosni, Y. (2019). Assessment of a Naturally Ventilated Hospital Ward from an Infection Control Perspective using Key Design Indicators. *AARJMD Asian Academic Research Journal of Multidisciplinary, Multidisciplinary*, *5*(February), 51–71.

Hensen, J., & Lamberts, R. (2012). Building performance simulation for design and operation. In J. L. . Hensen & R. Lamberts (Eds.), *Building Performance Simulating for Design and Operation* (Vol. 9780203891, pp. 1–512). Spon press, Oxfordshire, UK. https://doi.org/10.4324/9780203891612

Hossain. (2016). *Bangladesh Healthcare Industry: The Thriving Industry that is Growing Faster than the GDP*. Light Castle BD. https://www.lightcastlebd.com/insights/2016/04/11/bangladesh-healthcare-industry-the-thriving-industry-that-is-growing-faster-than-the-gdp

Hossain, M. E., & Nooruddin, M. (1993). Global Solar Rdiation on Horizontal Surface in Dhaka. *International Technical Conference on Tropical Urban Climates*.

Hou, C., & Ma, C. (2008). Boundary setting in simulating greenhouse ventilation by fluent software. In L. Daoliang (Ed.), *IFIP International Federation for Information Processing* (Vol. 259, pp. 1391–1395). Springer). https://doi.org/10.1007/978-0-387-77253-0_86

Humphreys, M. (1978). Outdoor Temperatures and Comfort Indoors. *Batim Int Build Res Pract*, *6*(2), 92–105. https://doi.org/10.1080/09613217808550656

Huppert, H. E. (1990). The Fluid Mechanics of Solidification. *Journal of Fluid Mechanics*, *212*(1), 209–240. https://doi.org/10.1017/S0022112090001938

Hwang, R. L., Lin, T. P., Cheng, M. J., & Chien, J. H. (2007). Patient thermal comfort requirement for hospital environments in Taiwan. *Building and Environment*, *42*(8), 2980–2987. https://doi.org/10.1016/j.buildenv.2006.07.035

ICDDR, B. (2009). Population-based influenza surveillance, Dhaka. *Health and Science Bulletin*, *4*, 1–5.

Ilgin, H. E., & Gunel, M. H. (2007). The Role of Aerodynamic Modifications in the Form of Tall Buildings Against Wind Excitation. *Metu Jfa*, *2*(24), 2.

IPCC. (1996). Climate Change 1995: synthesis report. In *Environmental Science & Technology* (Vol. 48, Issue 8). https://doi.org/10.1021/es405168b

Islam, A. (2014). Health System in Bangladesh: Challenges and Opportunities. *American Journal of Health Research*, *2*(6), 366. https://doi.org/10.11648/j.ajhr.20140206.18

Islam, D. K. R. (2021). Bangladesh spends the least in the health sector in South Asia. *Prothom Alo, Bangla Edition*. https://www.prothomalo.com/opinion/column/

Islam, M. M., Afrin, S., Ahmed, T., & Ashraf Ali, M. (2015). Meteorological and seasonal influences in ambient air quality parameters of Dhaka city. *Journal of Civil Engineering (IEB)*, *43*(1), 67–77.

Islam, M. T., Talukder, A. K., Siddiqui, M. N., & Islam, T. (2020). Tackling the COVID-19 pandemic: The Bangladesh perspective. *Journal of Public Health Research*, *9*(1794), 389–397.

Islam, S., & Khan, M. Z. R. (2017). A Review of Energy Sector of Bangladesh. *Energy Procedia*, *110*, 611–618. https://doi.org/10.1016/j.egypro.2017.03.193

ISO. (2005). ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. *Management*.

Izadyar, N., Miller, W., Rismanchi, B., & Garcia-Hansenc, V. (2020). Impacts of façade openings' geometry on natural ventilation and occupants' perception: A review. *Building and Environment*, *170*. https://doi.org/doi.org/10.1016/j.buildenv.2019.106613

J. Chandler, T. (1991). Urban design in different climates. In *Atmospheric*

Environment. Part B. Urban Atmosphere (Vol. 25, Issue 1). World Meteorological Organization (WMO). https://doi.org/10.1016/0957-1272(91)90049-k

JICA. (2018). *Data Collection Survey for Universal Health Coverage Promotion Project in the People's Republic of Bangladesh : Final Report*.

Jones, A. P. (1999). Indoor air quality and health. *Atmospheric Environment*, *33*(28), 4535–4564.

Kang, B., & Carillo, L. (2007). *Indirect Passive air flow systems* [UTSoA - Seminar in Sustainable Architecture]. University of Texas at Austin.

Karava, P., Stathopoulos, T., & Athienitis, A. K. (2011). Airflow assessment in cross-ventilated buildings with operable façade elements. *Building and Environment*, *46*(1), 266–279. https://doi.org/10.1016/j.buildenv.2010.07.022

Katz, J. D. (2017). Control of the Environment in the Operating Room. *Anesthesia and Analgesia*, *125*(4), 1214–1218. https://doi.org/10.1213/ANE.0000000000001626

Khatun, M., Khatun, R., & Hossen, M. S. (2020). URBAN HEAT ISLAND CHARACTERISTICS UNDER DIFFERENT LAND USE LAND COVER. *International Journal of Current Research*, *12*(1), 9627–9635. https://doi.org/10.24941/ijcr.37639.01.2020

Khodakarami, J., & Nasrollahi, N. (2012). Thermal comfort in hospitals - A literature review. *Renewable and Sustainable Energy Reviews*, *16*(6), 4071–4077. https://doi.org/10.1016/j.rser.2012.03.054

Kiwan, A., Berg, W., Fiedler, M., Ammon, C., & Gläser, M. (2013). Air exchange rate measurements in naturally ventilated dairy buildings using the tracer gas decay method with 85Kr, compared to CO2 mass balance and discharge coefficient methods. *Biosystems Engineering*, *116*(3), 286–296. https://doi.org/10.1016/j.biosystemseng.2012.11.011

Kolokotsa, D., Tsoutsos, T., & Papantoniou, S. (2012). Energy conservation techniques for hospital buildings. *Advances in Building Energy Research*, *6*(1), 159–172. https://doi.org/10.1080/17512549.2012.672007

Koskosas, I. V., & Asimopoulos, N. (2011). Information System Security Goals. *International Journal of Advanced Science and Technology*, *27*, 15–25.

Kosutova, K., Hooff, T., Vanderwel, C., Blocken, B., & Hensen, J. (2019). Cross-ventilation in a generic isolated building equipped with louvers: Wind-tunnel experiments and CFD simulations. *Building and Environment*, *154*, 263–280. https://doi.org/doi.org/10.1016/j.buildenv.2019.03.019.

Kwon, B., & Park, Y. (2013). Interior noise control with an active window system. *Applied Acoustics*, *74*(5), 647–652. https://doi.org/10.1016/j.apacoust.2012.11.005

Laussmann, D., Dieter, H., & Helm, D. (2012). Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality. In N. A. Mazzeo (Ed.), *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality* (pp. 365–404). InTech publishers, Janeza, Croatia. https://doi.org/10.5772/1030

Li, Y. G., Leung, M., Seto, W. H., Yuen, P. L., & Leung, J. (2007). Factors affecting ventilation effectiveness in SARS wards. *Hong Kong Medical Journal*, *14*(1), 33–36.

Li, Y., Leung, G. M., Tang, J. W., Yang, X., Chao, C. Y. H., & Lin, J. Z. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment - A multidisciplinary systematic review. *Indoor Air*, *17*(1), 2–18. https://doi.org/10.1111/j.1600-0668.2006.00445.x

Liao, C. M., Chang, C. F., & Liang, H. M. (2005). A probabilistic transmission dynamic model to assess indoor airborne infection risks. *Risk Analysis*, *25*(5), 1097–1107. https://doi.org/10.1111/j.1539-6924.2005.00663.x

Liping, W., & Hien, W. N. (2007). Applying natural ventilation for thermal comfort in residential buildings in singapore. *Architectural Science Review*, *50*(3), 224–233. https://doi.org/10.3763/asre.2007.5028

Liping, W., & Hien, W. N. (2008). The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore. *Building and Environment*, *42*(12), 4006–4015. https://doi.org/10.1016/j.buildenv.2006.06.027

Lipinski, T., Ahmad, D., Serey, N., & Jouhara, H. (2020). Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings. *International Journal of Thermofluids*, *7*(8).

Loomans, M. G. L. C., Boerstra, A., Franchimon, F., & Wisse, C. J. (2020). Calculating the risk of infection. *REHVA Journal*, *October*, 19–24.

Lowen, A. C., Mubareka, S., Steel, J., & Palese, P. (2007). Influenza virus transmission is dependent on relative humidity and temperature. *PLoS Pathogens*, *3*(10), 1470–1476. https://doi.org/10.1371/journal.ppat.0030151

Lowen, A. C., & Steel, J. (2014). Roles of Humidity and Temperature in Shaping Influenza Seasonality. *Journal of Virology*, *88*(14), 7692–7695.

Maarof, S., & Jones, P. (2009). THERMAL COMFORT FACTORS IN HOT AND HUMID REGION: MALAYSIA. *International Conference on Smart and Sustainable Built Environments, Delft,*.

Mallick, F. H. (1994). *Thermal comfort for urban housing in Bangladesh* [Architecture Association, London]. http://dspace.bracu.ac.bd/xmlui/handle/10361/3356

Mallick, F. H. (1996). Thermal comfort and building design in the tropical climates. *Energy and Buildings*, *23*(3), 161–167. https://doi.org/10.1016/0378-7788(95)00940-X

Markus, E., & Morris, N. (1979). *Buildings, climate, and energy*. Pitman. https://doi.org/720.4

Megahed, N. A., & Ghoneim, E. M. (2020). Indoor Air Quality: Rethinking rules of building design strategies in post-pandemic architecture. *Environmental Research*, *193*(2021).

Memarzadeh, F. (2012). Literature review of the effect of temperature and humidity on viruses. *ASHRAE Transactions*, *118*(PART 1), 1049–1060.

Memarzadeh, F., & Manning, A. (2000). Thermal comfort, uniformity, and ventilation effectiveness in patient rooms: performance assessment using ventilation indices. *ASHRAE Transactions*, *106*(2), 748–761.

Menzies, D., Fanning, A., Yuan, L., Fitzgerald, J. M., Blanchette, G., & Bolduc, P. (2000). Hospital ventilation and risk for tuberculous infection in Canadian health care workers. *Annals of Internal Medicine*, *133*(10), 779-789. https://doi.org/10.7326/0003-4819-133-10-200011210-00010

Mirza, A. (2011). *Hospital-Acquired Infections.* (R. W. Steele (ed.)). Medscape, WebMD LLC.

Mohammed, M. A. (2015). *Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates* [Doctoral Thesis]. Newcastle University.

Mohammed, M. A., Dudek, S. J. M., & Hamza, N. (2013). Natural Ventilation in Hospital Wards of Semi-Arid Climates : a Case for Acceptable Indoor Air Quality and Patients ' Health Natural Ventilation in Hospital Wards of Semi - Arid Climates : a Case for Acceptable Indoor Air Quality and Patients ' Health. *Proceedings of the 34th AIVC - 3rd TightVent - 2nd Cool Roofs' - 1st Venticool Conference*, *October 2016*.

Mohammed, M. A., Dudek, S. J. M., & Hamza, N. (2014). Simulation of natural ventilation in hospitals of semiarid climates for harmattan dust and mosquitoes: A conundrum. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, 1827–1834.

Mridha, A. M. (2005). *A study of thermal performance of operable roof insulation, with special reference to Dhaka, 2002.* (Vol. 11, Issue 1988). BUET.

Mulia, Y., Hardiman, G., & Arif, K. A. (2018). The Relation between Thermal Performance and Architecture Design Aspects in Lowland Warm Humid Tropics Ward. *International Journal of Engineering and Technology*, *10*(4), 1181–1190. https://doi.org/DOI: 10.21817/ijet/2018/v10i4/181004061

Nardell, E. A., Keegan, J., Cheney, S. A., & Etkind, S. C. (1992). Airborne infection. Theoretical Natural Ventilation for the Prevention of Airborne Contagion. *PLoS Medicine*, *4*(2), e68.

Nathan, A. J., & Scobell, A. (2012). *How China sees America*. Foreign Affairs. https://doi.org/10.1017/CBO9781107415324.004

Nightingale, F. (2018). Notes on nursing: What it is, and what it is not:Commemorative Edition. In *Notes on Nursing: What It Is, and What It Is Not: Commemorative Edition* (Vol. 9, Issue 1). Harrison.

Ninomura, P., & Bartley, J. (2001). New ventilation guidelines for health-care facilities. *ASHRAE Journal*, *43*(6). w.w.w.ashraejournal.org

NIPORT. (2017). *Bangladesh Health Facility Survey 2017: Final Report*.

Olesen, B. W., & Olsen, B. W. (2004). International standards for the indoor environment. *Indoor Air*, *14*(Suppl. 7), 18–26. https://doi.org/10.1111/j.1600-0668.2004.00268.x

Olesen, Bjarne W. (2011). Standards for Ventilation and Indoor Air Quality in relation to the EPBD. *REHVA Journal*, *January*, 28–32.

Omrani, S., Garcia-Hansen, V., Capra, B., & Drogemuller, R. (2017). Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. *Building and Environment*, *116*, 182–194. https://doi.org/10.1016/j.buildenv.2017.02.012

Omrani, S., Garcia-Hansen, V., Capra, B. R., & Drogemuller, R. (2018). Effect of natural ventilation mode on thermal comfort and ventilation performance: Full-scale measurement. *Energy and Buildings*, *156*(Supplement C), 1–16. https://doi.org/10.1016/j.enbuild.2017.09.061

Omrani, Sara, Capra, B., Hansen, V. G., & Drogemuller, R. (2015). Investigation of the effect of balconies on natural ventilation of dwellings in high-rise residential buildings in subtropical climate. *Living and Learning: Research for a Better Built Environment:*, 1–11.

Orosa, J. A. (2010). A Review of General and Local Thermal Comfort Models for Controlling Indoor Ambiences. In A. Kumar (Ed.), *Air Quality*. InTech. https://doi.org/10.5772/9763

Orosa, J. A., & Oliveira, A. C. (2012). Indoor air standards and models. In *Green Energy and Technology* (Vol. 84). Springer-Verlag London Limited. https://doi.org/10.1007/978-1-4471-2336-1_2

Pantelic, J., & Tham, K. W. (2012). Assessment of the mixing air delivery system ability to protect occupants from the airborne infectious disease transmission using Wells-Riley approach. *HVAC and R Research*, *18*(4), 562–574. https://doi.org/10.1080/10789669.2012.647230

Pargal, S. (2017). *Lighting the Way: Achievements, Opportunities, and Challenges in Bangladesh's Power Sector, Energy and Extractives South Asia The World Bank*.

Qian, H., Li, Y., Nielsen, P. V., & Huang, X. (2009). Spatial distribution of infection risk of SARS transmission in a hospital ward. *Building and Environment*, *44*(8), 1651–1658. https://doi.org/10.1016/j.buildenv.2008.11.002

Qian, H., Li, Y., Seto, W. H., Ching, P., Ching, W. H., & Sun, H. Q. (2010). Natural ventilation for reducing airborne infection in hospitals. *Building and Environment*, *45*(3), 559–565. https://doi.org/10.1016/j.buildenv.2009.07.011

Raji, B., Tenpierik, M. J., Bokel, R., & Dobbelsteen, A. van den. (2020). Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. *International Journal of Ventilation*, *19*(1), 25–48.

Rashid, H. E. (2019). Geography of Bangladesh. In *Geography of Bangladesh* (2nd ed.). University Press Ltd, Dhaka. https://doi.org/10.4324/9780429048098

Reddy, S., Sandbhor, S., & Dabir, V. (2019). Bringing energy efficiency for hospital building through the conservative and preventive measures. *International Journal of Innovative Technology and Exploring Engineering*, *8*(12), 3056–3060. https://doi.org/10.35940/ijitee.L2470.1081219

Ribeiro, C., Ramos, N. M. M., & Flores-Colen, I. (2020). A Review of Balcony Impacts on the Indoor Environmental Quality of Dwellings. *Sustainability*, *12*(16: 6453).

Riley, E. C., Murphy, G., & Riley, R. L. (1978). Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*, *107*(5), 421–432. https://doi.org/10.1093/oxfordjournals.aje.a112560

Rimi1, N. A., Sultana, R., Luby, S. P., Islam, M. S., & Uddin, M. (2014). Infrastructure and Contamination of the Physical Environment in Three Bangladeshi Hospitals: Putting Infection Control into Context. *PLoS ONE*, *9*(2).

Rizk, A. A., El-Morsi, M. S., & Elwan, M. M. (2018). A Review on Wind - Driven Cross - Ventilation Techniques Inside Single Rooms. *International Journal of Scientific Engineering and Research (*, *6*(8), 56–67.

Robert, F. C. (2011). *Health Care Facilities: Hospital*. National Institute of Building Sciences, Washington. http://www.wbdg.org/design/hospital.php

Rofail, T. (2006). Natural Ventilation in Buildings. *NEERG Seminar*.

Rudnick, S. N., & Milton, D. K. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air*, *13*(3), 237–245. https://doi.org/10.1034/j.1600-0668.2003.00189.x

Rycroft, M. (2018). Energy usage and efficiency at medical facilities - EE Publishers. *EE Publishers*. https://www.ee.co.za/article/energy-usage-and-efficiency-in-hospitals-clinics-and-medical-facilities.html

Santamouris, M., & Wouters, P. (2006). *Building Ventilation: State of the Art*. Earthscan Publishers, Bath press, UK.

SarkinGobir, Y., Zayyanu, M. M., & SarkinGobir, S. (2017). Sick Building Syndrome: A Review of Related Literatures. *International Journal of Medical and Biosciences*, *1*(1).

Sarma, B. (2002). *A Study of the Factors for Thermal Comfort in Residential High-*

Rise in Dhaka City [BUET]. http://lib.buet.ac.bd:8080/xmlui/handle/123456789/1340

Sattayakorn, S., Ichinose, M., & Sasaki, R. (2017). Clarifying thermal comfort of healthcare occupants in tropical region: A case of indoor environment in Thai hospitals. *Energy and Buildings*, *149*, 45–57. https://doi.org/doi.org/10.1016/j.enbuild.2017.05.025

Shahid, S. (2013). Spatial assessment of drought hazard, vulnerability and risk in Bangladesh. *Droughts: New Research*, 215–241.

Shajahan, A., Culp, C. H., & Williamson, B. (2019). Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: A review of scientific research on hospital buildings. *Indoor Air*, *29*, 161–176.

Shetabivash, H. (2015). Investigation of opening position and shape on the natural cross ventilation. *Energy and Buildings*, *93*, 1–15. https://doi.org/10.1016/j.enbuild.2014.12.053

Shih, T. H., Liou, W. W., Shabbir, A., Yang, Z., & Zhu, J. (1995). A new k-ϵ eddy viscosity model for high reynolds number turbulent flows. *Computers and Fluids*, *24*(3), 227–238. https://doi.org/10.1016/0045-7930(94)00032-T

Smieszek, T., Lazzari, G., & Salathé, M. (2019). Assessing the Dynamics and Control of Droplet- and Aerosol-Transmitted Influenza Using an Indoor Positioning System. *Scientific Reports*, *9*(1), 2185. https://doi.org/10.1038/s41598-019-38825-y

Srebric, J. (2011). Introduction to building performance simulation. In J. L. . Hensen & R. Lamberts (Eds.), *Building Performance Simulation for Design and Operation.* (pp. 43–175). Spon press, Oxfordshire, UK.

Statista Research Department. (2021). *Share of rural population in Bangladesh from 2010 to 2019.* https://www.statista.com/statistics/760934/bangladesh-share-of-rural-population/#statisticContainer

Sze To, G. N., & Chao, C. Y. H. (2010). Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. *Indoor Air*, *20*(1), 2–16. https://doi.org/10.1111/j.1600-0668.2009.00621.x

Szokolay, S. V. (1980). *'Manual of Tropical Housing and Building' Longmans*. Orient Longman private limited.

Szokolay, S. V. (2008). *Introduction to Architectural Science: The Basis of Sustainable Development.* Architectural Press, Elsevier. Oxford, UK.

Taheruzzaman, M., & Janik, P. (2016). Electric Energy Access in Bangladesh. *Transactions on Environment and Electrical Engineering*, *1*(12).

Tang, J. W. (2009). The effect of environmental parameters on the survival of airborne infectious agents. *Journal of the Royal Society Interface*, *6*(SUPPL. 6), S737–S746. https://doi.org/10.1098/rsif.2009.0227.focus

Tantasavasdi, C., Srebric, J., & Chen, Q. (2001). Natural ventilation design for houses in Thailand. *Energy and Buildings*, *33*(8), 815–824. https://doi.org/10.1016/S0378-7788(01)00073-1

Taylor, P., Fuller, R. J., & Luther, M. B. (2008). Energy use and thermal comfort in a rammed earth office building. *Energy and Buildings*, *40*(5), 793–800. https://doi.org/10.1016/j.enbuild.2007.05.013

Tecle, A., & Girma T. Bitsuamlak, T. E. J. (2013). Wind-driven natural ventilation in a low-rise building: A Boundary Layer Wind Tunnel study. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2012.08.026

Thangprasert, N., & Suwanarat, S. (2017). The Relationships between Wind Speed and Temperature Time Series in Bangkok, Thailand. *Journal of Physics: Conference Series*, *901*(1). https://doi.org/10.1088/1742-6596/901/1/012043

Titumir, R. A. M. (2020). *Health sector gets priority in the budget for 2020-21*. The Business Standard. https://www.tbsnews.net/economy/budget/health-sector-gets-priority-budget-2020-21-91807

Toe, D. H. C., & Kubota, T. (2012). Reanalysing the ASHRAE RP-884 database to determine thermal comfort criteria for naturally ventilated buildings in hot-humid climate. *Proceedings - 28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture, PLEA 2012*.

Ulrich, R. S. (1992). How design impacts wellness. *The Healthcare Forum Journal*, *35*(5), 20–25.

Ulrich, Roger S, Zimring, C., Zhu, X., DuBose, J., & Seo, H. B. (2008). A review of the research literature on evidence-based healthcare design. *Herd*, *1*(3), 61–125. https://doi.org/10.1177/193758670800100306

University of South Carolina. (2012). *Bangladesh Health Facility Survey. Revised Final Report*.

Vinet, L., & Zhedanov, A. (2011). A “missing” family of classical orthogonal polynomials. In *Journal of Physics A: Mathematical and Theoretical* (Vol. 44, Issue 8). https://doi.org/10.1088/1751-8113/44/8/085201

Virtanen, M., Terho, K., Oksanen, T., Kurvinen, T., & Pentti, J. (2011). Patients with infectious diseases, overcrowding, and health in hospital staff. *Archives of Internal Medicine*, *171*(14), 1296–1298. https://doi.org/10.1001/archinternmed.2011.313

Wagner, A., Gossauer, E., Moosmann, C., Gropp, T., & Leonhart, R. (2007). Thermal comfort and workplace occupant satisfaction-Results of field studies in German low energy office buildings. *Energy and Buildings*, *39*(7), 758–769. https://doi.org/10.1016/j.enbuild.2007.02.013

Walker, A. (2010). Natural ventilations. *National Renewable Energy Laboratory*, *6*, 2640.

Wang, F., Lee, M., Cheng, T., & Law, Y. (2012). Field evaluation of thermal comfort and indoor environment quality for a hospital in a hot and humid climate. *HVAC&R Research*, *18*(4), 671–680.

Wells. (1955). Airborne Contagion and Air Hygiene. In *Southern Medical Journal* (Vol. 48, Issue 12). Cambridge, MA, Harvard University Press. https://doi.org/10.1097/00007611-195512000-00044

WHO. (2017). *Primary Health Care Systems*. World Health Organization. http://www.who.int/alliance-hpsr

WHO. (2018). World Health Statistic 2018: Monitoring Health For The SDGs. In *World Development*. https://doi.org/10.1016/j.worlddev.2018.08.012

Willemsen, E., & Wisse, J. A. (2002). Accuracy of assessment of wind speed in the built environment. *Journal of Wind Engineering and Industrial Aerodynamics*, *90*(10), 1183–1190. https://doi.org/10.1016/S0167-6105(02)00231-3

Williams, R. E. O. (1966). Principles of Hospital Design. *Journal of Clinical Pathology*, *19*(1), 95–95. https://doi.org/10.1136/jcp.19.1.95-a

Wilson, C. B. (1975). Manual of tropical housing and building. Part one: Climatic design. In *Building Science* (Vol. 10, Issue 1). Orient Longman, Madras. https://doi.org/10.1016/0007-3628(75)90012-2

Yang, T., Wright, N. G., Etheridge, D. W., & Quinn, A. D. (2006). A comparison of CFD and full-scale measurements for analysis of natural ventilation. *International Journal of Ventilation*, *4*(4), 337–348. https://doi.org/10.1080/14733315.2005.11683713

Yau, Y. H., Badaruddeen, A., & Chandrasegaran, D. (2011). The Ventilation of Multiple-bed Ward in the Tropics: A review. *Building and Environment, 46*, 1125–1132.

Yu, H. C., Mui, K. W., Wong, L. T., & Chu, H. S. (2017). Ventilation of general hospital wards for mitigating infection risks of three kinds of viruses including Middle East respiratory syndrome coronavirus. *Indoor and Built Environment*, *26*(4), 514–527. https://doi.org/10.1177/1420326X16631596

Z, A., C, M., J, N., & Z., L. (2011). Effect of balconies on thermal comfort in wind-induced, naturally ventilated low-rise buildings. *Building Services Engineering Research and Technology*, *32*(3), 277–292.

Zaman, R. U., Alamgir, A. S. M., Rahman, M., & Azziz-Baumgartner, E. (2009). Influenza in outpatient ILI case-patients in national hospital-based surveillance, Bangladesh, 2007-2008. *PLoS ONE*, *4*(12), e8452. https://doi.org/10.1371/journal.pone.0008452

Zaman, S. (2006). Beds in a Bangladeshi hospital. *Medische Antropologie*, *18*(1), 193–204.

Zhang, W., Wang, L., Ji, Z., Ma, L., & Hui, Y. (2015). Test on Ventilation Rates of Dormitories and Offices in University by the CO2 Tracer Gas Method. *Procedia Engineering*, *121*, 662–666. https://doi.org/10.1016/j.proeng.2015.08.1061

Zhang, X. (2009). CFD simulation of neutral ABL flows [Unpublished Master's Thesis, Technical University of Denmark]. In *Energy: Vol. Risø-R-168* (Issue April). http://orbit.dtu.dk/getResource?recordId=242267&objectId=1&versionId=1

Appendices

Appendix A: Questionnaire Form

Questionnaire Form

A Study on the Natural Ventilation Strategies for Hospital Wards in the Tropics

[DOCTORS, NURSES AND HEALTHCARE WORKERS]

Hospital Name:	Date	Time

Section I: Personal Information

1. Gender: ☐ Male ☐ Female	2. Age:
3. Department/Section:	4. Rank:

Section II: Indoor Air Quality (IAQ) Consideration

5. Do you often experience the following symptoms inside the ward?		
	☐ Dry eyes ☐ Difficulty concentrating ☐ Dry or irritated throat ☐ Dizziness	☐ Headaches ☐ Skin dryness, rash, or itch ☐ Breathing difficulty ☐ None
6. Have you ever considered Indoor Air Quality as a Problem In the wards?	☐ Yes	☐ No
How?	☐ Inadequate Ventilation (High temperature, discomfort)	☐ Affects patients' health
	☐ Congestion and overcrowding (Patient bed spacing)	☐ Spread of pathogens in the form of airborne disease
	☐ Odor/smell (Due to infected wounds, toilets)	☐ Lack of stable electricity
7. Do you usually experience some smell or odor in the wards?	☐ Yes	☐ No
How?	☐ Toilet Odour	☐ Congestion and overcrowd
	☐ Wounds (Infected, septic, Infected operations, orthopedic cases, and Bedsores)	☐ Dustbins/disposed waste /Food Remnants
	☐ Human Waste (Patient body, secretions, Spilling of blood,	☐ Chemicals (Disinfectants, medications)
8. Do you recognize any indoor air contaminant sources within/around the wards?	☐ Yes	☐ No
Where?	☐ Toilets	☐ Dustbins/Waste Bins

	☐ Direct body smells and Human waste (Such as Bloods/body fluids/Un-emptied blood cloths, e.g., secretions)	☐ Patients' bedsides, (Properties due to lack of enough storage)
	☐ Wounds (Dirty/undressed, infectious, septic, Soiled Linen)	☐ Contaminants around the wards (Improper disposal of waste, and Patients Foods remnants)

Section III: Thermal Comfort

9. How would you describe your typical thermal comfort?

Uncomfortable	Neutral	Comfortable

10. Is the ward draught?

Still	Just Right	Draughty

11. Is the ward humid?

Low	Just Right	High

Section IV: Ventilation

12. What is the nature of the airflow in the ward space?

Good	Fairly Good	Not So Good

13. Have you experienced any cases of deterioration in patient health due to indoor air quality problems in the wards?

Yes	No

Section V: infection prevention measures

14. How would you describe the cleanliness of the ward?

Unsatisfactory	Okay	Satisfactory

15. What is the average number of attendances per patient in the ward?

1	2	More

16. What are Ward's window conditions for most of the time?

Open	Close	Open	close
Day Time		Night Time	

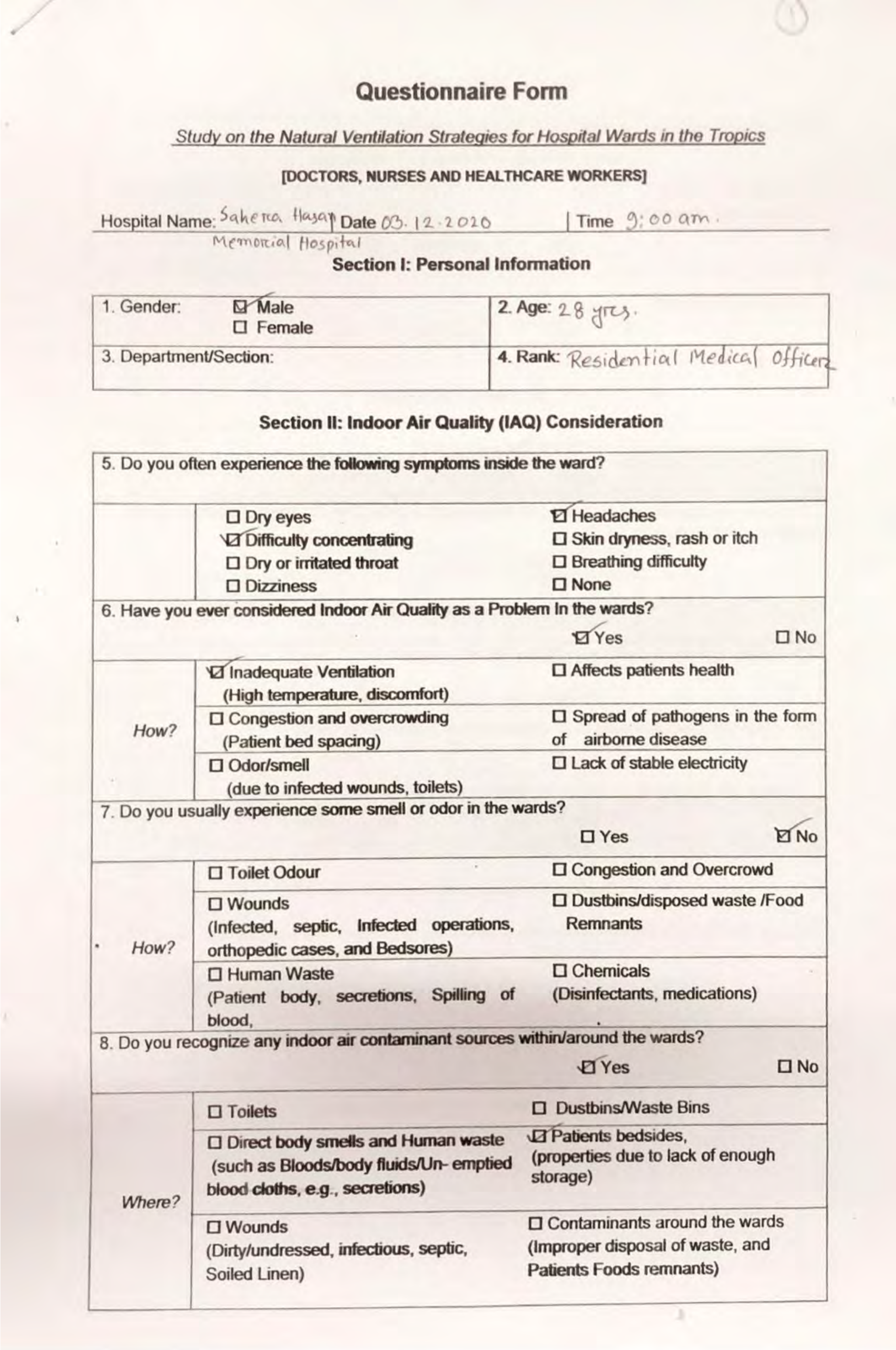
Section VI: Indoor Air Quality On health

17. Do you think the overall indoor ward condition has an impact on patient smooth recovery?

Interferes	No Effects	Enhances

Thank you for completing this survey

Appendix B: Survey Response Form



①

Questionnaire Form

Study on the Natural Ventilation Strategies for Hospital Wards in the Tropics

[DOCTORS, NURSES AND HEALTHCARE WORKERS]

Hospital Name: Sahera Hasan Memorial Hospital | Date 03. 12. 2020 | Time 9:00 am.

Section I: Personal Information

1. Gender: ☑ Male ☐ Female	2. Age: 28 yrs.
3. Department/Section:	**4. Rank:** Residential Medical Officer

Section II: Indoor Air Quality (IAQ) Consideration

5. Do you often experience **the following symptoms inside the ward?**		
	☐ Dry eyes ☑ Difficulty concentrating ☐ Dry or irritated throat ☐ Dizziness	☑ Headaches ☐ Skin dryness, rash or itch ☐ Breathing difficulty ☐ None
6. Have you ever considered Indoor Air Quality as a Problem In the wards?	☑ Yes	☐ No
How?	☑ Inadequate Ventilation (High temperature, discomfort)	☐ Affects patients health
	☐ Congestion and overcrowding (Patient bed spacing)	☐ Spread of pathogens in the form of airborne disease
	☐ Odor/smell (due to infected wounds, toilets)	☐ Lack of stable electricity
7. Do you usually experience some smell or odor in the wards?	☐ Yes	☑ No
How?	☐ Toilet Odour	☐ Congestion and Overcrowd
	☐ Wounds (Infected, septic, Infected operations, orthopedic cases, and Bedsores)	☐ Dustbins/disposed waste /Food Remnants
	☐ Human Waste (Patient body, secretions, Spilling of blood,	☐ Chemicals (Disinfectants, medications)
8. Do you recognize any indoor air contaminant sources within/around the wards?	☑ Yes	☐ No
Where?	☐ Toilets	☐ Dustbins/Waste Bins
	☐ Direct body smells and Human waste (such as Bloods/body fluids/Un- emptied blood cloths, e.g., secretions)	☑ Patients bedsides, (properties due to lack of enough storage)
	☐ Wounds (Dirty/undressed, infectious, septic, Soiled Linen)	☐ Contaminants around the wards (Improper disposal of waste, and Patients Foods remnants)

Questionnaire Form

Study on the Natural Ventilation Strategies for Hospital Wards in the Tropics

[DOCTORS, NURSES AND HEALTHCARE WORKERS]

Hospital Name: shahera Hasan Hospital | Date 03.12.2020 | Time 02.55

Section I: Personal Information

1. Gender: ☐ Male ☑ Female	2. Age: 20Yrs
3. Department/Section: genaral word	4. Rank: midwifery

Section II: Indoor Air Quality (IAQ) Consideration

5. Do you often experience the following symptoms inside the ward?		
	☐ Dry eyes ☐ Difficulty concentrating ☐ Dry or irritated throat ☑ Dizziness	☐ Headaches ☑ Skin dryness, rash or itch ☑ Breathing difficulty ☐ None
6. Have you ever considered Indoor Air Quality as a Problem In the wards?	☑ Yes	☐ No
How?	☑ Inadequate Ventilation (High temperature, discomfort)	☐ Affects patients health
	☑ Congestion and overcrowding (Patient bed spacing)	☐ Spread of pathogens in the form of airborne disease
	☐ Odor/smell (due to infected wounds, toilets)	☐ Lack of stable electricity
7. Do you usually experience some smell or odor in the wards?	☑ Yes	☐ No
How?	☑ Toilet Odour	☐ Congestion and Overcrowd
	☑ Wounds (Infected, septic, Infected operations, orthopedic cases, and Bedsores)	☑ Dustbins/disposed waste /Food Remnants
	☐ Human Waste (Patient body, secretions, Spilling of blood,	☐ Chemicals (Disinfectants, medications)
8. Do you recognize any indoor air contaminant sources within/around the wards?	☐ Yes	☐ No
Where?	☑ Toilets	☐ Dustbins/Waste Bins
	☑ Direct body smells and Human waste (such as Bloods/body fluids/Un- emptied blood cloths, e.g., secretions)	☐ Patients bedsides, (properties due to lack of enough storage)
	☐ Wounds (Dirty/undressed, infectious, septic, Soiled Linen)	☐ Contaminants around the wards (Improper disposal of waste, and Patients Foods remnants)

Appendix C: Walkthrough Evaluation Checklist

A Study on the Natural Ventilation Strategies for Hospital Wards in the Tropics

Walkthrough Evaluation Checklist

S/ N	**Performance Indicators**	**Evaluation Terms**	**Comments**
Name of Hospital/Ward			
Building Parameters			
01	Building age		
02	Number of storeys		
03	Availability of Balcony		
04	Surrounding vegetation		
05	Building Density Nearby		
06	The existing type of ventilation		
Multi-Bed Ward Parameters			
01	Investigated Ward Size		
02	Investigated Ward Floor Area		
03	Investigated Ward Shape and Form		
04	Isolated or space within a building		
05	Investigated Ward Level		
06	Investigated Ward Height		
07	Ward Orientation		
08	Internal partitions		
09	Staircase inside the ward		
10	Nurses area		
11	Doctors room		
12	Utility rooms		
13	Conveniences		
14	Treatment area		
15	No of access and entrance Lobby		
16	Investigated Ward Occupancy		
Multi-Bed Ward Openings			
01	Number of windows		
02	Type of Windows		
03	Size of Windows		
04	Forms and Materials of Windows		
05	High-level windows		
06	Number of Doors		
07	Type of Doors		

08	Size of Doors		
09	Forms and Materials of Doors		
10	Types and Materials of Curtains		
11	Types and Materials of Netting		

12	Window orientation		
Multi-Bed Ward Furniture			
01	Furniture Types		
02	Number of Beds		
03	Material and type of waiting chairs		
Multi-Bed Ward Ceiling			
01	Type ceiling		
02	Ceiling color		
03	Ceiling shape/form		
04	Ceiling skirting		
Multi-Bed Ward Floor			
01	Types of floor finishing		
02	Type of floor tiles		
03	Tiles shape and form		
04	Tiles color		
05	Type and shape of floor Skirting		
Multi-Bed Ward Wall			
01	Wall type		
02	Walling Material		
03	Wall shape and form		
04	Type and color of paint		
Multi-Bed Ward Ventilation System			
01	Mechanical Ventilation		
02	Natural Ventilation		
03	Hybrid Ventilation		
04	Ceiling Fans		

Appendix D: Meteorological data of Dhaka (2016-2020)

Bangladesh Meteorological Department

Climate Division, Agargaon, Dhaka 1207

Station: Dhaka

Monthly & Yearly Maximum Temperature in degree Celsius.

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Spt.	Oct.	Nov.	Dec.	Annual
2016	28.5	30.4	38.0	40.2	38.0	37.0	35.8	34.4	34.8	36.0	33.8	29.2	40.2
2017	29.9	32.2	36.4	35.5	36.4	36.5	35.5	34.7	36.5	35.5	32.9	30.3	36.5
2018	27.6	34.0	34.8	39.0	37.0	36.0	34.6	36.1	34.7	36.0	34.5	31.0	39.0
2019	30.2	32.0	33.6	36.5	37.0	36.1	35.8	34.2	36.0	36.5	33.2	29.4	37.0
2020	26.8	33.6	34.6	36.5	36.3	35.6	37.6	36.5	36.5	36.1	32.8	28.9	37.6

Station: Dhaka

Monthly & Yearly Minimum Temperature in degree Celsius

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Spt.	Oct.	Nov.	Dec.	Annual
2016	10.3	11.6	16.0	18.9	21.1	23.2	24.0	24.3	24.2	19.5	15.4	12.3	10.3
2017	11.4	12.8	15.0	19.5	20.1	23.2	23.6	23.8	24.0	20.3	17.5	11.5	11.4
2018	10.0	13.3	19.5	18.2	21.3	22.8	24.5	24.0	25.3	22.8	17.6	14.9	10.0
2019	11.3	14.2	16.0	20.0	21.0	22.8	24.8	25.2	24.0	19.1	17.1	14.2	11.3
2020	9.5	14.4	17.5	19.4	20.8	23.6	24.8	25.4	25.0	20.8	17.4	11.8	9.5

Station: Dhaka

Monthly average Dry-Bulb Temperature in degree Celsius

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
2016	18.3	21.0	26.5	30.7	30.2	29.6	29.5	28.8	29.2	27.7	24.3	19.0
2017	19.1	22.4	26.3	27.9	29.7	29.3	28.4	29.2	29.0	27.7	24.5	20.4
2018	18.9	24.0	27.3	30.4	28.5	29.9	28.8	29.6	29.0	28.6	24.2	21.6
2019	20.1	23.3	25.2	28.0	29.9	29.2	28.8	29.1	29.3	27.7	24.7	21.2
2020	17.5	23.2	27.3	27.3	27.6	29.4	29.3	29.8	29.8	27.3	24.2	20.3

Station: Dhaka

Monthly & Yearly Average Humidity in %

Year	Jan	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
2016	72	62	52	56	68	78	77	82	76	72	66	77	69
2017	70	63	52	68	71	77	81	79	78	73	69	68	70
2018	68	63	59	72	74	75	82	77	82	74	73	72	72
2019	62	57	67	72	73	80	83	83	82	79	67	76	73
2020	68	61	59	69	79	81	81	78	77	72	68	66	71

Monthly average cloud amount (octa) data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2016	1	1	2	1	3	5	6	6	4	2	1	1
2017	2	1	1	4	3	5	7	5	5	3	1	3
2018	1	2	2	3	4	4	6	5	4	3	1	0
2019	0	0	3	3	3	5	5	5	4	4	1	2
2020	0	1	2	3	4	5	6	5	4	3	1	2

Station: Dhaka

Monthly Prevailing Wind Speed in Knots

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2016	2.5	2.5	2.4	2.2	2.8	2.1	2.4	2.4	2.1	2.1	2.1	2.2
2017	2.2	2.4	2.2	2.5	2.3	2.6	2.4	2.7	3.0	1.9	2.5	2.1
2018	2.7	2.6	2.3	3.0	3.6	2.4	2.3	2.8	2.1	2.0	2.5	2.0
2019	2.2	2.3	2.5	3.1	2.5	2.4	2.0	2.2	2.2	3.3	2.4	2.0
2020	2.2	2.3	2.4	3.2	3.7	3.9	3.5	3.6	3.3	3.3	3.2	3.7

Station: Dhaka

Monthly Prevailing Wind Direction

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2016	W	W	NW	S	S	S	SE	SE	SE	W	W	W
2017	W	W	W	S	S	S	E	S	SE	S	N	W
2018	W	W	S	S	S	S	S	E	S	W	NE	W
2019	NW	S	S	S	S	S	S	S	S	E	E	NW
2020	W	W	S	E	S	S	S	S	S	N	WNW	NE

Station: Dhaka

Monthly & Yearly Total Rainfall in mm.

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Spt.	Oct.	Nov.	Dec.	Annual
2016	0	12	10	80	147	342	212	391	156	49	0	0	1399
2017	3	17	4	166	185	375	623	395	346	51	0	1	2166
2018	3	13	55	55	212	212	405	171	138	76	25	0	1365
2019	0	2	100	228	188	414	584	544	381	412	6	33	2892
2020	0	20	3	309	392	366	354	141	76	45	13	13	1732

Station: Dhaka

Monthly average Sunshine hours data of Dhaka

Year	Jan	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
2016	4.2	6.3	8.6	8.6	6.7	3.3	3.9	3.2	4.8	5.8	5.2	2.8	5.3
2017	4.4	5.4	8.5	6.4	6.4	4.7	2.5	3.4	4.2	6.1	6.2	4.6	5.3
2018	5.1	6.2	7.1	7.4	5.8	5.5	3.4	4.8	4	5.3	5.6	5.2	5.5
2019	6.2	7.3	6.1	6.1	6.8	4.2	3	3.4	3.8	4.9	5.6	4.4	5.2
2020	5.3	5.5	7.4	6.8	4.7	4.3	3.5	4.4	5.4	5.2	5.2	4.3	5.2

Appendix E: Summary Output of CO2 Concentration Decay Curve

The CO2 Concentration Decay Curve for Closed window

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.964586876
R Square	0.930427841
Adjusted R Square	0.920488962
Standard Error	0.044610494
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.1863028	0.1863028	93.614961	2.65805E-05
Residual	15	0.0139307	0.0019901		
Total	16	0.2002334			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.435092369	0.0282305	227.94842	8.255E-15	6.36833790	6.501846	6.368337	6.501846
Minutes	-0.009287157	0.0009599	-9.6754825	2.658E-05	-0.01155687	-0.007017	-0.011556	-0.007017

The CO2 Concentration Decay Curve for Opened window

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.960163322
R Square	0.921913605
Adjusted R Square	0.912152805
Standard Error	0.378070378
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	13.500509	13.500509	94.450625	1.05002E-05
Residual	15	1.1434977	0.1429372		
Total	16	14.644007			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	8.997580585	0.2280905	39.44740	1.875E-10	8.47160285	9.523558	8.471602	9.523558
Minutes	-0.067421257	0.0069374	-9.718571	1.05E-05	-0.08341884	-0.051423	-0.083418	-0.051423

Appendix F: Clothing types for patients and staff in hospital wards (ISO 7730)

Clothing types for patients and staff in hospital wards*

Clothing	Clothing level (clo)	Patients without cover	Patients with cover	Staff
Light-weight shirts with long sleeves	0.20	0.20	0.20	–
Normal shirts with long sleeves	0.25	-	-	0.25
Light-weight trousers	0.20	0.20	0.20	–
Normal trousers	0.25	-	-	0.25
Light summer jackets	0.25	-	-	0.25
Socks	0.02	0.02	0.02	0.02
Shoes (thin-soled)	0.04	-	-	0.04
Pantie pants and bra	0.03	0.03	0.03	0.03
Singlet	0.04	0.04	0.04	0.04
Blanket **	0.90	-	0.90	-
Total clothing ***		0.49 clo	1.39 clo	0.88 clo

---

* ISO 7730: Moderate thermal environments- Determination of the PMV and PPD indices and specification of the conditions for thermal comfort

** - the clo for blankets assumed to be same as boiler suit in ISO 7730

*** - Total clothing =? clothing

Appendix G: Activity rates for patients and staff in hospital's wards (ISO 7730)

Activity rates for patients and staff in hospital's wards ****

Activity	**Metabolic rate (met)**	**Patients % of time**	**Staff % of time**
Reclining	0.8	90	-
Seated, relaxed	1.0	10	5
Sedentary activity	1.2	-	30
Standing, light activity	1.6	-	50
Standing, medium activity	2.0	-	10
Walking on the level	1.9	-	5
Total activity		0.82 met	1.50 met

**** SO 7730: Moderate thermal environments- Determination of the PMV and PPD indices and specification of the conditions for thermal comfort

Appendix H: UDF for simulation

UDF File for Simulation

```
#include "udf.h"
#define UREF .77/* ref. speed in m/s */
#define CMU 0.09
#define VKC 0.4
#define ZREF 10 /* ref. height in m */
#define Z0 0.5 /* roughness height in m */

DEFINE_PROFILE (velocity_profile, thread, position)
{
        float x[ND_ND];
        float y;
        float u, u_star;
        face_t f;
        u_star = UREF*VKC/log ((ZREF+Z0)/Z0) ; // ref [1]
        begin_f_loop(f, thread)
        {
                F_CENTROID(x,f,thread);
                y=x[1];
                u = u_star/VKC*log((y+Z0)/Z0);
                F_PROFILE (f,thread,position) = u;
        }
        end_f_loop(f, thread)
}

/*  profile for kinetic energy  */


DEFINE_PROFILE(k_profile, thread, position)
{
        float x[ND_ND];
        face_t f;
        float u_star ;
                u_star = UREF*VKC/log((ZREF+Z0)/Z0) ; // ref [1]
        begin_f_loop(f, thread)
        {
                F_CENTROID(x,f,thread);

                F_PROFILE(f,thread,position)=u_star*u_star/sqrt(CMU);
                        }
        end_f_loop(f, thread)
}

/* profile for dissipation rate  */


DEFINE_PROFILE(dissip_profile, thread, position)
{
        float x[ND_ND];
        face_t f;
        float u_star, y ;
                u_star = UREF*VKC/log((ZREF+Z0)/Z0) ; // ref [2]
        begin_f_loop(f, thread)
        {
                F_CENTROID(x,f,thread);
                y=x[1];
                F_PROFILE(f,thread,position)=pow(u_star,3.)/(VKC*(y+Z0));
        }
        end_f_loop(f,thread)
}
/*profile for temperature  */
/*
References: D.M. Hargreaves, N.G. Wright / J. Wind Eng. Ind. Aerodyn. 95 (2007) 355–369, doi:10.1016/j.jweia.2006.08.002*/
```

Appendix I: Simulation Results for all the Cases

Simulation Result: Base Case

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	26.650232	0.15874435	0.438864887	5.04248762	0.015391
	C1	4.9816	1.06	-2.389	27.062433	0.045567788	0.424029052	7.46166658	0.343976
	L1	7.142	1.06	-2.389	26.811456	0.032694183	0.403547734	6.78262043	0.292875
	W2	2.8212	1.06	-4.956	26.821649	0.021979217	0.397290826	6.80831242	0.294984
	C2	4.9816	1.06	-4.956	26.92489	0.034193039	0.403576672	7.07980394	0.316288
	L2	7.142	1.06	-4.956	26.5422	0.018713193	0.381768584	6.16618252	0.237026
	W3	2.8212	1.06	-7.2942	26.172327	0.040216088	0.360914290	5.53780937	0.160903
	C3	4.9816	1.06	-7.2942	26.58999	0.040065751	0.402161837	6.2664361	0.246979
	L3	7.142	1.06	-7.2942	26.324426	0.085573865	0.473448783	5.64346647	0.174948
1m	W1	2.8212	1.46	-2.389	27.226831	0.339112312	0.220698106	5.53272915	-0.15724
	C1	4.9816	1.46	-2.389	27.182001	0.071957968	0.450912356	7.82652473	0.368465
	L1	7.142	1.46	-2.389	27.045618	0.063395113	0.439895481	7.41752625	0.340805
	W2	2.8212	1.46	-4.956	26.951074	0.010994777	0.491175232	7.15218639	0.321696
	C2	4.9816	1.46	-4.956	27.031641	0.065451421	0.428286672	7.38008261	0.338266
	L2	7.142	1.46	-4.956	26.656885	0.037427012	0.411726058	6.41315508	0.260867
	W3	2.8212	1.46	-7.2942	26.249841	0.022168381	0.287437165	5.65103579	0.177089
	C3	4.9816	1.46	-7.2942	26.676874	0.066453368	0.427817851	6.45846748	0.265016
	L3	7.142	1.46	-7.2942	26.42547	0.148738235	0.391466447	5.01544237	-0.00789

Simulation Result: Case 1

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6 m	W1	2.8212	1.06	-2.389	27.317194	0.22075215	0.424904317	5.03891468	-0.014891015
	C1	4.9816	1.06	-2.389	27.571771	0.088027693	0.379624069	8.55320168	0.41241762
	L1	7.142	1.06	-2.389	27.026514	0.07702712	0.383298576	7.13893747	0.320114195
	W2	2.8212	1.06	-4.956	27.35885	0.067335382	0.369649976	8.20886612	0.392452598
	C2	4.9816	1.06	-4.956	27.620355	0.067443848	0.35213834	9.21343327	0.449325472
	L2	7.142	1.06	-4.956	27.225549	0.029457631	0.365041256	7.91012812	0.373813301
	W3	2.8212	1.06	-7.2942	27.615961	0.149220482	0.284970939	6.74750233	0.286906779
	C3	4.9816	1.06	-7.2942	27.705804	0.078998208	0.361250524	8.98294544	0.436624706
	L3	7.142	1.06	-7.2942	27.330194	0.144187242	0.462506891	5.83310032	0.193054885
1m	W1	2.8212	1.46	-2.389	28.251337	0.523476541	0.217212152	5.05544567	-0.046240337
	C1	4.9816	1.46	-2.389	27.654108	0.127384409	0.403667271	7.28171539	0.33121565
	L1	7.142	1.46	-2.389	27.145349	0.139086097	0.418066621	5.56199074	0.164157823
	W2	2.8212	1.46	-4.956	27.431177	0.024852878	0.489221916	8.52836895	0.41140306

	C2	4.9816	1.46	-4.956	27.727075	0.107823223	0.371392757	7.81049347	0.367419094
	L2	7.142	1.46	-4.956	27.352228	0.060389169	0.394268095	8.31915474	0.399120808
	W3	2.8212	1.46	-7.2942	28.249597	0.355508178	0.174794185	5.34484816	0.129014894
	C3	4.9816	1.46	-7.2942	27.810571	0.12308047	0.379662037	7.40949821	0.340291709
	L3	7.142	1.46	-7.2942	27.479761	0.275149047	0.344771093	5.00905132	-0.011194971

Simulation Result: Case 2

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	27.240564	0.227179319	0.409737706	5.0173645	0.011099545
	C1	4.9816	1.06	-2.389	27.518915	0.08972542	0.379453897	8.17732048	0.390277237
	L1	7.142	1.06	-2.389	26.837885	0.028459413	0.378058195	6.82879591	0.296647012
	W2	2.8212	1.06	-4.956	27.25567	0.064485557	0.351219803	8.04302692	0.382011682
	C2	4.9816	1.06	-4.956	27.35	0.060377043	0.355125278	8.40675068	0.404314816
	L2	7.142	1.06	-4.956	26.950372	0.016848497	0.369960546	7.15961885	0.322268546
	W3	2.8212	1.06	-7.2942	27.749231	0.13571398	0.284507245	7.11355448	0.317121208
	C3	4.9816	1.06	-7.2942	27.540277	0.066939466	0.357923418	8.97925091	0.436690003
	L3	7.142	1.06	-7.2942	27.020074	0.040429775	0.400510609	7.34451056	0.335704803
1m	W1	2.8212	1.46	-2.389	28.376764	0.494713932	0.494962841	5.0353651	0.038755294
	C1	4.9816	1.46	-2.389	27.616846	0.122808762	0.403709233	7.01237774	0.311128318
	L1	7.142	1.46	-2.389	26.957361	0.065794364	0.412345351	7.1483202	0.321421266
	W2	2.8212	1.46	-4.956	27.323877	0.029889949	0.369609058	8.31039238	0.398597807
	C2	4.9816	1.46	-4.956	27.461694	0.107443206	0.364537388	7.18885326	0.324364632
	L2	7.142	1.46	-4.956	27.080347	0.052931938	0.397703886	7.52325726	0.348236918
	W3	2.8212	1.46	-7.2942	28.450922	0.311585635	0.332575858	6.01510096	0.221189052
	C3	4.9816	1.46	-7.2942	27.643121	0.110498622	0.371732533	7.52939987	0.348579794
	L3	7.142	1.46	-7.2942	27.157037	0.125649795	0.449848951	5.93460941	0.210919172

Simulation Result: Case 3

Plane	Point	X	Y	Z	Temperature (C)	Velocity	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	27.21673	0.233867988	0.416552097	5.00907421	-0.002947952
	C1	4.9816	1.06	-2.389	27.554102	0.087698169	0.392957271	8.36225414	0.401494354
	L1	7.142	1.06	-2.389	27.06106	0.139765844	0.414833546	5.50121355	0.154549316
	W2	2.8212	1.06	-4.956	27.263757	0.049099751	0.355195224	8.09255409	0.385330528
	C2	4.9816	1.06	-4.956	27.392511	0.056165561	0.37895155	8.53876019	0.412025571
	L2	7.142	1.06	-4.956	27.042291	0.041807935	0.389714777	7.40753555	0.340182602
	W3	2.8212	1.06	-7.2942	27.941095	0.131471574	0.292283922	7.72632313	0.359914064
	C3	4.9816	1.06	-7.2942	27.561456	0.074715443	0.385312557	9.00687885	0.438142926
	L3	7.142	1.06	-7.2942	27.262689	0.27173689	0.519986629	5.06872034	-0.053767875
1m	W1	2.8212	1.46	-2.389	28.370691	0.511067867	0.499340594	5.02464247	0.029947132

	C1	4.9816	1.46	-2.389	27.642267	0.118157439	0.418146759	7.28476334	0.33143425
	L1	7.142	1.46	-2.389	27.123132	0.152125224	0.441121608	5.39509058	0.137476116
	W2	2.8212	1.46	-4.956	27.343378	0.026019216	0.383235693	8.35540771	0.401277632
	C2	4.9816	1.46	-4.956	27.48678	0.0977313	0.392753243	7.66041517	0.357483685
	L2	7.142	1.46	-4.956	27.147058	0.058284957	0.419013679	7.71573591	0.361201197
	W3	2.8212	1.46	-7.2942	28.465326	0.294251889	0.333527386	6.21757936	0.242165029
	C3	4.9816	1.46	-7.2942	27.649591	0.109165616	0.404893994	7.64865351	0.356700659
	L3	7.142	1.46	-7.2942	27.31814	0.289676517	0.527499735	5.09480762	-0.065118015

Simulation Result: Case 4

Plane	Point	X	Y	Z	Temperature (C)	Velocity	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	27.049951	0.0715938	0.441908598	7.38616943	0.338426
	C1	4.9816	1.06	-2.389	27.441736	0.0681024	0.414380252	8.72449875	0.42263
	L1	7.142	1.06	-2.389	27.223566	0.156561	0.432512641	5.46862793	0.149386
	W2	2.8212	1.06	-4.956	27.240442	0.0216252	0.392358363	8.01653862	0.38056
	C2	4.9816	1.06	-4.956	27.594354	0.0611531	0.387630492	9.29188442	0.453477
	L2	7.142	1.06	-4.956	27.321405	0.0441623	0.392598629	8.27831936	0.396655
	W3	2.8212	1.06	-7.2942	27.322809	0.0444049	0.378668725	8.28582954	0.397055
	C3	4.9816	1.06	-7.2942	27.619745	0.0783363	0.388646841	9.01972103	0.43874
	L3	7.142	1.06	-7.2942	27.493127	0.3051436	0.524978101	5.04264736	-0.03848
1m	W1	2.8212	1.46	-2.389	27.027948	0.0869842	0.477672338	6.75373077	0.285192
	C1	4.9816	1.46	-2.389	27.575342	0.0967331	0.436877966	7.9651041	0.377341
	L1	7.142	1.46	-2.389	27.311426	0.1606095	0.466203421	5.5284791	0.159254
	W2	2.8212	1.46	-4.956	27.385217	0.0151454	0.412759274	8.5107584	0.410379
	C2	4.9816	1.46	-4.956	27.708551	0.0953227	0.407147765	8.45008659	0.406854
	L2	7.142	1.46	-4.956	27.420984	0.0613025	0.421380639	8.65264416	0.418565
	W3	2.8212	1.46	-7.2942	27.496667	0.0597374	0.379334658	8.91947079	0.433417
	C3	4.9816	1.46	-7.2942	27.736902	0.1128368	0.405296385	7.75913858	0.364031
	L3	7.142	1.46	-7.2942	27.559778	0.320506	0.537714661	5.03872681	-0.04033

Simulation Result: Case 5

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	28.394617	0.657561421	0.608366432	5.05977678	-0.05293
	C1	4.9816	1.06	-2.389	27.809778	0.107934564	0.382964075	8.18474579	0.390964
	L1	7.142	1.06	-2.389	26.965051	0.03716154	0.403349638	7.1910615	0.324576
	W2	2.8212	1.06	-4.956	27.518945	0.089782715	0.382241279	8.11806583	0.38524
	C2	4.9816	1.06	-4.956	27.619165	0.069046542	0.373672187	9.36008358	0.457036
	L2	7.142	1.06	-4.956	27.097772	0.024978867	0.398119718	7.56319761	0.350957
	W3	2.8212	1.06	-7.2942	28.461328	0.384040028	0.438755572	5.50160789	0.155427

	C3	4.9816	1.06	-7.2942	27.770502	0.089978166	0.374166816	8.93701935	0.434336
	L3	7.142	1.06	-7.2942	27.150659	0.055853616	0.420871258	7.72544575	0.36182
1m	W1	2.8212	1.46	-2.389	28.176172	0.594644725	0.567809939	5.17937565	-0.09072
	C1	4.9816	1.46	-2.389	27.763696	0.114529863	0.42021961	7.76591682	0.364521
	L1	7.142	1.46	-2.389	27.080774	0.068473801	0.445821285	7.51299572	0.347518
	W2	2.8212	1.46	-4.956	27.546899	0.045212347	0.402270317	9.11008453	0.443831
	C2	4.9816	1.46	-4.956	27.704065	0.098624736	0.397173584	8.27492809	0.396463
	L2	7.142	1.46	-4.956	27.233331	0.047503784	0.430178434	7.99333572	0.379117
	W3	2.8212	1.46	-7.2942	28.345911	0.359318972	0.429342806	5.42719412	0.14345
	C3	4.9816	1.46	-7.2942	27.810144	0.112687454	0.398172259	7.97954273	0.378243
	L3	7.142	1.46	-7.2942	27.296228	0.133911192	0.477421641	6.02816296	0.220854

Simulation Result: Case 6

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	27.136377	0.071278729	0.477885336	7.61129236	0.354075
	C1	4.9816	1.06	-2.389	27.457208	0.068385124	0.418473572	8.73543835	0.423256
	L1	7.142	1.06	-2.389	26.962305	0.034541782	0.413377136	7.18524837	0.324127
	W2	2.8212	1.06	-4.956	27.261316	0.014150675	0.420446396	8.05060101	0.382664
	C2	4.9816	1.06	-4.956	27.577173	0.068484187	0.388855278	9.21623898	0.449489
	L2	7.142	1.06	-4.956	27.167474	0.026747165	0.395807505	7.75679541	0.363897
	W3	2.8212	1.06	-7.2942	27.344812	0.034903046	0.405322284	8.46069241	0.40741
	C3	4.9816	1.06	-7.2942	27.574823	0.079366639	0.389230281	8.88917542	0.431632
	L3	7.142	1.06	-7.2942	27.171259	0.06023673	0.431921303	7.87283087	0.371453
1m	W1	2.8212	1.46	-2.389	27.1271	0.042359833	0.527942538	7.52346706	0.347852
	C1	4.9816	1.46	-2.389	27.602441	0.096217595	0.437308788	7.92499876	0.374798
	L1	7.142	1.46	-2.389	27.100549	0.073403657	0.448788077	7.5494585	0.350017
	W2	2.8212	1.46	-4.956	27.418176	0.026378451	0.438563555	8.57947445	0.414337
	C2	4.9816	1.46	-4.956	27.700006	0.101169944	0.402780831	8.06557465	0.383638
	L2	7.142	1.46	-4.956	27.309015	0.054483738	0.423788011	8.22300434	0.393327
	W3	2.8212	1.46	-7.2942	27.552545	0.063616157	0.397341431	9.19052315	0.44806
	C3	4.9816	1.46	-7.2942	27.70141	0.112398379	0.401707053	7.69446707	0.359785
	L3	7.142	1.46	-7.2942	27.323206	0.149329528	0.487608254	5.82281637	0.198289

Simulation Result: Case7

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	28.457208	0.608985066	0.529079556	5.00193787	-0.00358051
	C1	4.9816	1.06	-2.389	27.725946	0.116044208	0.371017396	7.59940147	0.353268683
	L1	7.142	1.06	-2.389	27.018152	0.134242341	0.399327964	5.53671122	0.16007413
	W2	2.8212	1.06	-4.956	27.387476	0.094088867	0.361227363	7.57684278	0.349944383

	C2	4.9816	1.06	-4.956	27.368036	0.062230628	0.359653443	8.43888187	0.406207025
	L2	7.142	1.06	-4.956	27.000635	0.046306476	0.375112146	7.29133606	0.331890374
	W3	2.8212	1.06	-7.2942	28.491602	0.346823364	0.366824746	5.80798006	0.197378933
	C3	4.9816	1.06	-7.2942	27.649133	0.084049836	0.355601371	8.86720467	0.430119127
	L3	7.142	1.06	-7.2942	27.249963	0.274237812	0.507356048	5.08385754	-0.061018363
1m	W1	2.8212	1.46	-2.389	28.004083	0.507301807	0.462153971	5.17124319	-0.086543456
	C1	4.9816	1.46	-2.389	27.645837	0.130118385	0.401670635	6.89001846	0.30155918
	L1	7.142	1.46	-2.389	27.06759	0.144697636	0.426416218	5.43004131	0.14336957
	W2	2.8212	1.46	-4.956	27.380396	0.041699078	0.378603011	8.48813438	0.409096271
	C2	4.9816	1.46	-4.956	27.453821	0.105482124	0.373055637	7.24066639	0.328203768
	L2	7.142	1.46	-4.956	27.101343	0.063743152	0.404118717	7.57381773	0.351697356
	W3	2.8212	1.46	-7.2942	28.285364	0.29369092	0.341941088	5.77853489	0.193728372
	C3	4.9816	1.46	-7.2942	27.681848	0.120104343	0.376508296	7.31992006	0.33390218
	L3	7.142	1.46	-7.2942	27.303735	0.29645139	0.513028443	5.13376427	-0.07861647

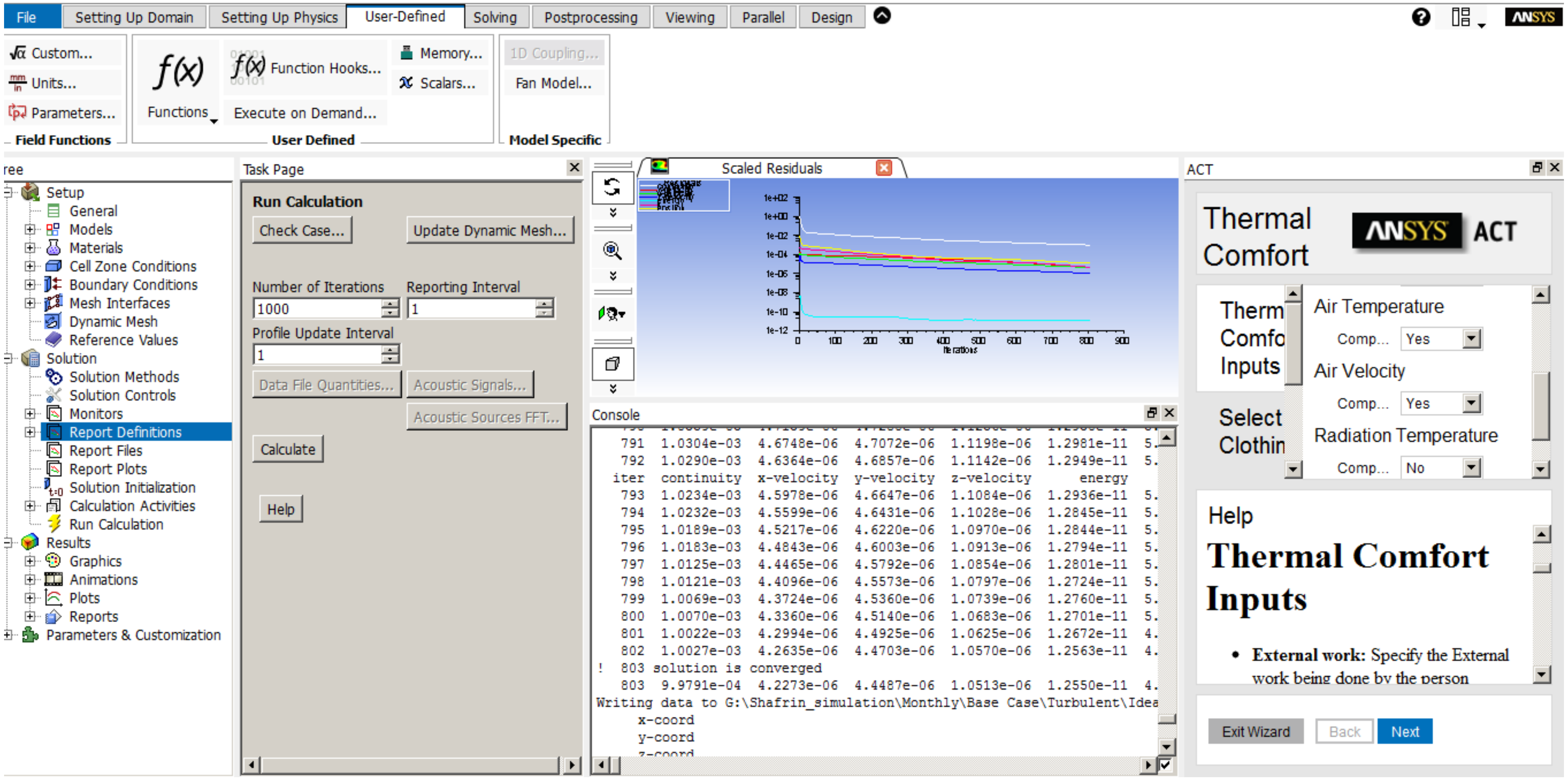
Simulation Result: Case 8

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity (%)	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	27.617761	0.1049228	0.291579187	7.72499752	0.360864
	C1	4.9816	1.06	-2.389	26.948206	0.0558733	0.471233994	7.14416885	0.321097
	L1	7.142	1.06	-2.389	26.006006	0.0462093	0.511210144	5.32968235	0.126064
	W2	2.8212	1.06	-4.956	26.140588	0.008856	0.446482509	5.49472475	0.154265
	C2	4.9816	1.06	-4.956	26.094171	0.0191972	0.519988954	5.43353271	0.144546
	L2	7.142	1.06	-4.956	25.462518	0.0088362	0.494748145	5.00311279	0.01137
	W3	2.8212	1.06	-7.2942	25.593774	0.008267	0.514565885	5.03247786	0.039191
	C3	4.9816	1.06	-7.2942	25.211481	0.0056326	0.552088559	5.0370326	-0.04206
	L3	7.142	1.06	-7.2942	24.86355	0.0038801	0.495092273	5.28155661	-0.11652
1m	W1	2.8212	1.46	-2.389	28.215326	0.2329596	0.327394843	6.29308176	0.249567
	C1	4.9816	1.46	-2.389	27.027094	0.0677164	0.512306511	7.36611128	0.337252
	L1	7.142	1.46	-2.389	26.099176	0.0525975	0.559601724	5.43948174	0.145594
	W2	2.8212	1.46	-4.956	26.269006	0.0144384	0.483818742	5.68085003	0.181075
	C2	4.9816	1.46	-4.956	26.157922	0.0169547	0.566622019	5.51716423	0.157886
	L2	7.142	1.46	-4.956	25.541315	0.0135122	0.543155134	5.01671362	0.028079
	W3	2.8212	1.46	-7.2942	25.770349	0.0168883	0.574604213	5.12270164	0.076499
	C3	4.9816	1.46	-7.2942	25.26626	0.0034256	0.603707433	5.01936626	-0.03037
	L3	7.142	1.46	-7.2942	24.928979	0.0066256	0.542106807	5.21777248	-0.10248

Simulation Result: Case 9

Plane	Point	X	Y	Z	Temperature (C)	Velocity m/s	Turbulent Intensity	PPD in percentage	PMV
.6m	W1	2.8212	1.06	-2.389	28.1357365	0.181210905	0.117794	13.48488	0.634411
	C1	4.9816	1.06	-2.389	28.0267277	0.070882045	0.167289	20.39989	0.854230
	L1	7.142	1.06	-2.389	27.4147282	0.031930603	0.173975	16.06182	0.724983
	W2	2.8212	1.06	-4.956	27.8221073	0.051224463	0.154011	19.01373	0.815153
	C2	4.9816	1.06	-4.956	27.9412174	0.09293431	0.168254	17.6317	0.774177
	L2	7.142	1.06	-4.956	27.4038029	0.054878127	0.171055	15.98563	0.722505
	W3	2.8212	1.06	-7.2942	27.7922611	0.043648653	0.123154	18.78294	0.808466
	C3	4.9816	1.06	-7.2942	27.7743168	0.106194407	0.163779	15.41494	0.703519
	L3	7.142	1.06	-7.2942	27.2753544	0.065812826	0.175071	15.15196	0.694821
1m	W1	2.8212	1.46	-2.389	28.5231571	0.389633417	0.14597	10.28653	0.502889
	C1	4.9816	1.46	-2.389	28.0263309	0.081596836	0.1782	19.31043	0.823675
	L1	7.142	1.46	-2.389	27.398798	0.041244961	0.188858	15.95162	0.721398
	W2	2.8212	1.46	-4.956	27.8097782	0.068403468	0.163928	18.77956	0.808357
	C2	4.9816	1.46	-4.956	27.9412479	0.110919826	0.178725	16.10968	0.726545
	L2	7.142	1.46	-4.956	27.4071293	0.072092615	0.184407	15.95024	0.721361
	W3	2.8212	1.46	-7.2942	27.9892826	0.098482251	0.122435	17.39037	0.766716
	C3	4.9816	1.46	-7.2942	27.778101	0.135181636	0.172645	13.43007	0.633725
	L3	7.142	1.46	-7.2942	27.2805729	0.082901649	0.186943	14.43739	0.670071

Appendix J: Ansys Fluent 18.1 with Thermal ACT



Number of Iterations: 1000

Reporting Interval: 1

Profile Update Interval: 1

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 796  1.0183e-03  4.4843e-06  4.6003e-06  1.0913e-06  1.2794e-11  5.
 797  1.0125e-03  4.4465e-06  4.5792e-06  1.0854e-06  1.2801e-11  5.
 798  1.0121e-03  4.4096e-06  4.5573e-06  1.0797e-06  1.2724e-11  5.
 799  1.0069e-03  4.3724e-06  4.5360e-06  1.0739e-06  1.2760e-11  5.
 800  1.0070e-03  4.3360e-06  4.5140e-06  1.0683e-06  1.2701e-11  5.
 801  1.0022e-03  4.2994e-06  4.4925e-06  1.0625e-06  1.2672e-11  4.
 802  1.0027e-03  4.2635e-06  4.4703e-06  1.0570e-06  1.2563e-11  4.
!  803 solution is converged
 803  9.9791e-04  4.2273e-06  4.4487e-06  1.0513e-06  1.2550e-11  4.
Writing data to G:\Shafrin_simulation\Monthly\Base Case\Turbulent\Idea
      x-coord
      y-coord
      z-coord
```

Air Temperature: Comp... Yes

Air Velocity: Comp... Yes

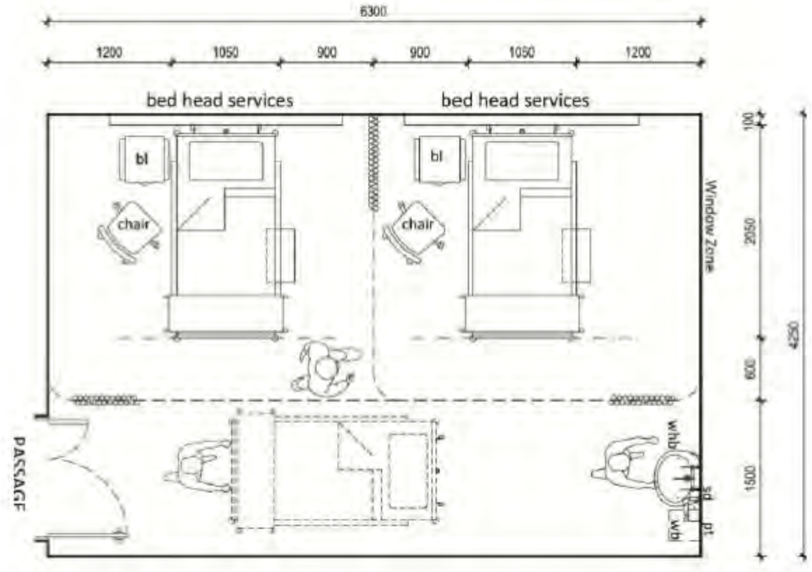
Radiation Temperature: Comp... No

Thermal Comfort Inputs

- **External work:** Specify the External work being done by the person

Figure: Ansys Fluent 18.1 with Thermal ACT screenshot

Appendix K: The Ideal Bed Space Requirements



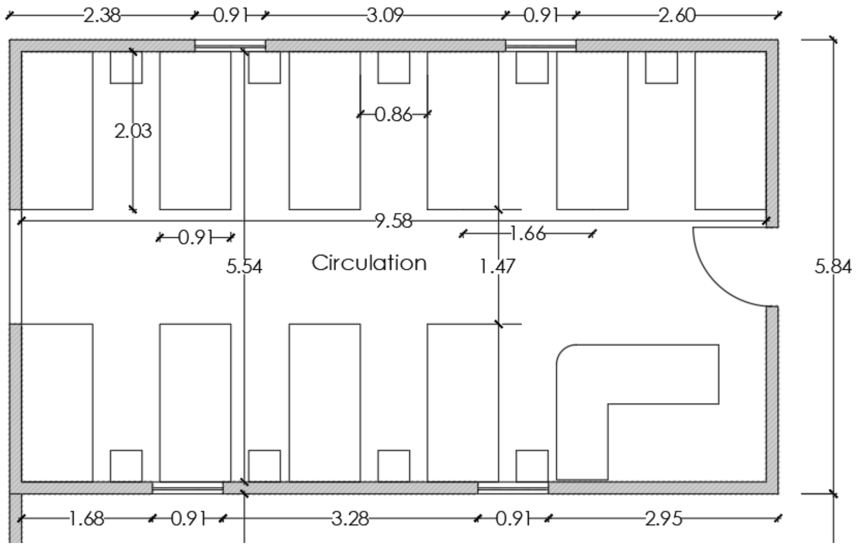


Figure: Bed space standard (Time-Saver Standards)

Figure: The existing bed space of SHMH

Appendix L: The Plans of Investigated UHCs

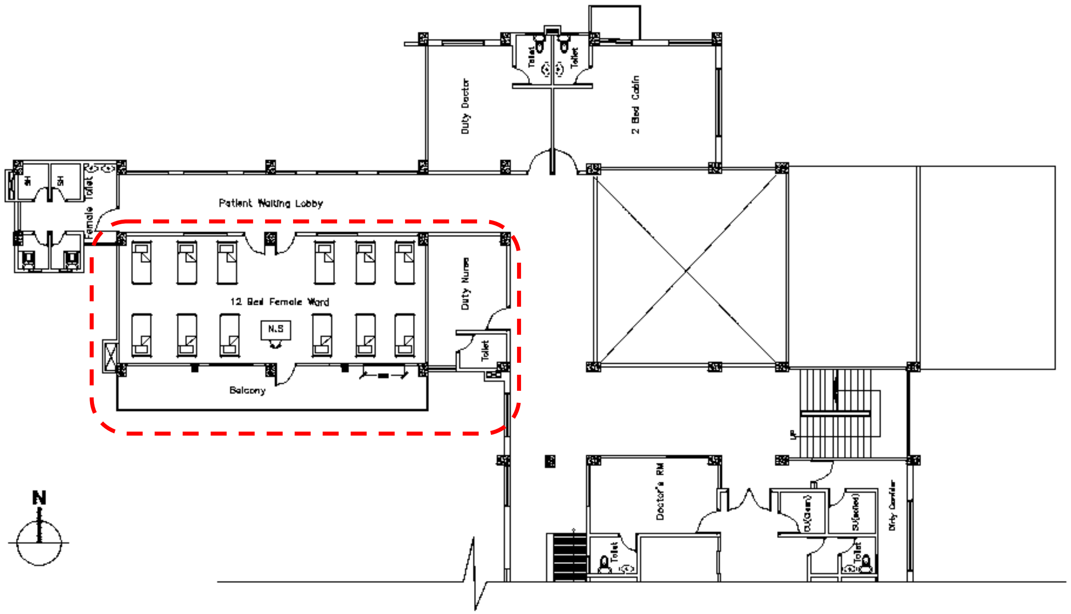


Figure: Plan of UHC Puthiya, Rajshahi

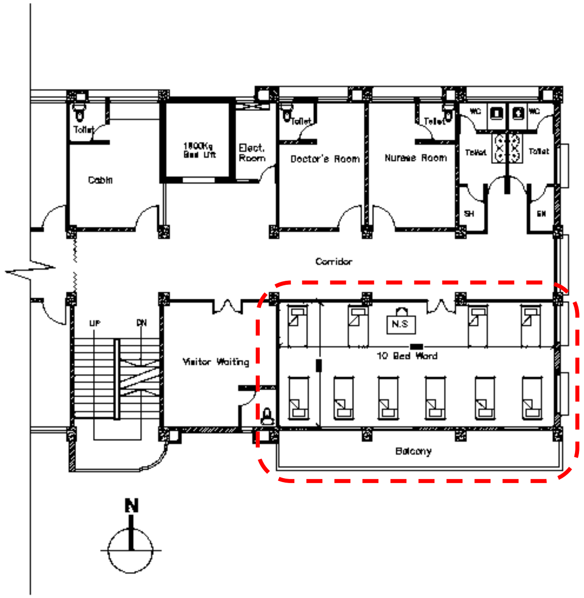
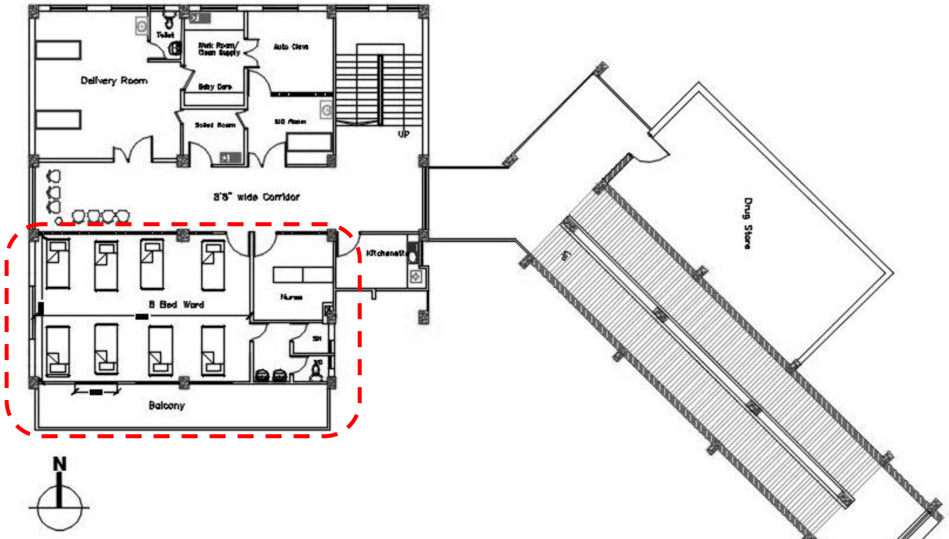


Figure: Plan of UHC Poba, Rajshahi



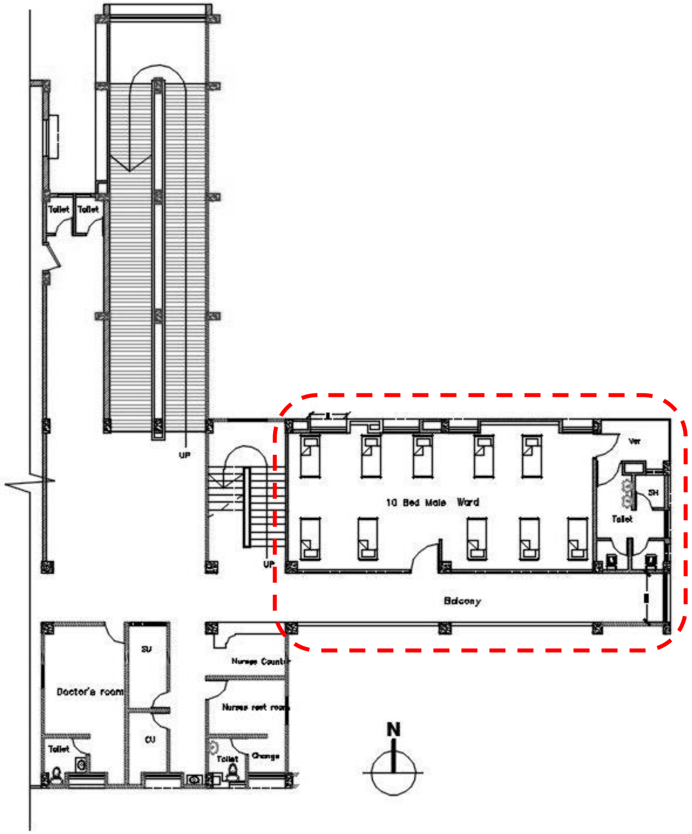


Figure: Plan of MCWC Kaliganj, Gazipur

Figure: Plan of UHC Poba, Rajshahi

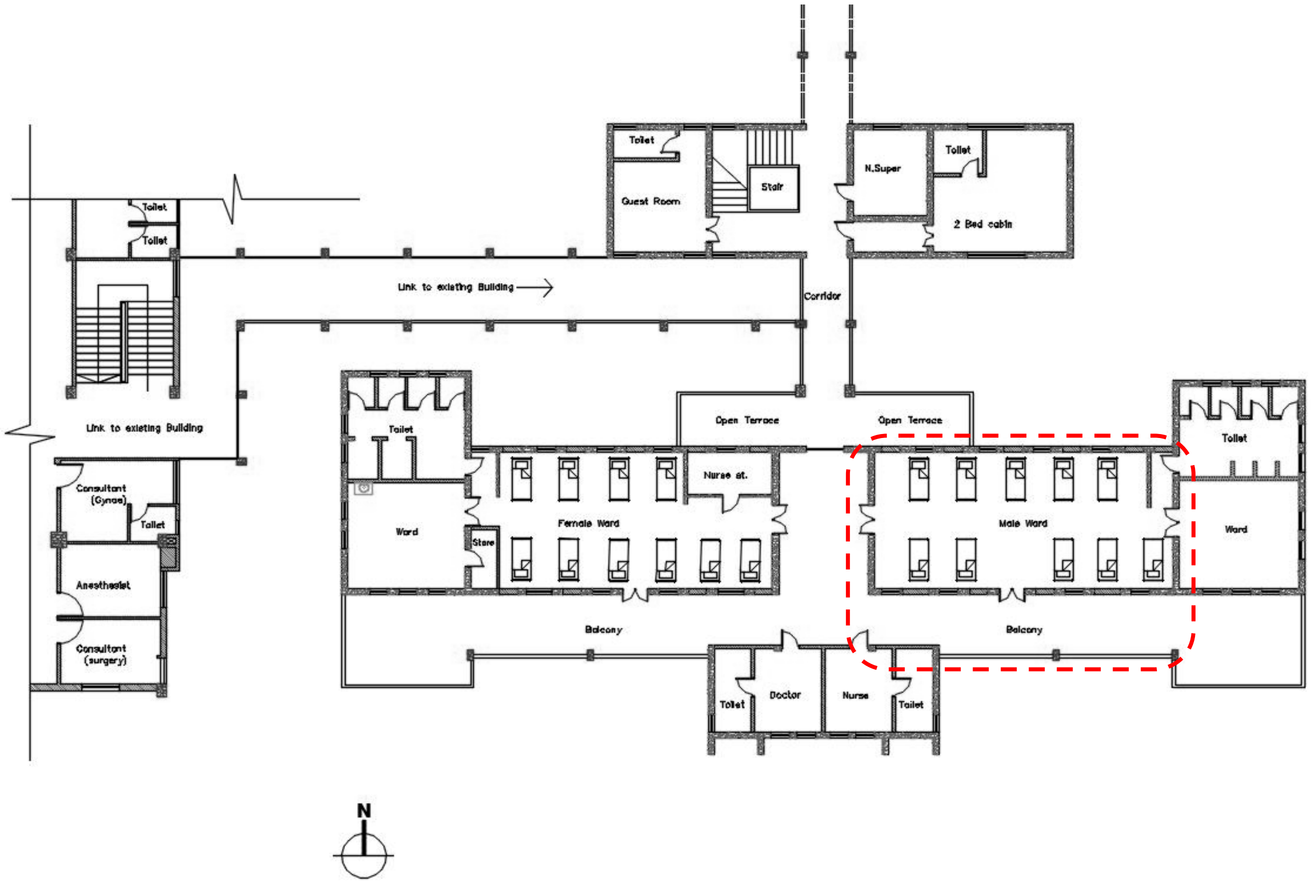


Figure: Plan of UHC Mohonpur, Rajshahi