EXERGETIC AND POWER AUGMENTATION ANALYSES OF GAS TURBINE WITH AIR-BOTTOMING COMBINED CYCLE

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Certificate of Approval

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ABSTRACT

Concept of exergy based analysis for the thermodynamic evaluation of energy conversion systems is steadily growing. Exergy analysis efficiently acts as a supplement with energy analysis to identify the origin of losses and the options for loss reductions to boost the power output of any thermal energy conversion system. To pander the immense energy demand especially in the hot summer days, the application of power augmentation technique on the existing thermodynamic power generating model is an emerging research field. In the present work, the exergetic and power augmentation analyses of a simple gas turbine cycle and a gas turbine with air bottoming cycle (ABC) is performed. To identify the effect of important parameters on the performance characteristics of the conventional gas turbine cycle and ABC is presented with the presence and absence of inlet fogging power augmenting technology, based on the first and second law of thermodynamics. In this study, work output, specific fuel consumption (SFC) and the quantitative exergy balance for each component and for the whole system are investigated using thermodynamic modeling software Cycle-Tempo. Power output and exergetic variations of simple gas turbine cycle due to the inlet fogging system are comprehensively discussed and compared with those of the ABC cycle. The results indicate that, in the air bottoming combined cycle (ABC), exergy recovery is greater than the exergy loss due to additional components, approximately 8.5% of fuel exergy is recovered; 3.4% accounts for the exergy destruction of the additional components in the ABC, while 5.1% results in the increase of the work output. And this gives a boon of 9% less SFC in ABC than that of the simple gas turbine cycle. Due to the installation of the inlet fogging system in the cycle, compressor mass flow increases averagely 21.6% and GT fuel flow rate experiences approximately 22.6% increment and the net result is increment of cycle power output. Average Power augmentation of simple gas turbine cycle is around 21.9%, and of ABC approximately 25.2 %, due to inlet fogging. First law and second law efficiency of the combined cycle (ABC) is higher than that of simple GT cycle, irrespective of presence and absence of inlet fogging system, due to the substantial exergy recovery in the air bottoming combined cycle over the simple gas turbine cycle. The rate of power augmentation by the inlet fogging still cause an extra energy input to the gas turbine, this makes a small change in efficiency of the power plant. So, cycle power augmentation with the inlet fogging is at the expense of marginal improvement of efficiency in order to boost power output.

List of Symbols

EX_W	Exergy associated with work transfer
EX_Q	Exergy associated with heat transfer
EX_{th}	Thermomechanical exergy
EX_{ch}	Chemical exergy
EX_{total}	Total Exergy
g	Specific Gibbs free energy
e_f	Specific flow exergy
ε_{HE}	Effectiveness of heat exchanger
$\dot{E}_d$	Exergy destruction
R_p	Pressure ratio in topping cycle
r_p	Pressure ratio in bottoming cycle
k	specific heat ratio
η	Efficiency
η_I	First law efficiency
η_{II}	Second-law efficiency
ABC	Air bottoming cycle
CC	Combustion chamber
c_p	Specific heat at constant pressure
h	Specific enthalpy
$\dot{m}$	Mass flow rate
R	Specific-gas constant
SFC	Specific fuel consumption
SWO	Specific work output
T_0	Ambient temperature
TIT	Turbine inlet temperature
RH	Relative humidity
ϑ_a	Volume of mixture per unit mass of dry air
$\dot{V}$	Volume flow rate

W	Work output
$E_{d,comb}$	Combustion chamber exergy destruction
$E_{d,ex}$	Exhaust exergy destruction
$E_{d,comP}$	Compressor exergy destruction
$E_{d,turb}$	Turbine exergy destruction

Subscripts

ref	Reference state
i	Identifies constituent of a mixture
0	Restricted equilibrium with the environment
00	Unrestricted equilibrium with the environment
amb	Ambient
$comp$	Compressor
$turb$	Turbine
$comb$	Combustion chamber
a	Dry air
bF	Before filter(GT with inlet fogging system)
In	Compressor inlet without an inlet fogging system
inF	Compressor inlet with an inlet fogging system
w	Fogging water
v	Water vapor
top	Top
bot	Bottom

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Chapter 1

INTRODUCTION

Chapter 1

Introduction

Energy consumption is one of the most important indicator showing the development stages of countries and living standards of communities. Population growth, urbanization, industrialization, and technological development result directly in increasing energy consumption. To meet the pressing need of the energy consumption, Gas turbine based technology playing a significant role for harnessing the resources.

Gas turbine power plants are increasingly popular because of higher energy conversion efficiencies and low emission [1]. Moreover, Low capital cost, environmental advantages and short construction lead time and quick response to load demand have made the gas turbines superior to steam power plant [2].Gas turbines are used by themselves in a very wide range of services. Nowadays, the gas turbine has a large share of the world electricity generation. According to Diesel and Gas turbine worldwide's 32nd Annual Power Generation Order Survey, the total output of the ordered gas turbines reached about 43 GW from June 2008 to May 2009 [3]. In recent years, the performance of industrial gas turbines has been improved due to considerable investment in research and development [4].

The development of the gas turbine aptly illustrates the so called S- curve principle. In the beginning, gas turbines were inefficient, bulky, and unreliable engines. In order to improve their performance, modifications, such as reheat, intercooling, or recuperation, were applied. Another approach was combining the turbines with other, more developed cycles, such as the Rankine cycle. But as soon as the break-through period was achieved in the 1960s, and industrial gas turbines could utilize the achievements obtained in jet engine technology, the use of advanced/combined schemes was no longer required for efficient plant operation. The open-cycle gas turbines offered low capital costs, compactness, and efficiency close to that of the steam plants. Nevertheless, after the oil crisis in the 1970s the efficiency of power plants became the top priority, and combined-cycle plants, first in the form of existing steam plant repowering, and later, as specially-designed gas-and-steam turbine plants, have become a common power plant configuration [5].

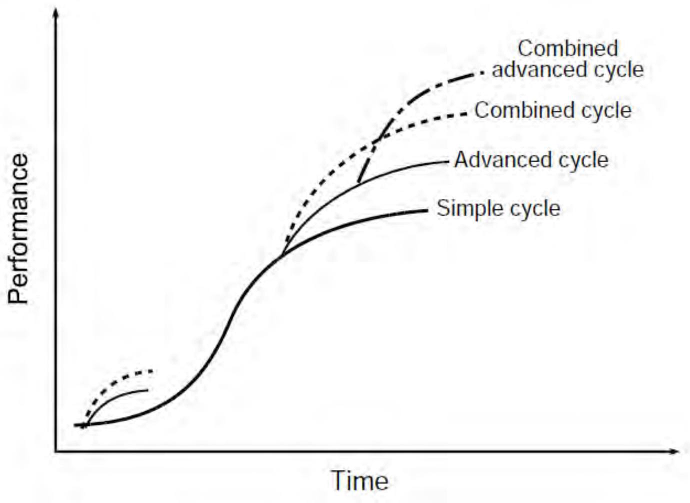


Figure 1.1: Technology development path [5].

Gas-Steam combined cycle has given to a considerable improvement of the power effectiveness of power plants during the past decades, with effectiveness values of conversion

to electricity approaching 60 % for power plants MWe and higher [6]. Even such a combined cycle offers a high fuel to power conversion efficiency and effectiveness, but the installation costs of the high-pressure steam generator, the steam turbine, and the condenser might prove to be prohibitive in small-scale power generation [7]. Air bottoming cycle (ABC) together with a topping gas turbine cycle is another advanced combined cycle offering efficiency close to that of a combined gas-steam turbine cycle [8]. However, combination and integration of two cycles may not always be beneficial. To maintain a performance gain, developments in combined-cycle technology should be assessed on the basis of several criteria, the most important of which is efficiency. The concept of efficiency in the traditional sense is based on the axiom of conservation of energy, or the first law of thermodynamics. The pitfall of this concept originates with the very law: it accounts for energy quantity only, but never for the quality. The quality of energy in the thermodynamic sense is synonymous to its ability to be transformed to useful work, as stipulated by the second law of thermodynamics, which bestows a much greater glory on ordered forms of energy (e.g work) than disordered form of energy (e.g heat) [9]. Thus second law of thermodynamics opened a brand new window to measure and compare performance of energy conversions. This is called exergy method.
Unlike energy, exergy or availability is not a conserved quantity. Every reversible process causes a loss in availability which is irrevocable as dictated by the second law of thermodynamics. Since no natural process is totally reversible, we always have to accept some form of loss in availability no matter how hard we try. But acceptance of loss in availability should always be compensated by some economic justification. Non-existence of such a justification indicates that the availability loss results only from an error in the art of engineering. Thus presence of an availability loss invariably indicates the opportunity of a thermodynamic improvement [10].

Exergy is defined as the maximum theoretical work that can be obtained from a combined system (combination of a system and its reference environment) when the system comes into equilibrium (as thermally, mechanically and chemically) with the environment without violating any laws of thermodynamics. The maximum available work from a system emerges as the sum of two contributions: thermo-mechanical exergy and chemical exergy. Thermo-mechanical exergy is defined as the maximum extractable work from the combined system as the system comes into thermal and mechanical equilibria with the environment, and its value is calculated with respect to restricted dead-state condition. At the restricted dead-state conditions, no work potential exists between the system and the environment due to temperature and pressure differences. In this state, the control mass is in thermo-mechanical equilibrium with the environment, but not necessarily in chemical equilibrium with it [11]. In principle, the difference between the compositions of the system at the restricted dead-state and the environment, and the difference in species concentrations between the system and environment can be used to obtain additional work to reach chemical equilibrium through reaction and diffusion respectively. The maximum additional work obtained in this way is called the chemical exregy [9].

As the exergy based analysis of systems having different types of fuel is more common; so, naturally there should have a reasoning of fuel selection of a particular system analysis. Nowadays because of increasing strain on world fossil fuel reserves and the capricious nature of the crude oil market have strongly influenced the growth of interest in the research on natural gas. Natural gas occupied a virile field of research for combined cycle power generation. Both the energy and exergy based analyses of this cycle indicated their importance over coal or oil based cycle [12].But the problem is, a sustained increase in summer peak period power demands and peak period duration combined with escalation of peak energy rates have encouraged owners and operators of existing plants to seek power-enhancing alternatives for optimizing plant performance and revenue streams [13]. A variety of options for enhancing combined cycle performance (primarily plant output) exists. Modeling and simulation of these options is an invaluable tool for plant performance evaluation and development. Aided by an unwonted growth of digital computers, modeling has allowed exploration of cycle operational parameters, and effect of their variation on performance. Level of detail of the model varies significantly still, depending on the nature of study. Exergy (second law of thermodynamics) based modeling of combined cycle has been established as a key indicator in identifying the effects of variations in operational parameters and provide guidance for future development [14].

1.1 Objective of the Thesis

The present study concentrates on the investigation of a gas turbine with air bottoming cycle (ABC) using inlet fogging power augmentation technique. The objectives and specific aims of this study are as follows:

1. To carry out energy and exergy analyses for the conventional gas turbine and the gas turbine with air bottoming cycle (ABC).
2. To study a power augmentation technique (inlet fogging) for the gas turbine with ABC.
3. To figure out possible change of second law efficiency for the modified cycle from the conventional gas turbine cycle.
4. To apply exergy destruction analysis to identify the performance improvement potentials of the studied process.

1.2 Outline of the Thesis

The present work takes a thermodynamic approach to analyze simple and combined power generation cycle, without and with the presence of power augmentation technique. Since the exergy approach is ideally suited for this kind of analysis, majority of the post-processing and analyses are done using exergy method. The most relevant literature review on thermodynamic analyses of simple and combined cycle in general case and as well as with the power augmentation technologies have been reviewed in chapter 2 in a chronological order.

Comprehensive exergy analysis of thermodynamic systems require calculation of both physical and chemical exergies. In chapter 3, all the required terminology and concepts for the development of exergy balance equations are first discussed. Then, balance equations are developed for both control mass and control volume systems. Special attention has been paid to integrate chemical exergies of the contents of the system by ensuring calculation of both reactive and diffusive components.

Details thermodynamic modeling and simulation procedures of the considered simple and combined cycles are discussed in chapter 4. Energy and exergy based analyses of the power cycles are modelled here from the governing thermodynamic equations. Also the inlet fogging thermodynamics are briefly discussed. End of this chapter validation of this study is done with the previously performed experimental and modeling data.

The influence of key operating variables such as ambient temperature, pressure ratio and turbine inlet temperature (TIT) on specific work output (SWO), specific fuel consumption (SFC), energy and exergy efficiencies were investigated in chapter 5. In the exergy analysis, component wise exergy destruction/losses were evaluated to determine distribution of the exergy destruction in the systems.

Chapter 2

LITERATURE REVIEW

Chapter 2

Literature Review

The Brayton cycle was first proposed by George Brayton in 1870 for the use in the reciprocating oil-burning engine. Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery [15]. The interest in the combined cycle operation was aroused through the world in mid1970's. The enormity of the present state of combined cycle research makes reviewing it quite a challenge. Research in many areas like combustion, emission, advanced cycle, power augmentation, and exergy have grown to a myriad today. This chapter attempts to review the most relevant ones in a chronological approach.

2.1 ABC Cycle Evolution and General Analysis

In regard to the simple-cycle gas turbine technology, the major driver to enhance the engine performance has been the increase in process conditions (temperature and pressure) through advancements in materials and cooling methods. Ongoing development and near term introduction of advanced gas turbines will improve the efficiency of the simple-cycle operation more than 40%. The combination of the gas turbine cycle (Brayton cycle) with a medium or low temperature bottoming cycle (like the Rankine cycle), known as the conventional combined cycle, is the most effective way to increase the thermal efficiency of a gas turbine cycle. Heavy duty natural gas fired gas turbines in combination with heat recovery steam generators and steam turbines represent the state of the art of this approach [16].

Small-scale power generation is often characterized by low efficiency, which is caused by both physical and economic constraints. For example, simple-cycle gas turbines below 1 MW have efficiency no higher than 25% [17]. To obtain higher values, some modifications are required. As a gas turbine's exhaust has a relatively high temperature and a large mass flow, utilization of this waste heat is the most common solution. Waste heat can be recovered directly within the gas turbine by thermal recuperation, or indirectly using another working fluid (steam injection). Alternatively, the conversion of waste heat into power can be done in a bottoming cycle.

Several engines that employ recuperation have been developed. With the exception of the 21 MW Westinghouse/Rolls-Royce turbine, these are small engines ranging from 65 kW (Allied Signal, NREC) to 1.4 MW (Heron) and 4.2 MW (Solar Mercury). These turbines have been specifically designed for operation in the recuperative mode. For existing non-recuperated turbines to achieve higher efficiency two other options are available: steam injection or a bottoming cycle. The steam injection, while being a relatively simple solution, may pose problems when applied to the engines that were not designed for. These problems include erosion of turbine blades, an overload of the expander, an increased production of CO and unburned hydrocarbons. Also, water treatment is required [18].

In the case of steam bottoming, the need for a high-pressure steam generator, a steam turbine, and a condenser might be unfeasible on a small scale. It should be mentioned that special requirements are imposed on water quality, high-pressure equipment and operators of the steam plant.

An alternative is ABC (air bottoming cycle).In the ABC, the exhaust flow of an existing, topping gas turbine is sent to a gas-air heat exchanger, which heats the air in the secondary gas turbine cycle. The air bottoming cycle was patented by Farrell of General Electric Company in 1988 [19]. William Farrell claims that the ABC provides greater thermodynamic efficiency compared to that of the gas turbine alone, while retaining the operational flexibility of the gas turbine. He notes that a steam and gas turbine combined cycle has a number of drawbacks such as difficulties in handling water steam and the need for large capital investment. The especial application of the air bottoming cycle was also invented in Nov. 1988 by ED Alderson [20].

In 1995, Kambanis [21] showed that an LM2500 gas turbine coupled to the ABC has a considerably better off-design performance, especially at lower power rating levels, where gas turbines run very inefficiently. Also in 1996, O. Bolland [22] found that the ABC adds 10.5% points to the efficiency of an LM2500PE gas turbine. He also claimed that according to the feasibility study, the ABC is an economical alternative for power generation on both new oil/gas platforms and on the existing platforms with demand for more power. In 1996, Najjar et al. [2], proposed a parametric analysis of a gas turbine with air bottoming cycle using a computer program. He found, besides reducing the cost of hardware installations, it could achieve a higher thermal efficiency than simple gas turbine which does not deteriorate at part load as happens in a simple one. In 1998, Korobitsyn [5] discussed about the advanced gas turbines and compared the conventional steam bottoming cycle with air bottoming cycle. He demonstrated that the ABC shows performance values close to and exceeding those of the steam bottoming cycle. Also Korobitsyn [18] in 2002 concluded that the combination of a gas turbine and an ABC represents a high efficiency Combined Heat and Power (CHP) plant that provides clean and hot air for process needs [4]. The technical-economic analysis showed that an implementation of this scheme at industries that require hot air will result in significant fuel savings and will have a payback time of 3 years. Korobitsyn notes that the ABC allows low-maintenance costs and a short start-up time. Furthermore the plant can be implemented in regions where water resources are limited.

2.2 Second Law Based Analysis

Energy in our world is found manifest in many forms, each with its own characteristics and its quality. The historical acceptance of the quality of energy finds itself in performing mechanical work. Hence, quality of energy today is synonymous with its capacity to cause change or do useful work. Natural observation shows that particular forms of energy differ in their ability to be transformed into other forms. Moreover, this ability if found to be dependent on composition and state properties of both system and surrounding. It is then only rational to have the quality index of energy acknowledge the transformability of a certain form of energy with respect to the environment; a fact overlooked by the universal law of energy conversion. Exergy bridges this gap in the analysis of energy transformations by using the second law of thermodynamics, which imposes certain restrictions in the direction and amount of energy transformations. Exergy is a measure of the maximum derivable work output (or, the minimum required work input) from a given thermodynamic process with specified conditions for both system and surrounding [9].
Though the quest for qualitative energy index can be traced back to the work of Gibbs [23] as available energy, the term exergy was first coined by Zoran Rant in 1953 from Greek root words [24]. Exergy means that fraction of the total energy that can be extracted as work. The concept of

exergy has been greatly explored and brought up to the applied sciences over the past 50 years [25].

Much of the earlier works on the developments in the applied level can be attributed to Szargut and Kotas in the eightes [26, 27, 28]. Especially the works on standard chemical exergy of the elements and some compounds by Szargut et al. has to be mentioned as one of the seminal works in the field [9, 29]. On the other hand, there has been a parallel theoretical development of the exregy concept from pure thermodynamics point of view by Haywood [30] and Sussman [31, 32].

It was not long before the concepts of second law analysis and exergy destruction started appearing in combined cycle. But in the recent past there was tremendous contribution in the exergy based analysis for combined cycle. There are many researchers such as Kotas [33] and Moran and Shapiro [34] who carried out the exergy analysis for the combined cycles. They found out the exergy losses in each part. Facchini et al. [35] have calculated the exergy losses in combined cycle and found out that combustion chamber and heat recovery steam generator (HRSG) are the main sources of losses. An exergy analysis was carried out by Habib and Al-Bagawi [36] for the Ghazlan power plant to specify the irreversibility in the system. Casarosa et al. [37] have presented the optimization of HRSGs by using two or more water streams, exchanging with the exhaust gas stream. This method will decrease the exergy losses due to temperature difference between the hot and cold streams.

The modeling, numerical optimization and irreversibility reduction of a triple-pressure reheat combined cycle was investigated by Bassily [38]. Ertesvag et al. (2005) have shown the exergy analysis of a gas-turbine combined-cycle power plant with precombustion CO2 capture. Sengupta et al. (2007) have studied the exergy analysis of a coal-based 210 MW thermal power plant. Khaliq and Choudhary (2007) have studied the combined first and second-law analysis of gas turbine cogeneration system with inlet air cooling and evaporative after cooling of the compressor discharge. Sanjay et al. (2007) have performed research work on energy and exergy analysis of steam cooled reheat gas steam combined cycle. Butcher and Reddy (2007) have studied Second law analysis of a waste heat recovery based power generation system. Ameri et al. (2008) have studied the exergy analysis of a 420MW combined cycle power plant. Their objective is to evaluate irreversibility of each part of Neka CCPP using the exergy analysis. Borelli and Junior (2008) have studied the exergy-based method for analyzing the composition of the electricity cost generated in gas-fired combined cycle plants.

Though started in the last decade, conventional and some modified combined cycle experienced innumerable exergy based performance analysis. But there was meager contribution of second law based analysis for gas turbine with ABC. Korobitsyn MA (1998) conducted an exergy analysis of the GT-ABC plant. M.Ghazikhani et al. [39] recently performed a details energy and exergy based analysis for simple gas turbine and gas turbine with ABC cycle. He indicated that the exergy destruction analysis can be applied to identify the reasons why the performance of a gas turbine with ABC is higher than that of a simple gas turbine.

2.3 Augmentation Technologies and Exercised Analysis

In recent years, global temperature has increased gradually due to global warming. Consequently, the demand for power during summer days has increased. Unfortunately the output of gas turbine will be reduced by 0.5% to 0.9% for every 1°c rise in ambient temperature [40, 41]. Since gas turbine performance plays an important role in combined cycle power plants, high ambient temperature will result in loss of power output for combined cycles.

Summer peak period power demands and peak period duration combined with escalation of peak energy rates have encouraged owners and operators of existing plants and developers of combined- cycle power plants to seek power-enhancing alternatives for optimizing plant performance. A variety of options available for enhancing combined-cycle performance.

Steam or water injection in the combustor is commonly applied for NO_x control. Injecting steam or water into the head end of the combustor for NOx abatement increases mass flow and, therefore, output. Generally, the amount of water is limited to the amount required to meet the NOx requirement in order to minimize operating cost and impact on inspection intervals. Steam injection for power augmentation has been an available option for over 30 years. When steam is injected for power augmentation, it can be introduced into the compressor discharge casing of the gas turbine as well as the combustor. In combined-cycle operation, the cycle heat rate increases with steam or water injection. In the case of water injection, this is primarily due to the use of high-grade fuel energy to vaporize and heat the water. In the case of steam injection, this is primarily due to the use of bottoming cycle energy to generate the steam for the gas turbine that could otherwise be used in the steam turbine [13].

For applications where significant power demand and highest electricity prices occur during the warm months, a gas turbine air inlet cooling system is a useful option for increasing output. Inlet air cooling increases output by taking advantage of the gas turbine's characteristic of higher mass flow rate and thus, output, as the compressor inlet temperature decreases. Industrial gas turbines that run at constant speed are constant-volume-flow machines. The specific volume of air is directly proportional to the temperature. Because the cooled air is denser, it gives the machine a higher air mass flow rate and pressure ratio, resulting in an increase in output. In combined-cycle applications there is also a small improvement in thermal efficiency.

Several methods are available for reducing gas turbine inlet temperature. There are two basic systems currently available for inlet cooling. The first and perhaps the most widely accepted system is evaporative cooling (conventional evaporative cooling, inlet fogging, evaporative intercooling). The second system employs various ways to chill the inlet air.

Evaporative cooling is a cost-effective way to add machine capacity during warm weather when peaking power periods are usually encountered on electric utility systems, provided the relative humidity is not too high.

Evaporative cooling works on the principle of reducing the temperature of an air stream through water evaporation. The process of converting the water from a liquid to a vapor state requires energy. This energy is drawn from the air stream. The result is cooler, more humid air. A psychrometric chart is useful in exploring the theoretical and practical limitations of evaporative cooling.

Traditional gas turbine evaporative cooling also falls into the low-risk, moderate-reward category. Evaporative cooling requires a somewhat larger capital cost investment than is required for inlet fogging, has a slightly larger negative impact on plant performance than inlet fogging and has the lowest incremental peak power-generating capacity. The economic trends associated with the evaporative cooling system are similar to those that exist for inlet air fogging; however, evaporative cooling requires a slightly higher incremental peak power energy rate to achieve parity with the base plant arrangement than what is required for inlet air fogging [50].

Foggers were first applied to gas turbine inlet air cooling in the mid-1980s. Nearly 100 fog systems are installed on turbines in North America, from aeroderivatives to large-frame machines [51]. Fog systems create a large evaporative surface area by atomizing the supply of water into billions of super-small spherical droplets. Droplet diameter plays an important role with respect to the surface area of water exposed to the airstream and, therefore, to the speed of evaporation. The fogging system sprays atomized water into the gas-turbine inlet by high pressure (100-200 bar) demineralized water. This system includes minute holes in arrays of nozzles which are arranged across the gas-turbine inlet ducting [52].
Gas turbine inlet air fogging falls into the low risk, moderate-reward category. Of all the alternatives, inlet fogging requires the lowest up-front capital investment. Gas turbine inlet pressure drop is lower than that of evaporative media and provides increased output. Potential for higher effectiveness than evaporative media. And faster installation time due to reduced duct modifications compared to evaporative media.
Evaporative intercooling, also called overspray or overcooling, can be accomplished by purposefully injecting more fog into the inlet airstream than can be evaporated with the given ambient climate conditions. The airstream carries unevaporated fog droplets into the compressor section. Higher temperatures in the compressor increase the moisture-holding capacity of air, so the fog droplets that did not evaporate in the inlet air duct do so in the compressor. When the fog evaporates, it cools, making the air denser. This increases the total mass flow of air through the gas turbine and reduces the relative work of compression, giving an additional power boost. Fog intercooling allows turbine operators to get power boosts that are greater than would be possible with a conventional evaporative cooling system [53].

There is one possible drawback to intercooling: if water droplets are too large, there is a potential for liquid-impaction erosion of the compressor blading. Bombardment of a metal surface with water droplets can lead to the development of micro-fractures in the metal's surface and can cause surface pitting [13].
The two basic categories of inlet chilling systems are direct chillers and thermal storage. Liquefied natural gas (LNG) systems take advantage of the fuel supply, utilizing the cooling effect associated with the vaporization of liquefied gas. Thermal storage systems take advantage of off-peak power periods to store thermal energy in the form of ice to perform inlet chilling during periods of peak power demand. Direct chilling systems use mechanical or absorption chilling. Unlike evaporative coolers, however, cooling coils are able to lower the inlet dry-bulb temperature below the ambient wet-bulb temperature. The actual temperature reduction is limited only by the capacity of the chilling device, the effectiveness of the coils and the compressor's acceptable temperature/humidity limits.

Where premium prices are paid for power during daytime peak power consumption periods, off-peak thermal energy storage may be the answer. Ice or cold water is produced using mechanical chillers during off-peak hours and weekends and stored in large storage tanks. Capacity enhancement is possible only for a few hours each day. During periods of peak power demand, the cold water or cold water produced from melted ice is used to chill the gas turbine inlet air. This system is capable of reducing gas turbine inlet air temperature to temperatures of between 50 and 60°F. However, significant space is required for the ice or cold water storage [13].

Gas turbine inlet air chilling for the sole purpose of capturing additional peak-period power revenues falls into a high-risk, high-reward category. Of the alternatives discussed, inlet chilling requires the largest up-front capital cost investment. Inlet air chilling has the highest sensitivity to peak-period operating hours.

In the implemented study De Lucia et al. [42] concluded that evaporative inlet cooling could enhance the power by 2% to 4% depending on the weather condition. The results of Alhazmy and Najjar [43] also concluded that water-spray coolers are less expensive and more effective than cold-coil coolers, especially during hot and dry climate conditions.

A moisture air turbine (MAT) cycle was proposed by Utamura et al. [44] for improving the performance of land based gas turbines by injecting atomized water through inlet into compressors. In their study, the output of the gas turbine can be increased by 10 % using 1% fogging (water spray/incoming air ratio) under 35°c and 53% relative humidity ambient conditions.
A detailed study was performed by Tawney et al [45] to evaluate several power augmentation options for combined cycle power plants. The results concluded that inlet fogging has the minimal engineering procurement and construction cost. Many researchers [40, 41, 46, 47] have studied the power augmentation of gas turbines by inlet fogging in the past. However, most of the studies focused on gas turbines operating with simple cycles. Recently, Bharagava et al [48] studied the effects of different types of gas turbines operating with combined cycles using inlet fogging.

Previous investigations provided decisive insight into energy and exergy and power augmentation analysis of simple gas turbine. Even though very few studies were conducted on combined cycle power augmentation systems, but gas turbine with ABC deprived from such improvement technique analysis. There is an utmost need for the details exergetic and power augmentation analysis of gas turbine with ABC for better understanding and improvements in fuel consumption and the control of environmental emissions.

Chapter 3

EXERGY

Chapter 3

Exergy

Exergy is the cornerstone of exergetic and thermo-economic analyses. From theoretical point of view this chapter explains what exergy is and how to calculate it for matter, heat, and work flows, as well as exergy destruction (irreversibility) associated with exergy transfer.

3.1 Exergy and its Physical Meaning

Quality of Energy

Exergy comes purely from thermodynamics. Exergy is the tool, which indicates how far the system departs from the equilibrium state. The concept of exergy was put forward by Gibbs in 1878. It was further developed by Rant in 1957 [N. Woudstra, Exergy: The quality of energy].

Quantitative evaluation of energy in a cycle or in a process can be done using the first law of thermodynamics. The direction of flow of heat or work in know from the second law of thermodynamics. However, it is equally important to assign the quality to the energy. Energy can be broadly classified into: High grade & Low grade energy. High grade form of energy are highly organized in nature and conversion of such energy to some other grade form is not dictated by the second law of thermodynamics. Conversion of high grade energy to low grade energy is not desirable. However, there may be some conversion to low grade energy as work is converted into other useful form. This is because of dissipation of heat due to friction (example: mechanical work→ electricity, some losses are there due to the friction in bearing of machineries). Thus both the first and second law of thermodynamics are to be considered for analysis.

Low grade energy such as heat due to combustion, fission, fusion reactions as well as internal energies are highly random in nature. Conversion of such form of energy into high grade energy is of interest. This is due to the high quality of organized form of energy obtained from low grade energy. Second law of thermodynamics dictates that conversion of 100 % heat into work is never possible. That part of low grade energy which is available for conversion is termed as available energy, availability or exergy.

So by combining the 1st and 2nd laws of thermodynamics we can say: “energy is conserved” and “things fall apart”. And energy has quantity and as well as quality

Energy quality is the ratio of exergy to energy.

$$\mathrm{Q} = \frac{EX}{E}$$

Exergy = Q * Energy

So, exergy is the useful portion of energy

Exergy is also synonymous to:

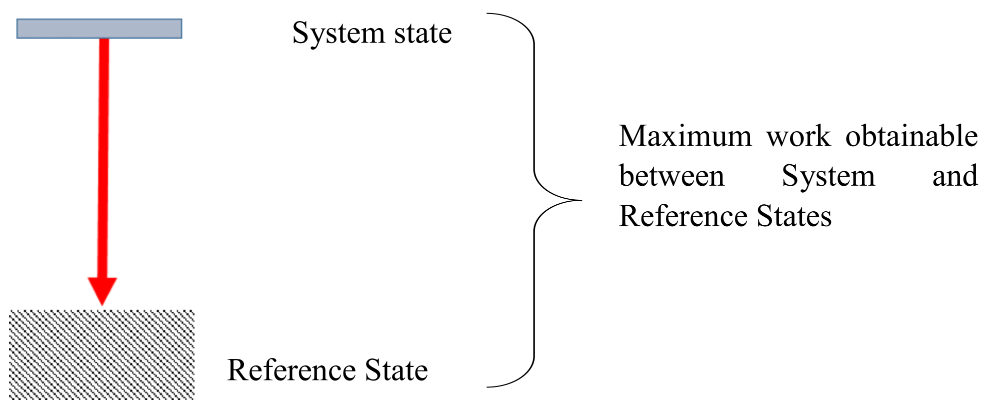
- Exergic energy
- Maximum work content
- Utilizable energy
- Essergy
- Maximum work
- Reversible work
- Ideal work
- Available useful work

Definitions and Aspects

Exergy is a measure of work potential or disequilibrium from the environment.

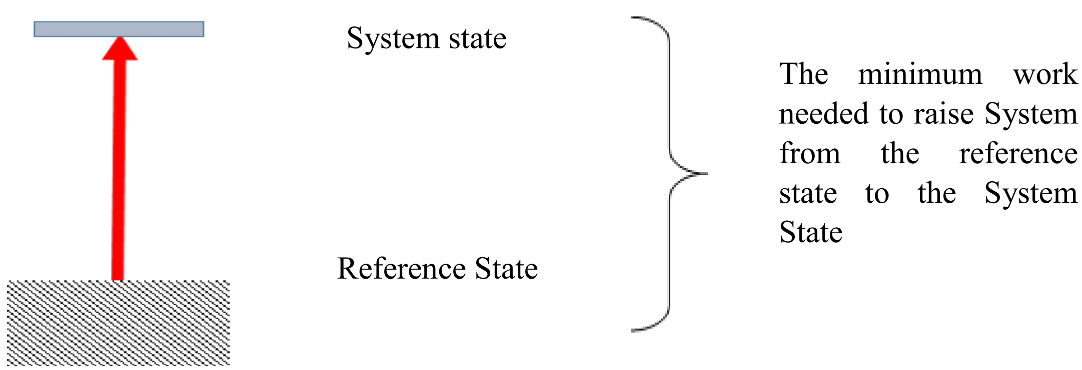
The formal definition of exergy of a system or resources can be given [49] as:

Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes.



Or,

Exergy is the work required to raise some matter from a state of thermodynamic equilibrium with the common components of the natural surroundings to a higher state by means of reversible processes.



So, Exergy: Minimum work needed and maximum work obtainable in system-reference interaction.

Exergy & Reversible work

Reversible Work, *W*rev is the max amount of useful work that can be produced (or the min work needs to be supplied) as the system undergoes a process between the initial and final states. When the final state is the dead state, the reversible work equals exergy.
Before introducing mathematical rigour, it is important to establish some important terminology unique to thermodynamics, or to be more specific, exergetic analyses.

Environment: The environment is defined as a very large body or medium in the state of perfect thermodynamic equilibrium implying there is no gradients or differences involving pressure, temperature, chemical potential, kinetic or potential energy. The environment may interact with systems in three different ways:

1. Through thermal interaction as a reservoir of thermal energy at temperature T_0.
2. Through mechanical interaction as a reservoir of unusable P_0dV work.
3. Through chemical interaction as a reservoir of a substance of low chemical potential in stable equilibrium.

For the present work the environment has been defined at a temperature T_0 = 298.15 K, and pressure P_0 = 1.01325 bar. The chemical composition of the reference environment is takes as defined in [9]:

Table 3.1: Reference Substances

Chemical Element	Chemical Symbol	Mole fraction in dry air	Standard Partial pressure in the environment $P_{i,00}$, bar
Ar	Ar	0.00933	0.00907
C	CO_2	0.0003	0.000294
D	D_2O (g)	--	0.00000137
H	H_2O (g)	--	0.0088
He	He	0.000005	0.0000049
Kr	Kr	0.000001	0.00000098
N	N_2	0.7803	0.7583
Ne	Ne	0.000018	0.0000177
O	O_2	0.2099	0.2040
Xe	Xe	0.00000009	0.000000088

Equilibrium: Definition of two types of equilibria are necessary,

Restricted Equilibrium (P_0, T_0): At restricted equilibrium, mechanical and thermal equilibrium between the system and the environment is established, i.e., $P = P_0$ and $T = T_0$. The term restricted implies there is a physical restriction between the system and environment preventing exchange of matter. The state of restricted equilibrium will be referred to as the environmental state.

Unrestricted Equilibrium (P_{00}, T_{00}, x_{00}): In addition to mechanical and thermal equilibrium ($P = P_0 = P_{00}$ and $T = T_0 = T_{00}$), when conditions for chemical equilibrium, i.e., equalization of chemical potentials is satisfied between the system and the surrounding, the unrestricted equilibrium or the dead state is achieved.

Reference Substances: Suitable substances that are present in the defined environment with known concentration, for calculation of chemical exergy of any given element or species. Among different environmental substances containing a particular chemical element the one with the lowest chemical potential is most suitable as a reference substance.

3.2 Classification of Exergy of a Thermodynamic System

Component-wise summary of types of exergy will be given in this section.

3.2.1 Exergy associated with work transfer, (EX_w)

Exergy is the useful work potential, and the exergy transfer by work can simply be expressed as

$$\begin{aligned} EX_W = W_C &= W - W_{surr} \quad \text{(for boundary work)} \\ &= W \qquad\qquad \text{(for other form of work)} \end{aligned} \tag{3.1}$$

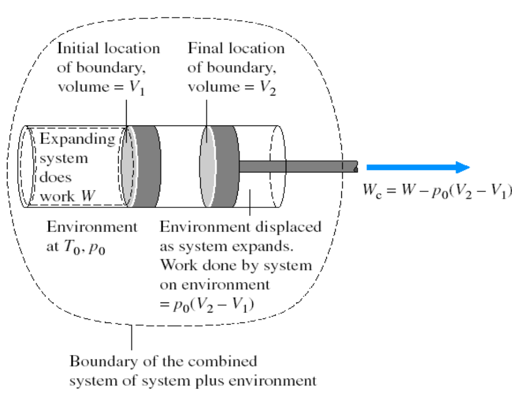


Figure 3.1: Illustration used to discuss the expression for an exergy transfer accompanying work [34].

Where, W_{surr} = P_0 (V_2-V_1), P_0 is atmospheric pressure, and V_1 and V_2 are the initial and final volumes of the system. The exergy transfer for shaft work and electrical work is equal to the work W itself.

Note that exergy transfer by work is zero for systems that have no work.

3.2.2 Exergy associated with heat transfer, (EX_Q)

The exergy of heat transfer at the control surface is determined from the maximum obtainable work from it using the environment as a reservoir of zero-grade thermal energy. For a heat transfer of q and a temperature at the control surface where heat transfer is taking place T, the maximum possible conversion from thermal efficiency to work is,

$$EX_Q = [1 - \frac{T}{T_0}] \,.\, q \qquad (3.2)$$

When the source temperature is lower than that of the environment, the exergy can be viewed as the minimum work input required in a reversible heat pump (RHP) to maintain that low temperature, as shown in Fig. 3.2

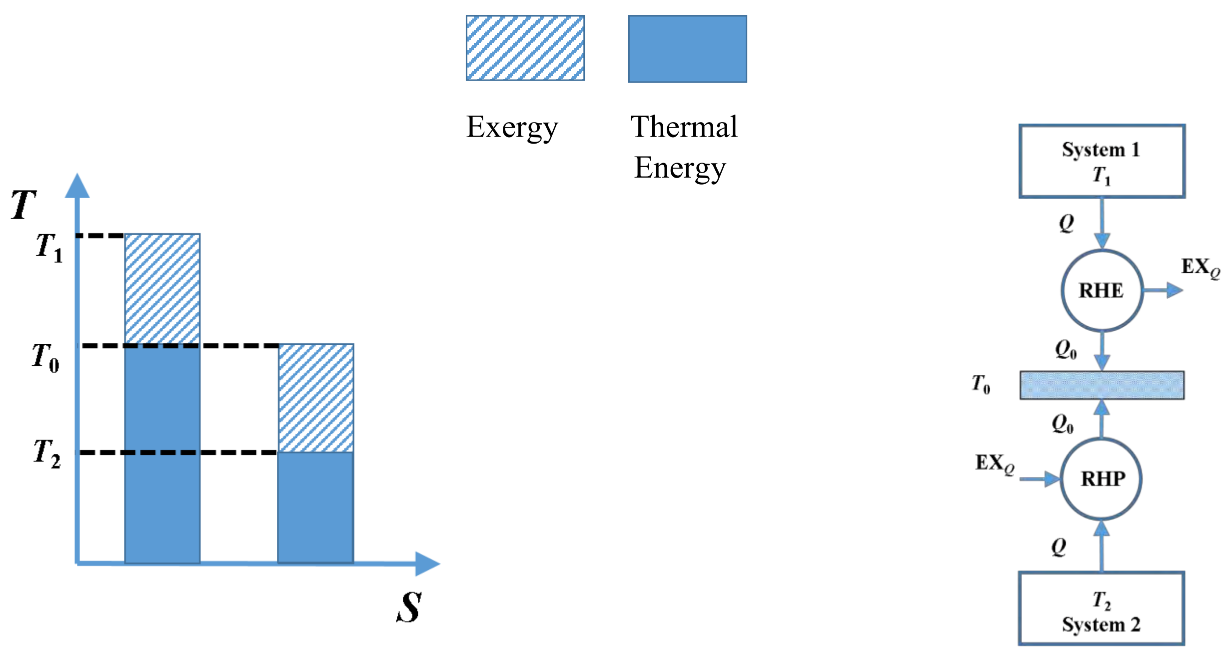


Figure 3.2: Exergy Transfer with Heat

3.2.3 Thermomechanical exergy, (EX_{th})

The thermomechanical exergy is equal to the maximum amount of work available when a stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0, by physical processes involving only thermal interaction with the environment. For any given state it is given by

$$EX_{th} = (h - T_0\ s) - (h_0 - T_0\ s_0) \tag{3.3}$$

Where,

h	is the specific enthalpy of the stream at the given state
s	is the specific entropy of the stream at the given state
h_0	is the specific enthalpy of the stream at environmental state
s_0	is the specific entropy of the stream at environmental state

For closed-mass system the expression is changed to

$$EX_{th} = (u + P_0\ v - T_0\ s) - (u_0 + P_0\ v_0 - T_0\ s_0) \tag{3.4}$$

where ,

u	is the specific internal energy of the stream at the given state
v	is the specific volume of the stream at the given state
u_0	is the specific internal energy of the stream at environmental state
v_0	is the specific volume of the stream at environmental state

3.2.4 Chemical exergy, (EX_{ch})

Thermodynamically, the maximum work of a chemical reaction can be put as,

$$[W_x]_{\max} = -\Delta g^0 \tag{3.5}$$

Where Δg^0 is the standard value of Gibbs function of the reaction. The relevance if equation (3.5) is not limited to chemical processes. Work in any reversible isothermal process (e.g., diffusion) is equal to the decrease of the Gibbs function of the stream [9].

3.2.4.1 Chemical exergy of reference substances

When the system contains any of the reference substances, its difference in concentration from of the environment is the source of work potential which could be equilibrated through diffusion. Hence, the molar chemical exergy for a reference substance is given by,

$$EX_{ch,rs} = (\mu_0 - \mu_{00})_{rs} \tag{3.6}$$

Which under ideal gas assumptions, can be shown as

$$EX_{ch,rs} = RT_0 \ln\left(\frac{P_0}{P_{00}}\right) \tag{3.7}$$

where, the subscript *rs* denotes reference substance, and

μ_0	is the chemical potential of the substance at environmental state
μ_{00}	is the chemical potential of the substance at dead state
R	is the gas constant
$P_{00,rs}$	is the partial pressure of the substance in the reference environment

3.2.4.2 Chemical exergy of non-reference substances

These substances are first converted to reference substances using fictitious reversible reactions involving only one mole of the reference substance while only heat transfer with the atmosphere is allowed. Thus chemical exregy for these substances comprises of the maximum work from these reactions, minus chemical exergies of the reactant reference substances taken from the environment, plus chemical exergies of the product reference substances. If the reference reaction takes *j* reference reactant species from the environment and one mole of the non-reference substance, and produces *k* reference products, the maximum work of this reaction is

$$-\Delta g^0 = \left(\sum_{prod,rs} n_k\ g_k^0 - \sum_{reac,rs} n_j\ g_j^0 - g_{nrs}^0\right) \tag{3.8}$$

Hence the expression for molar chemical exergy becomes

$$\widetilde{EX_{ch,rs}} = -\Delta g^0 - \sum_{reac} n_j\ \left(\widetilde{EX_{ch,rs}}\right)_j + \sum_{prod} n_k\ \left(\widetilde{EX_{ch,rs}}\right)_k \tag{3.9}$$

where, the subscript *nrs* denotes non-reference substance, and

n_j	is the number of moles of *j*-th reactant reference substance
n_k	is the number of moles of *k*-th product reference substance

3.2.4.3 Chemical exergy of a mixture

If the substances form an ideal gas mixture, for example gaseous fuels, combustion products, etc., the constituents of the mixture are separated by an ideal device through a reversible and isothermal separation and compression process. The work required for these processes per mole of the gas mixture is

$$\sum_i \left[\widetilde{W_{mix}}\right]_{rev} = \check{R}T_0 \sum_i x_i \ln x_i \tag{3.10}$$

where x_i is the mole fraction of the i-th component in the mixture. Thus exergy of the mixture is equal to the sum of molar chemical exergies of the constituents plus the reversible work that goes into separating them.

$$\widetilde{EX_{ch,mix}} = \sum_i \widetilde{EX}_{ch,i} + \check{R}T_0 \sum_i x_i \ln x_i \tag{3.11}$$

Investigation of equation (3.11) reveals the last summation term on the right to be negative. Physically, it signifies the reduction in work potential of the constituents as they form a mixture.

3.3 Exergy Balance of a Thermodynamic System

With the components defined, total exergy of a system or stream is defined as the sum of the thermomechanical and chemical components [11].

$$EX_{total} = EX_{th} + EX_{ch} \tag{3.12}$$

where for open system, EX_{ch} is calculated using equation (3.3), and for a closed system equation (3.4) is used instead.

Hence, the general exergy balance can now be expressed in extensive form using the component definitions stated in the previous subsections as

$$EX_i + EX_Q = EX_e + EX_w + E_d \tag{3.13}$$

where

- EX_i is the initial exergy of the system or stream,
- EX_e is the final exergy of the system or stream,
- EX_Q is the exergy transfer with heat,
- EX_w is the exergy transfer with work,
- E_d is the amount of exergy destruction (generated irreversibility) defined as follows,

3.3.1 Exergy Destruction (Irreversibility)

Exergy is not a conserved property. It is destroyed by the generation of entropy. The second law provides useful relations concerning entropy generation through dissipation (e.g., fluid friction, ohmic resistance) and spontaneous non-equilibrium processes (e.g., spontaneous chemical reaction, free diffusion, unrestrained expansion, equalization of temperature, etc.), called in general exergetic terms, exergy destruction (irreversibilities) of a process. The Gouy-Stodola relation [9] provides a convenient measure of the amount of exergy destruction of a process in an open system with multiple inlets and outlets, and a number of thermal interactions at different temperatures as

$$E_d = T_0 \left[\sum_{out} m_e s_e - \sum_{in} m_i s_i - \sum_{r} \frac{Q_r}{T_r} \right] \quad (3.14)$$

For a closed mass system, which can be modified as

$$E_d = T_0 \left[\Delta S - \sum_{r} \frac{Q_r}{T_r} \right] \quad (3.15)$$

where T_r is the temperature at the system boundary with a heat interaction Q_r

3.3.1 Rational Exergy Efficiency

Rational exergetic efficiency or, effectiveness is definedin general sense as the ratio of the sum of all output exergy, EX_{output} over the sum of all input exergy, EX_{input}

$$\in = \frac{EX_{output}}{EX_{input}} \quad (3.16)$$

As it considers the quality of energy using the exregy concept, thus this efficiency definition is superior to the conventional one. And it allows more sensible direction in energy auditing, decision making and thermodynamic design of power systems.

CHAPTER 4: THERMODYNAMIC MODELING AND SIMULATION OF GAS TURBINE CYCLES

Chapter 4

Thermodynamic Modeling and Simulation of Gas Turbine Cycles

Without any doubt, the best results under practical circumstances are those that have been done experimentally. Thermodynamic cycle research experienced those, cause, many show a penchant for experimental works. However, experimentation must also face problems like reliability of measurement, economic and time constraints, and most importantly, most of the variables must be kept constant in order to study a particular characteristics. Modeling processes allows to overcome these problems with ease. Specially, effects of parametric variations on one or a group of operating characteristics can be easily studied through a model. With adequate experimental validation, the analysis can be extended into much depth with significant reduction in expense in time and money. The present chapter describes the details thermodynamic modeling and simulation of the considered cycles and also validates the present model with those of the relevant previous study.

4.1 Thermodynamic Modeling

The thermodynamic system analysis consists of three statements concerning three system properties: mass, energy, and entropy. These encapsulated the mass conservation law, the energy conservation law (first law of thermodynamics), and the exergy (second law of thermodynamics). Exergy is not conserved as energy, which is destructed in the system due to internal and external irreversibilities. For a real process, the exergy input always exceeds the exergy outputs; this unbalance is due to irreversibilities, a process known as exergy destruction. Thus, thermodynamic inefficiencies and the processes that cause them is identified. Illustration of the above three in differential mathematical forms can be shown as follows.

The mass rate balance for control volumes with several inlets and exits which is commonly employed in engineering is,

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_\iota - \sum_e \dot{m}_e \tag{4.1}$$

Where, the subscripts *cv, i* and *e* = control volume, inlet and exit respectively; $\dot{m}$ = mass flow rate of the fluid stream.

An accounting balance for the energy of the control volume is,

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \quad (4.2)$$

Where, $\frac{dE_{cv}}{dt}$ represents the time rate of change of energy of the control volume; $\dot{Q}_{cv}$&$\dot{W}_{cv}$ are the time rate of heat input and work output in the control volume; ; h= enthalpy, V = bulk velocity of the working fluid, z = altitude of the stream above the sea level, g =specific gravitational force

The control volume exergy rate balance considering several inlets and exists in the control volume is,

$$\frac{dEX_{cv}}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \left(\dot{W}_{cv} - p_o \frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe} - \dot{E}_d \quad (4.3)$$

Where, the term $\frac{dEX_{cv}}{dt}$ represents the time rate of change of the exergy of the control volume. The term $\dot{Q}_j$ represents the time rate of heat transfer at the location on the boundary where the instantaneous temperature isT_j, the accompanying exergy transfer rate is given by $\left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j$ .The term $\dot{W}_{cv}$ represents the time rate of energy transfer by work other than flow work, the accompanying exergy transfer is given by $\left(\dot{W}_{cv} - p_o \frac{dV_{cv}}{dt}\right)$, where $\frac{dV_{cv}}{dt}$ is the time rate of change of volume. The terms $\dot{m}_i e_{fi}$ and $\dot{m}_e e_{fe}$ accounts for the time rate of exergy transfer accompanying mass flow and flow work at the inlet and exit. $\dot{E}_d$ accounts for the time rate of exergy destruction due to irreversibilities within the control volume.

The specific flow exergy is given by,

$$e_f = h - h_0 - T_0 (s - s_0) + \frac{V^2}{2} + gz \quad (4.4)$$

Where h and s represents specific enthalpy and entropy, respectively, at the inlet or exit under consideration; h_0 and s_0 represents the respective values of these properties when evaluated at the dead state.

4.2 Inlet Fogging Thermodynamics

As previously stated, that the fogging system sprays atomized water into the gas-turbine inlet by high pressure (100-200 bar). Fig.4.1 shows a simplified psychrometric chart for an inlet fogging system. The difference between dry-bulb and wet-bulb temperature can be viewed as evaporative cooling potential. Fig.4.2 is a simplified diagram for the compressor inlet at original design under ideal conditions. For ideal conditions, the inlet-duct pressure loss is assumed to be negligible. A simplified diagram for inlet conditions of compressor with an inlet fogging system is shown in Fig.4.3, where the ambient conditions are assumed the same as in Fig. 4.2. The mass flow rate of demineralized water through the fogger is denoted by

$\dot{m}_w$. As shown in Fig.4.2, the system is under ideal conditions, $p_{in} = p_0$, $T_{in} = T_0$, $RH_{in} = RH_0$, and $\dot{m}_{in} = \dot{m}_0$. A single-shaft gas turbine operating at constant speed will have constant-volumetric flow rate throughout. Consequently, the volumetric flow rate at the compressor inlet should be constant even after the fogger has been installed [66]. Therefore,

$$\dot{V}_{inF} = \dot{V}_{in} \tag{4.5}$$

Thus we have:

$$\dot{m}_{a,inF}\,\vartheta_{a,inF} = \dot{m}_{a,in}\vartheta_{a,in} \tag{4.6}$$

All other parameters can be expressed in terms of the given parameters as shown in Eqs. (4.7) and (4.8).

$$\dot{m}_{a0} = \frac{\dot{m}_0}{1+\omega_0} \tag{4.7}$$

$$\dot{m}_{a,inF} = \left[\frac{\vartheta_{a0}}{\vartheta_{a,inF}}\right]\left[\frac{\dot{m}_0}{1+\omega_0}\right] \tag{4.8}$$

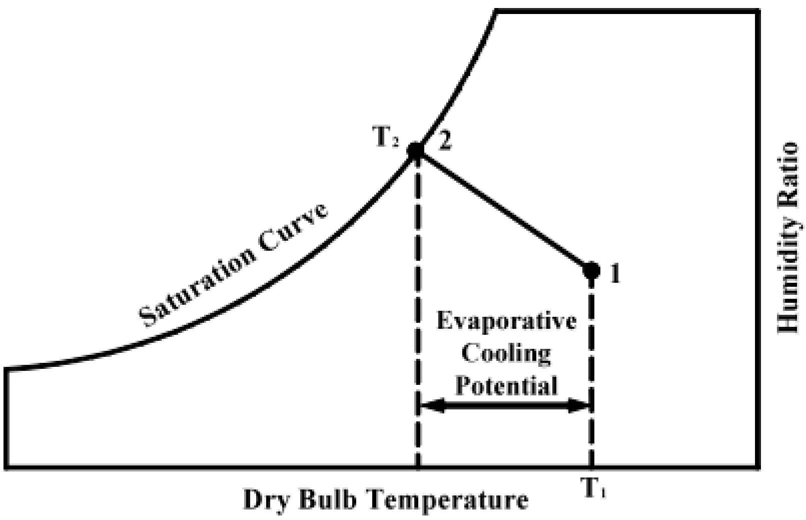


Figure 4.1: Simplified psychrometric chart for inlet fogging [66]

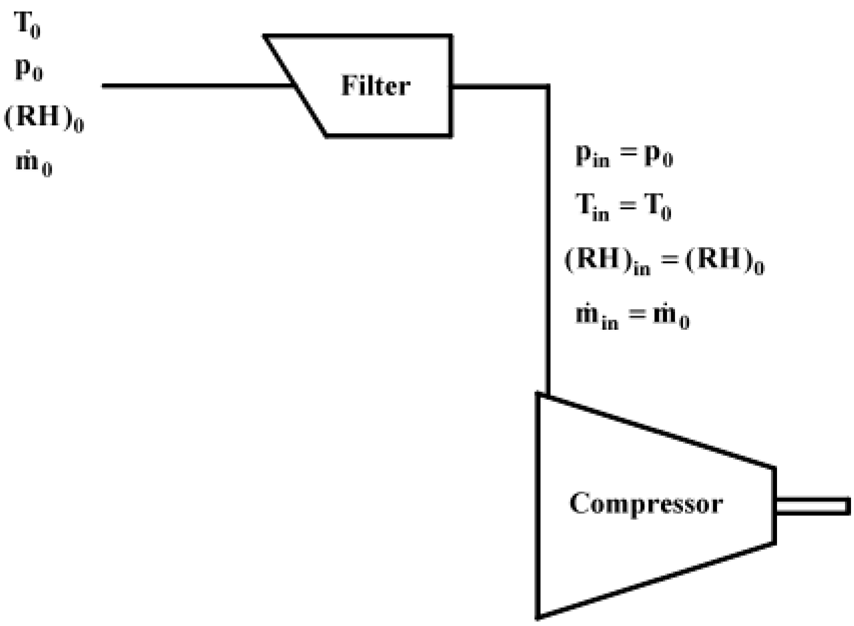


Figure 4.2: Simplified diagram for the compressor inlet at original design under ideal conditions [66]

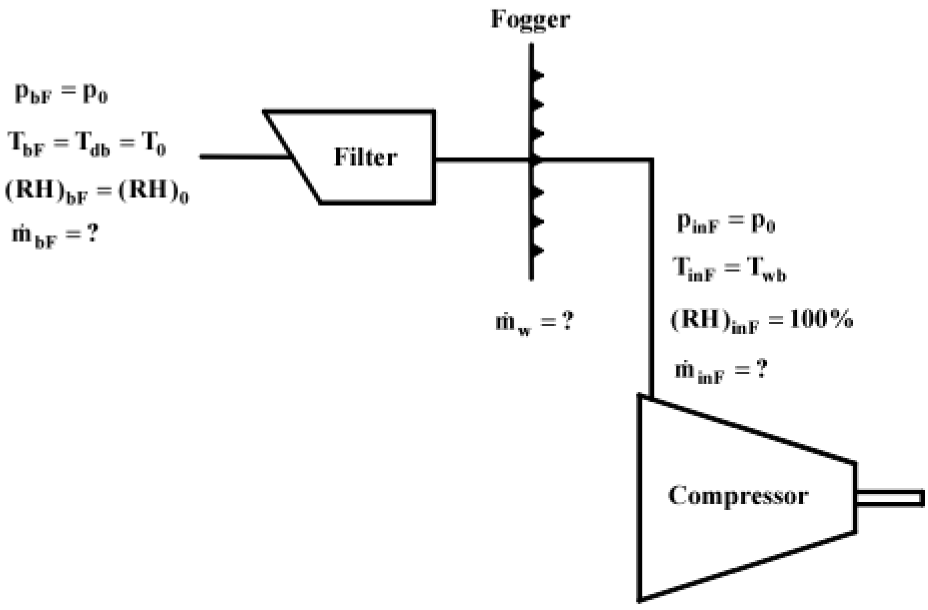


Figure 4.3: Simplified diagram for inlet conditions of compressor with an inlet fogging system [66]

The effectiveness of an ideal inlet fogging system is 100%. By neglecting the pressure drop in inlet ducts, we have $T_{inF} = T_{wb,inF} = T_{wb,bF}$ and the relative humidity is equal to 100 %. Thus,$RH_{inF} = 100$ %, and $T_{inF} = T_{wb}$ (corresponding to $p_{inF} = p_0$, $T_{bF} = T_{db} =$

$T_{0,}$ $and\ RH_{inF} = 100\ \%$). The value of $T_{inF}, \vartheta_{a,inF}, and\ \omega_{inF}$ can be found from the psychrometric chart. Thus, Eqs.(4.9) – (4.10) can be obtained [66].

$$\dot{m}_{v,inF} = \omega_{inF} \left[\frac{\vartheta_{a0}}{\vartheta_{a,inF}}\right] \left[\frac{\dot{m}_0}{1+\omega_0}\right] \tag{4.9}$$

$$\dot{m}_{a,bF} = \dot{m}_{a,inF} \tag{4.10}$$

$$\dot{m}_{v,bF} = \omega_{bF} \left[\frac{\vartheta_{a0}}{\vartheta_{a,inF}}\right] \left[\frac{\dot{m}_0}{1+\omega_0}\right] \tag{4.11}$$

$$\dot{m}_w = (\omega_{inF} - \omega_{bF}) \left[\frac{\vartheta_{a0}}{\vartheta_{a,inF}}\right] \left[\frac{\dot{m}_0}{1+\omega_0}\right] \tag{4.12}$$

$$\dot{m}_{inF} = \dot{m}_0 \left[\frac{\vartheta_{a0}}{\vartheta_{a,inF}}\right] \left[\frac{1+\omega_{inF}}{1+\omega_0}\right] \tag{4.13}$$

4.3 Description of the Cycles

A program named Cycle-Tempo is used in the present study, for the thermodynamic modeling and optimization of systems. Such systems often comprise various interconnected cycles each of which consists of (sometimes many) different apparatuses. These apparatuses are interconnected by pipes, thus forming a complex network of mass and energy flows.

The primary aim of Cycle-Tempo is to calculate the size of the relevant mass and energy flows in the system. The number of types of apparatuses, and the way in which they are interconnected may differ from case to case. Therefore, Cycle-Tempo leaves it up to the user, to enter the system configuration. The program contains a large number of models for apparatuses and pipes with which one can establish the desired system model.

This almost unlimited flexibility is a significant advantage over many existing programs in which the system configuration cannot be varied, or only to a limited extent.

Using Cycle-Tempo, cycles of gas turbine with different designs are obtained by adding components to them. Adding any components into a cycle affects all the working conditions and the characteristics of the cycle. In this study by adding regenerator and an inlet fogging system in the simple gas turbine cycle, the four cycles are obtained and analyzed.

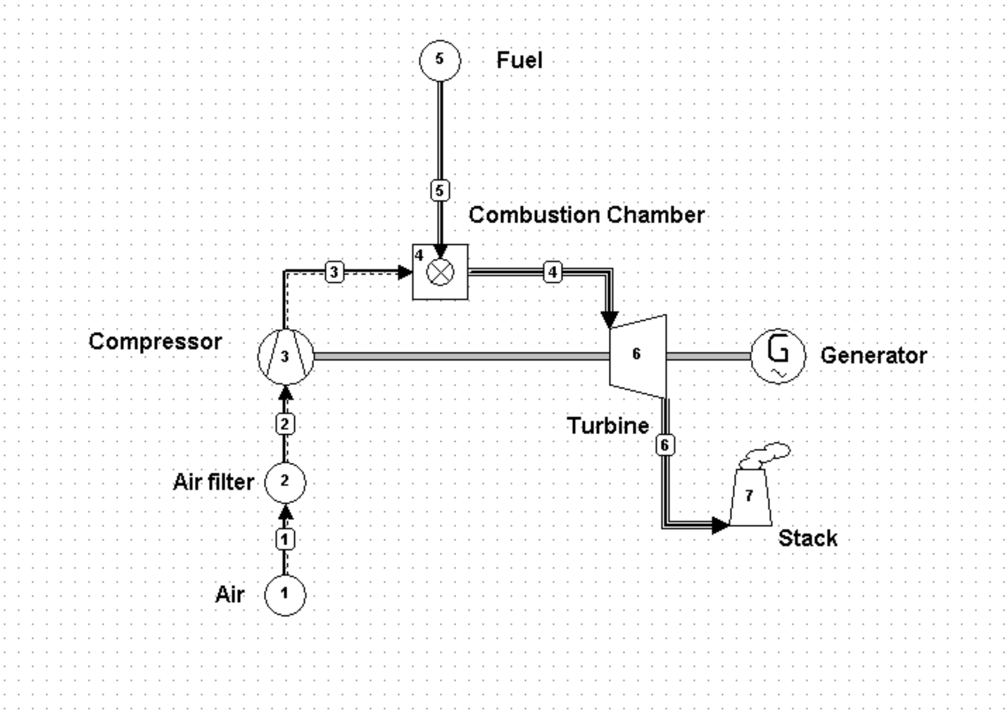


Figure 4.4: Simple open Cycle Gas Turbine Engine

The first cycle that is called Brayton cycle is actually an open cycle gas turbine engine as shown in Fig. 4.4. In this cycle, the filtered compressed air of the outlet of the compressor enters the combustion chamber, where it mixed with the fuel and after the combustion, the exhaust gases are expanded in a gas turbine to obtain work. Which in turn produces electrical power with the assistance of a generator, while the flue gases goes to environment through a stack.

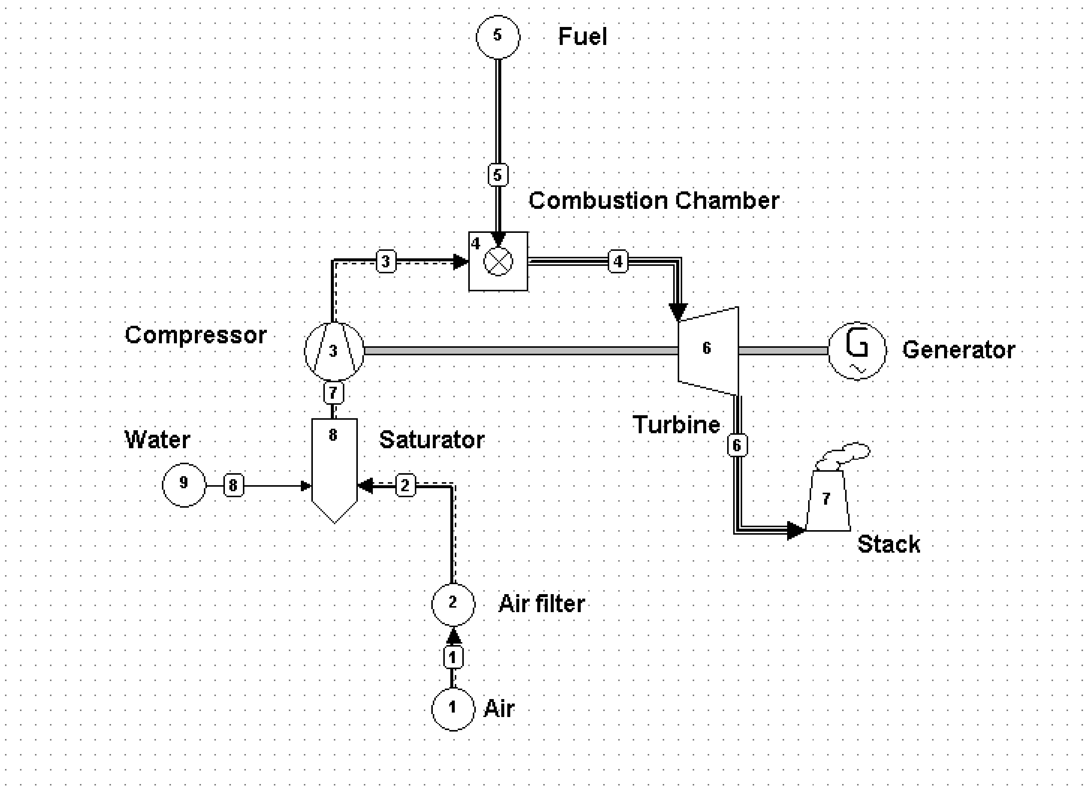


Figure 4.5: Simple Brayton Cycle with Inlet Fogging

Before compression, the inlet air is being saturated with the high pressure demineralized water, this is the inlet fogging Brayton cycle as shown in Fig. 4.5. Here the ambient air is cooled and saturated by spraying atomized water. The cooled air is then compressed and after that, the cycle works as the simple explained above.

The third cycle is a combined cycle, depicted in Fig. 4.6. It is a special type of combined cycle, known as Gas Turbine ABC (air bottoming cycle) combined cycle. In this cycle, the exhaust flow of an existing, topping gas turbine is sent to gas-air heat exchanger, which heats the air in the secondary gas turbine cycle. Heat exchanger in the air -bottoming cycle supplanted the need of a combustion chamber, while the function of a conventional combustion chamber of the topping cycle is as same as for the simple Brayton cycle. Power output is obtained in this combined cycle in two stages through two separate generator. Two stack placed at the end of the both topping and bottoming cycle has the role of dispersal of cycle exhaust products to the environment.

Another cycle analyzed in this study is a modified combined cycle. As Fig. 4.7 shows only modification is incorporated is the addition of a fogger at the inlet of the topping cycle compre-

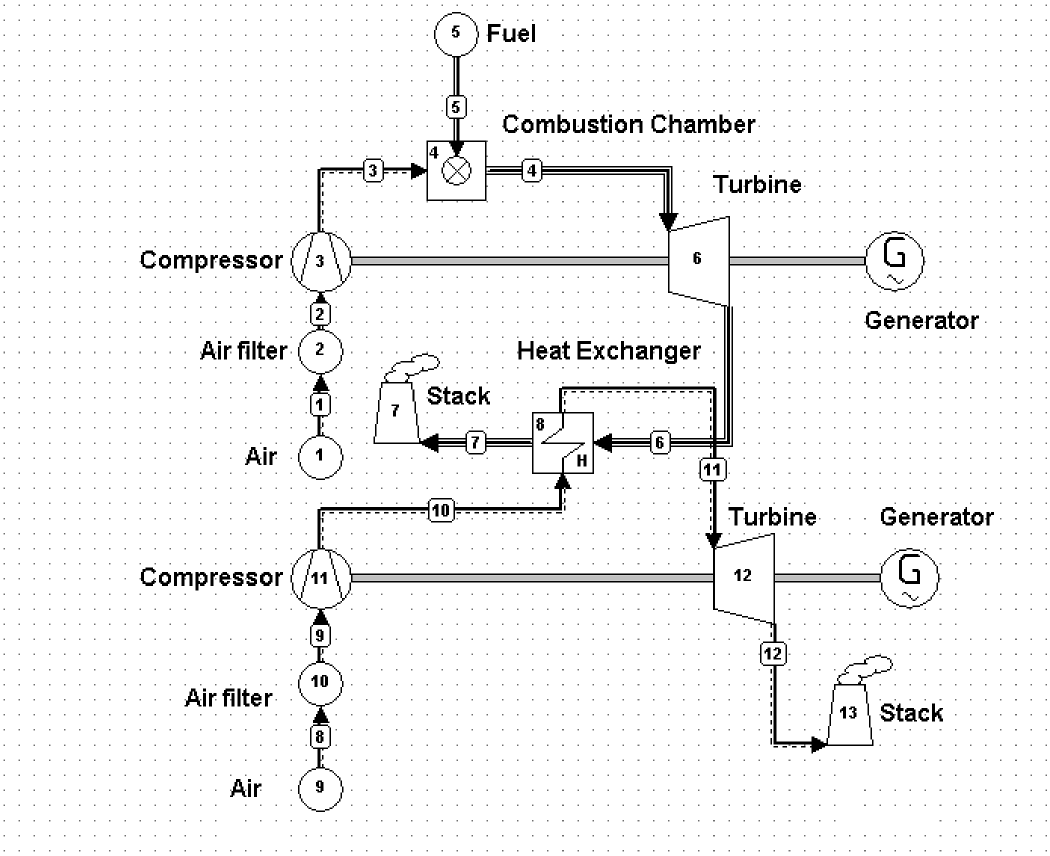


Figure 4.6: Gas Turbine with ABC (air bottoming cycle)

-ssor, function of which is as same as explained for the cycle in Fig. 4.5.

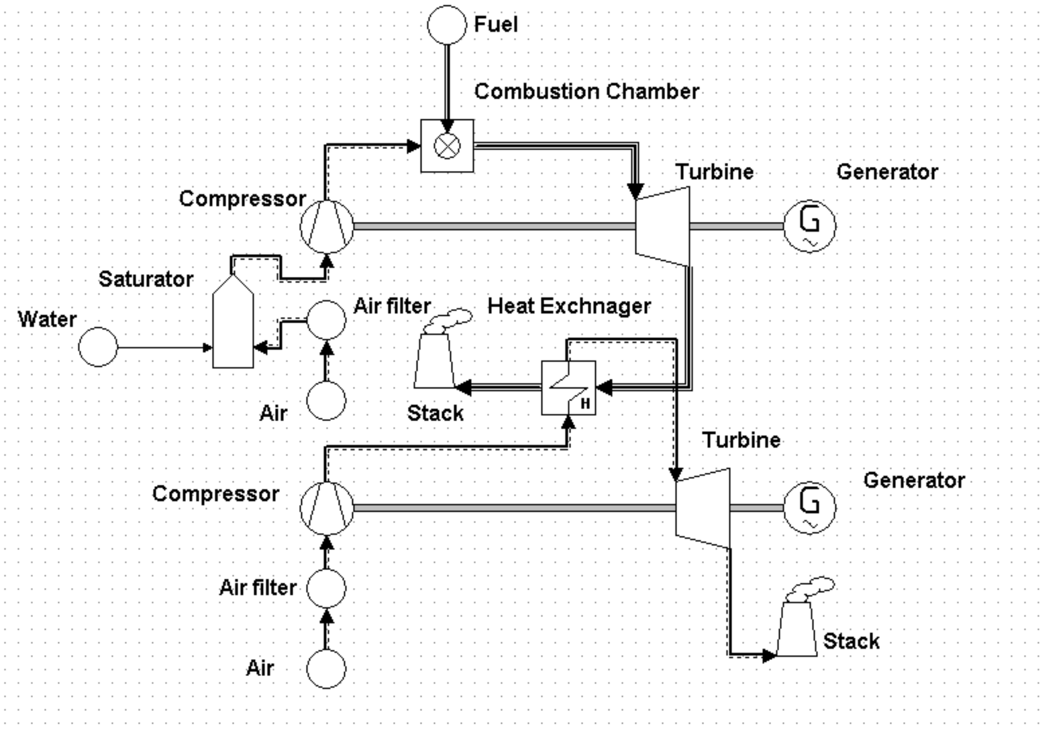


Figure 4.7: Inlet Fogging of Gas Turbine with ABC (air bottoming cycle) System

4.4 Energy and Exergy analysis of Cycle Components

In this section individual component's energy and exergy balance of the cycles introduced under the assumed consideration of the present study.

4.4.1 Energy analysis

To analyze the possible realistic performance, a detailed energy analysis of the simple gas turbine cycle & gas turbine with air bottoming combined cycle thermal power plant has been carried out by ignoring the kinetic and potential energy change. For steady state flow the energy balance for a thermal system can be written modifying the Eqn. 4.14 as below:

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \tag{4.14}$$

The energy or first law efficiency η_I of a system and/or system component is defined as the ratio of energy output to the energy input to system/ component i.e.

$$\eta_I = \frac{Desired\ Output\ Energy}{Input\ Energy\ Supplied}$$

4.4.1(a) Air Compressor

To analyze the compressor of the basic gas turbine cogeneration system a pressure ratio is selected. Based on the pressure ratio, the outlet temperature is evaluated. The ambient temperature and pressure are assumed. In order to evaluate the outlet temperature of the compressor, it is assumed that the air is compressed isentropically.

The temperature T_{3S} is thus estimated.

$$\frac{T_{3S}}{T_2} = \left(R_p \right)^{\frac{k-1}{k}} \tag{4.15}$$

Where, pressure ratio $R_p = \frac{P_3}{P_2}$; and k- specific heat ratio

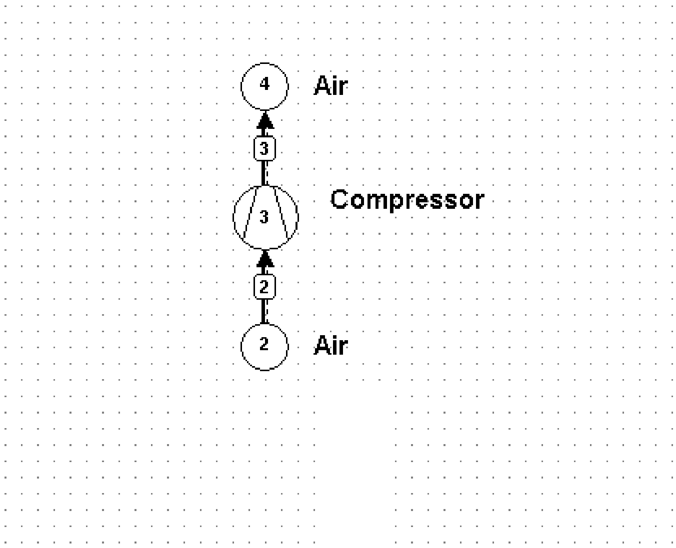


Figure 4.8: Schematic diagram of compressor of the basic gas turbine cycle.

The actual temperature can be calculated by isentropic efficiency and enthalpy. The isentropic efficiency of compressor is η_{comp} . Thus the actual temperature T_3 is determined by Eqn. 4.16.

$$\eta_{comp} = \left(\frac{T_{3s}-T_2}{T_3-T_2}\right) \tag{4.16}$$

Referring to the Figure 4.8, the mass of ambient air entering into the compressor and mass of compressed air going into the system are considered equal. It is assumed that there are no leakages at the compression stage. Thus mass balance equation at the"2 "and "3"states can be written as

$$\dot{m}_2 = \dot{m}_3 = \dot{m}_a \tag{4.17}$$

Similarly, considering the enthalpy of air at the inlet of the compressor and enthalpy of compressed air, the energy balance equation can be developed to obtain work output required for compressor. It is assumed that the compressor is adiabatic and there are some energy loss while air is compressed. Thus energy balance equation at the "2" and "3"states can be formulated as

$$\dot{W}_c = \dot{m}_a(h_2 - h_3) - Energy\ Loss \tag{4.18}$$

Where, $\dot{W}_c$- compressor work, alternatively the equation can be written as:

$$\dot{W}_c = m_a\dot{c}_{pa}(T_2 - T_3) - Energy\ Loss \tag{4.19}$$

The first law efficiency is:

$$\eta_{I,c} = 1 - \frac{Energy\ loss}{W_c} = \frac{\dot{m}_a(h_2 - h_3)}{W_c} \tag{4.20}$$

4.4.1(b) Combustion Chamber

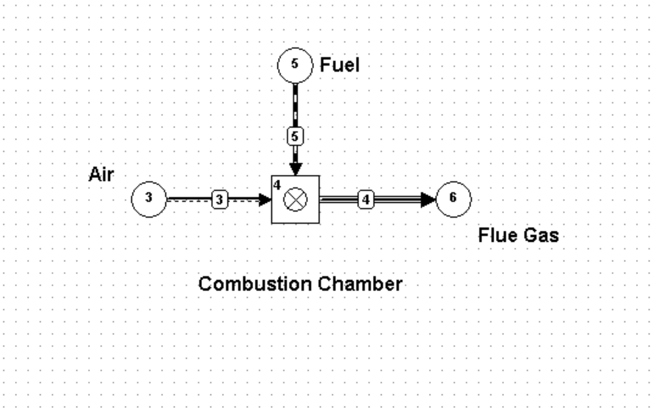


Figure 4.9: Schematic diagram of combustion chamber of the basic gas turbine cycle

The pressurized hot air from the compressor enters the combustion chamber where fuel is injected. The combustion product which is the working media is expanded through the turbine to produce power. It is assumed that the combustion takes place adiabatically with constant pressure. The products of the combustion are carbon dioxide, water vapor, nitrogen and heat energy. Practically there are no specific or definite ideal combustion conditions. Specific amount of oxygen is needed to burn the fuel and that is the theoretical air required to complete the combustion.

Insufficient air in combustion chamber leads to unburnt fuel, soot smoke, carbon monoxide which affects heat transfer, pollution, the system performance and efficiency. In this study, the specific heats of combustion products are determined by adding specific heat of each compound in the products of combustion in combustion gas mixture temperature and the composition of gases in terms of mole or mass fraction. The average specific heat for the combustion gas has been determined from the variable specific heat equations.

For excess air calculations, one must know the Stoichiometric air fuel ratio. The Stoichiometric air fuel ratio is the air fuel ratio with chemically correct proportion. During combustion process the whole air and fuel is consumed. In practice the excess air is always fed to the combustion chamber to burn the fuel completely. To avoid this, the excess air is provided.

Referring to Figure 4.9, the mass entering the combustor and the mass going out of the combustion chamber can be balanced. In the combustion chamber the compressed air and the fuel get mixed in the combustion reaction. The hot combustion gas formed as a result of combustion reactions goes out of the combustion chamber. It is assumed that the combustion chamber is leak proof. Thus mass balance equation at the combustion stage “3”and “4”can be formulated as:

$$\dot{m}_3 + \dot{m}_5 = \dot{m}_4 \qquad (4.21)$$

This equation can alternatively be represented as

$$\dot{m}_a + \dot{m}_f = \dot{m}_g \tag{4.22}$$

Where, $\dot{m}_a$, $\dot{m}_f$, $\dot{m}_g$ are the mass flow rate of air, fuel and combustion gas respectively.

In combustion process the enthalpy of the compressed air and enthalpy of injected fuel (calorific value) play an important role in the chemical reaction which produces the hot combustion gas with very high enthalpy. Considering the heat loss, thus the energy balance of the combustor can be formulated as:

$$\dot{m}_a h_3 + \dot{m}_f h_f = \dot{m}_g h_4 + Q_{L,cc} \tag{4.23}$$

where, h_f is the enthalpy of injected fuel which is lower calorific value of the fuel. $Q_{L,cc}$ is the heat loss in the combustion chamber, which is directly related to the fuel energy, $\dot{m}_f h_f$.

Combustion chamber efficiency can be stated as,

$$\eta_{comb} = \frac{\dot{m}_g h_4 - \dot{m}_a h_3}{\dot{m}_f h_f} \tag{4.24}$$

By using equation (4.22), (4.23) and (4.24) mass of air, fuel and finally the enthalpy of the combustion gas is evaluated.

4.4.1(c) Gas Turbine

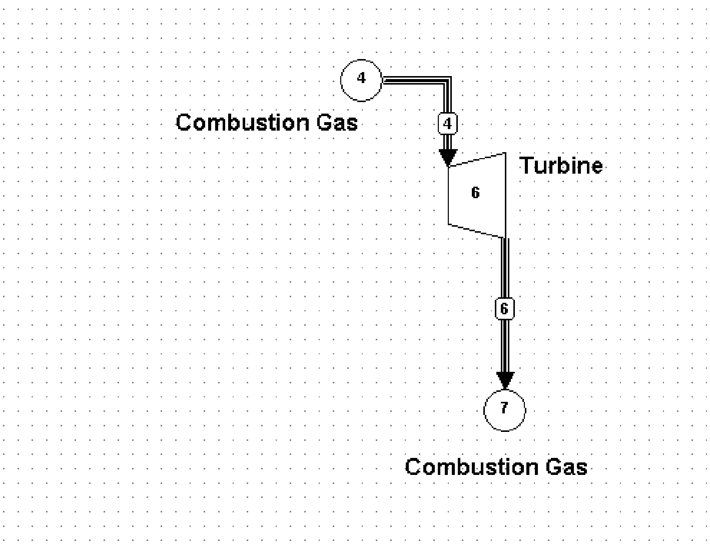


Figure 4.10: Schematic diagram of turbine of the basic gas turbine cycle

Gas turbine generates power by expanding hot combustion gas from combustion chamber. High turbine inlet temperature and lower exit temperature of the combustion gas is desirable in order to achieve high thermal efficiency and work output. Due to the metallurgical constraints the turbine inlet temperature has to be maintained at a maximum permissible limit.

In order to determine turbine exit temperature the expansion of combustion gases assumed to be isentropic. The exhaust gas temperature (isentropic) of the turbine T_{4s} is estimated as:

$$\frac{T_4}{T_{6s}} = \left(\frac{P_4}{P_6}\right)^{\frac{K-1}{K}} \tag{4.25}$$

The actual temperature can be calculated by isentropic efficiency and enthalpy. The isentropic efficiency of turbine is $\eta_{turbine}$. Thus the actual temperature T_6 is determined by Eqn. 4.26.

$$\eta_{turbine} = \left(\frac{T_6 - T_4}{T_{6s} - T_4}\right) \tag{4.26}$$

Referring to the Figure 4.10, the mass balance equation can developed by balancing mass of combustion gas entering into the gas turbine and the mass of combustion gases at the exit of the turbine. The equation is formulated as:

$$\dot{m}_4 = \dot{m}_6 = \dot{m}_g \tag{4.27}$$

Further, the energy balance equation is developed for the gas turbine to establish relationship between enthalpy entering the system at state "4"; turbine work output and enthalpy of combustion gases at turbine exit. It is assumed that the turbine is leak proof and adiabatic. Considering the possible energy loss, the energy balance across the gas turbine is formulated as:

$$\dot{W}_{GT} = \dot{m}_g(h_4 - h_6) - Energy\ Loss \tag{4.28}$$

Where, $\dot{W}_{GT}$- turbine work, alternatively the equation can be written as:

$$\dot{W}_{GT} = m_g\dot{c}_{pg}(T_4 - T_6) - Energy\ Loss \tag{4.29}$$

The first law efficiency is:

$$\eta_{I,GT} = 1 - \frac{Energy\ loss}{m_g\dot{c}_{pg}(T_4 - T_6)} = \frac{\dot{W}_{GT}}{m_g\dot{c}_{pg}(T_4 - T_6)} \tag{4.30}$$

4.4.1(d) Gas-Air Heat Exchanger

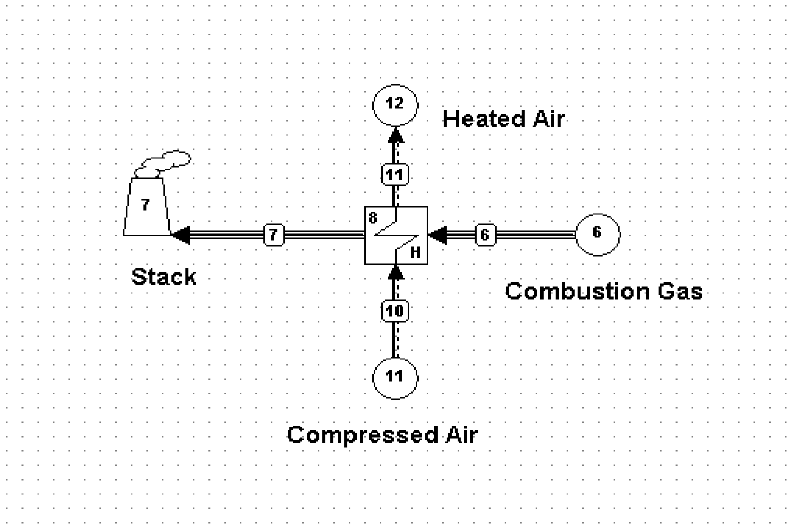


Figure 4.11: Schematic diagram of gas-air heat exchanger of gas turbine with air bottoming combined cycle

Before exhausting to the environment the combustion products of the topping cycle passes through a gas-air heat exchanger, where it transfers thermal energy to the compressed air from the bottoming air cycle.

Here, the effectiveness of the heat exchanger can be defined as

$$\varepsilon_{HE} = \frac{C_6 \quad (T_6 - T_7)}{(min\{C_6, C_{10}\}) \, (T_6 - T_{10})} \tag{4.31}$$

Where, c is the specific heat of the respective flow stream.

Considering all the flow stream around the heat exchanger the energy balance becomes:

$$\dot{m}_6 \, h_6 + \dot{m}_{10} \, h_{10} = \dot{m}_7 \, h_7 + \dot{m}_{11} \, h_{11} \tag{4.32}$$

Equation 4.32 can also be arranged as

$$\dot{m}_g \, (h_6 - h_7) + \dot{m}_a (h_{10} - h_{11}) = 0 \tag{4.33}$$

Where, $\dot{m}_a$ & $\dot{m}_g$ are the mass flow rate of the air and the combustion gas respectively.

Under the condition of the given mass flow rate and heat exchanger effectiveness, using equation (4.32), (4.33) the properties of turbine exit of the topping cycle and the turbine inlet of the bottoming cycle are evaluated.

4.4.2 Exergy analysis

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy systems. The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. Many engineers and scientists suggest that the thermodynamic performance of a process is best evaluated by performing an exergy analysis in addition to or in place of conventional energy analysis because exergy analysis appears to provide more insights and to be more useful in furthering efficiency improvement efforts than energy analysis [10].

The exergy (second law) analysis has become one of the significant methods to evaluate the performance of any thermal system application because the exergy analysis deals with the quality of energy. Exergy can be defined as availability, the highest available work, which is an evaluation of the maximum useful work that can be obtained when a system is brought to a state of equilibrium with the environment in a reversible process. For a real process, the exergy input always exceeds the exergy outputs; this unbalance is due to irreversibilities, which is known as exergy destruction.

A general form of the exergy equation for an open system control volume already stated in equation (4.3). For steady state flow the exergy balance for a thermal system is given in equation (4.34), where time rate variations are neglected.

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_J - \left(\dot{W_{cv}}\right) + \sum_i \dot{m}_\iota \, e_{fi} - \sum_e \dot{m}_e \, e_{fe} - \dot{E}_d \tag{4.34}$$

Rearranging equation (4.34) gives the exergy destruction of a steady state open system for a control volume

$$\dot{E}_d = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_J - \left(\dot{W_{cv}}\right) + \sum_i \dot{m}_\iota \, e_{fi} - \sum_e \dot{m}_e \, e_{fe} \tag{4.35}$$

In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system EXcan be divided into four components: physical exergy EX_{PH} , kinetic exergy EX_{KN} , potential exergy EX_{PT} , and chemical exergy EX_{CH} [54]. The two important ones are physical exergy and chemical exergy. In this study, the two other components, namely kinetic exergy and potential exergy, are assumed to be negligible as the elevation and speed have negligible changes.

The total exergy of a system EX consists of four different components:

$$EX = EX_{PH} + EX_{KN} + EX_{PT} + EX_{CH} \tag{4.36}$$

Neglecting potential and kinetic energy, equation (4.36) can be rewritten as

$$EX = EX_{PH} + EX_{CH} \tag{4.37}$$

Basic thermal equations of physical and chemical exergy already discussed in the chapter 3. The following section intended to analyze each component exergy balance considering all the possible exergy aspects for the respective component.

4.4.2(a) Air Compressor

Referring to the Figure 4.5, the exergy balance for the air compressor can be given as

$$\dot{W_{comp}} = \dot{m}_a(e_{f2} - e_{f3}) - \dot{E}_{d,comp} \tag{4.38}$$

where for the compressor adiabatic and steady state condition are considered.

Exergy destruction or the irreversibility of the compressor can be evaluated by

$$\dot{E}_{d,comp} = T_0\ \dot{s}_{gen,c} \tag{4.39}$$

and the entropy generation rate, $\dot{s}_{gen,c}$ is:

$$\dot{s}_{gen,c} = \dot{m}_a(s_3 - s_2) \tag{4.40}$$

$$s_3 - s_2 = c_{pa} \ln\left(\frac{T_3}{T_2}\right) - \frac{K-1}{K}\left(\ln\left(\frac{P_3}{P_2}\right)\right) \tag{4.41}$$

where s_2 and s_3 are the specific entropies at the given state.

The second law efficiency is:

$$\eta_{II,C} = 1 - \frac{\dot{E}_{d,comp}}{\dot{W_{comp}}} = \frac{\dot{m}_a(e_{f2} - e_{f3})}{\dot{W_{comp}}} \tag{4.42}$$

4.4.2(b) Combustion Chamber

In this study fuel injected to the combustion chamber is methane CH_4. Let us consider 1kmol of methane gas is used in combustion process. Also assume, adiabatic combustion takes place in combustion chamber. The energy balance in the combustion chamber is:

$$CH_4 + X(O_2 + 3.76\ N_2) = a\ CO_2 + b\ H_2O + \ \ CO_2 + d\ N_2 \tag{4.43}$$

The amount of air "X" in moles for fixed adiabatic flame temperature T_4 (referring to the Fig. 4.6) is determined as follows. The coefficients of the chemical equation are calculated by balancing the Equation 4.43.

$$a = 1; b = 2; c = X - 2; d = 3.76X \tag{4.44}$$

The energy balance across the combustion chamber is expressed as follows:

Sum of enthalpies of reactants = Sum of enthalpies of the products or

$$H_R = H_P \text{ (adiabatic)} \tag{4.45}$$

$$\left(h_{f,CH_4} + h_{CH_4}\right)_{T_3} + X\left(h_{O_2} + 3.76\, h_{N_2}\right)_{T_3} = \left(h_{f,CO_2} + h_{CO_2}\right)_{T_4} + 2\left(h_{f,H_2O} + h_{H_2O}\right)_{T_4} + (X-2)\, h_{O_{2,T_4}} + 3.76X\, h_{N_{2,T_4}} \tag{4.46}$$

Equation 4.37 can further be simplified to

$$X = \frac{\left(\left(h_{f,CH_4} + h_{CH_4}\right)_{T_3} - \left(h_{f,CO_2} + h_{CO_2}\right)_{T_4} - 2\left(h_{f,H_2O} + h_{H_2O}\right)_{T_4} + 2h_{O_{2,T_4}}\right)}{h_{O_{2,T_4}} + 3.76\, h_{N_{2,T_4}} - \left(h_{O_2} + 3.76\, h_{N_2}\right)_{T_3}} \tag{4.47}$$

In the exergy analysis of combustion chamber, in order to determine exergy of reactants and products, both physical and chemical exergy are considered.

Considering both physical exergy and chemical exergy for the combustion chamber we can write

$$(e_{PH} + e_{CH})_{air} + (e_{PH} + e_{CH})_{fuel} = (e_{PH} + e_{CH})_{comb.gas} \tag{4.48}$$

For evaluating the physical and chemical exergy of air standard equations are used as discussed in chapter 3. At ambient temperature the physical exergy of methane is considered as zero [55]. For a hydrocarbon fuel, C_aH_b, standard chemical exergy tables may be used .The chemical exergy of the methane is the standard value, which is 836510 kJ / kmol. Some other relations also popular for the chemical exergy of the hydrocarbon fuel. An approximate formulation for chemical exergy of gaseous hydrocarbon fuels is given as [10].

.

$$\frac{e_{CH,f}}{LHV} \cong 1.033 + 0.0169\,\frac{b}{a} - \frac{0.0698}{a} \tag{4.49}$$

If the fuel is methane, as impler relation may be given as [56]

$$\frac{e_{CH,f}}{HHV} \approx 0.94 \tag{4.50}$$

Physical exergy of products of combustion is determined by the standardized equation developed in chapter 3. The chemical exergy of product of combustion is determined by [57].

$$e_{CH,products} = n_P\left[x_{CO_2}\,\epsilon^0_{CO_2} + x_{H_2O}\,\epsilon^0_{H_2O} + x_{O_2}\,\epsilon^0_{O_2} + x_{N_2}\,\epsilon^0_{N_2}\right] + n_P R T_0\left[x_{CO_2}\ln x_{CO_2} + x_{H_2O}\ln x_{H_2O} + x_{O_2}\ln x_{O_2} + x_{N_2}\ln x_{N_2}\right] \quad (4.51)$$

The irreversibility or exergy destruction in the combustion chamber is then determined by balancing exergy in and exergy out. Referring to the figure 4.9, the exergy balance in combustion chamber is expressed as:

$$EX_{air} + EX_{fuel} = EX_{comb.gas} + E_{d,cc} \quad (4.52)$$

The second law efficiency is then defined as:

$$\eta_{II,CC} = 1 - \frac{E_{d,cc}}{EX_{air} + EX_{fuel}} = \frac{EX_{comb.gas}}{EX_{air} + EX_{fuel}} \quad (4.53)$$

4.4.2(c) Gas Turbine

Referring to Figure 4.10; the change in entropy due to the expansion of combustion gases in the gas turbine is the difference between entropy at state "4" and state "6". The entropy balance equation across the gas turbine is formulated as:

$$\dot{m}_4 s_4 = \dot{m}_6 s_6 - s_{gen,T} \quad (4.54)$$

The Equation 4.54 can be further simplified as:

$$s_{gen,T} = \dot{m}_g(s_6 - s_4) \quad (4.55)$$

The change in specific entropy at the state "4" and "6" can be determined by the following Equation 4.56.

$$s_6 - s_4 = c_{pg}\ln\left(\frac{T_6}{T_4}\right) - \frac{K-1}{K}\left(\ln\left(\frac{P_6}{P_4}\right)\right) \quad (4.56)$$

s_4; s_6 are the specific entropies at given state.

The exergy destruction in gas turbine ($E_{d,T}$) can thus be evaluated by the following equation.

$$\dot{E}_{d,T} = T_0\,\dot{s}_{gen,T} \quad (4.57)$$

The exergy at the state "6" can be determined by evaluating exergy balance equation.
The exergy balance equation can be expressed as:

$$\dot{W}_{GT} = \dot{m}_g(e_{f4} - e_{f6}) - \dot{E}_{d,T} \tag{4.58}$$

The second law efficiency is:

$$\eta_{II,T} = 1 - \frac{E_{d,T}}{\dot{m}_g(e_{f4}-e_{f6})} = \frac{\dot{W}_{GT}}{\dot{m}_g(e_{f4}-e_{f6})} \tag{4.59}$$

4.4.2(d) Gas-Air Heat Exchanger

The performance of the gas-air heat exchanger strongly affects the overall performance of the combined cycle power plant. Gas-Air Heat Exchanger is nothing but shell and tube heat exchanger, in that hot gas flow through the shell and air flow thorough tubes.

Referring to the Fig. 4.11, the exergy flow equation for the gas-air heat exchanger becomes:

$$0 = \dot{m}_6\, e_{f6} + \dot{m}_{10}\, e_{f10} - \dot{m}_7\, e_{f7} - \dot{m}_{11}\, e_{f11} - \dot{E}_{d,HE} \tag{4.60}$$

Equation 4.60 can also be arranged as

$$\dot{E}_{d,HE} = \dot{m}_g\,(e_{f6} - e_{f7}) + \dot{m}_a(\,e_{f10} - e_{f11}) \tag{4.61}$$

Exergy destruction rate of the heat exchanger can be determined using Equation 4.61.

4.5 Simulation & Validation

4.5.1 Modeling assumptions

The following assumptions are made in the model to simplify the analysis of the system:

a) Fuel is supposed to be pure methane and its temperature is equal to the ambient temperature.
b) All components of the system are assumed to operate under adiabatic conditions.
c) Working fluid is assumed to be treated as an ideal gas with variable specific heat.
d) The isentropic efficiency of the compressor and the turbine are assumed to be constant and equal to 0.85 and 0.87 respectively [59].
e) The mechanical efficiency is assumed to be constant and equal to 0.99 [60].
f) Heat loss during combustion is taken 2% of lower heating value of the fuel [61].
g) The effectiveness coefficient of the air-gas heat exchanger is equal to 0.85 [62].
h) The pressure drop through the air filter before the intake of the compressor, through the combustion chamber, and through both sides of the air-gas heat exchanger is a function of the inlet pressure of the component, and is given by the following equalities respectively [61].

$$\Delta P_{filter} = 0.02\ P_0 \quad (4.62)$$

$$\Delta P_{comb} = 0.03\ P_3 \quad (4.63)$$

$$\Delta P_{HE,air} = 0.03\ P_{10} \quad (4.64)$$

$$\Delta P_{HE,gas} = 0.02\ P_6 \quad (4.65)$$

In this work, Cycle Tempo 5.0 [58] software is employed to perform the calculation. Cycle-Tempo is a program for thermodynamic modeling and optimization of systems for the production of electricity, heat and refrigeration. The primary aim of Cycle-Tempo is to calculate the size of the relevant mass and energy flows in the system, as well as the exergy under the defined environmental condition.

4.5.2 Validation

In Cycle-Tempo modeling, for a simple gas turbine cycle, the calculation procedure is as follows. The pressure drop due to air filtering before the compressor is considered. Referring to Fig. 4.4, inlet air enters the compressor at state 2. Considering an isentropic efficiency η_{comp} for the compressor and a pressure ratio of R_p, properties at the state 3, at the compressor outlet is calculated.

For a specified TIT, the exhaust temperature and the specific work out of the cycle can be obtained as follows. Having considered the combustion chamber pressure drop, heat loss, turbine efficiency and mass flow rate of the fuel. In energy and exergy analysis section, governing equations solved by the model and procedures of the calculations depicted step wise.

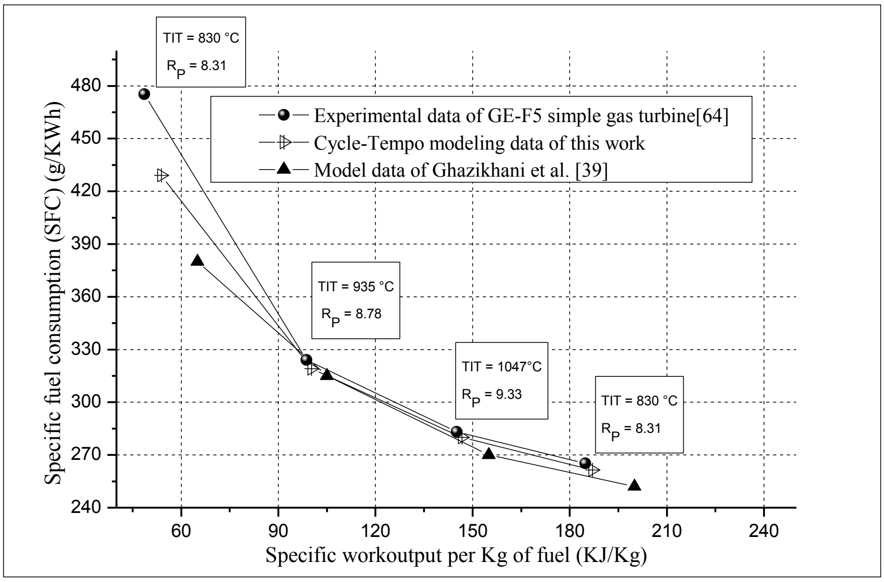


Figure 4.12: Comparison between the results of Cycle-Tempo model and those of the experiments [64] and model of Ghazikhani et al [39] for the GE-F5 simple gas turbine

To validate the model, the results are compared with the data obtained from the experiments performed and the model developed in the previous studies. As in the figure 4.12, specific fuel consumption is plotted against specific work output per Kg of fuel. Here the results of cycle-tempo model of the present study shows a good agreement with those of the experiment performed by Ghazikhani et al [64] and it also gives promising trend with the MATLAB model of Ghazikhani et al [39].

Figure 4.13 shows the comparison between the results of present model with those of previous for a gas turbine with ABC. Effect of TIT on the SFC is shown in this figure for gas turbine with ABC, where the cycle-tempo model results of this present study hold a difference less than 5% than those of the previous models, which indicates a good agreement. This variation is due to the ambient conditions differnce from the experimental region. In this model as the compressor inlet temperature is higher, so, the compressor discharge. So, for maintaing same turbine inlet temperature (TIT), it is needed to have more fuel consumption and as well as less power output due to higher ambient temperature.

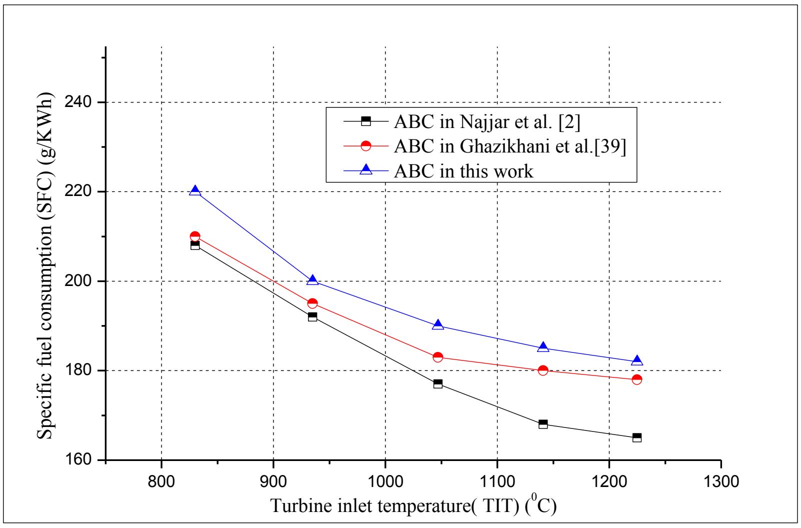


Figure 4.13: Comparison between the results of Cycle-Tempo model and those of Najjar et al [2] and Ghazikhani et al [39] for a gas turbine with ABC

Chapter 5

RESULTS AND DISCUSSIONS

Chapter 5

Results and Discussions

Methodology which was discussed above is used to analyze the performance of the basic gas turbine cycle and gas turbine with air bottoming combined cycle (ABC), without any power augmentation technique and with a power augmentation technique called inlet fogging. In the thermodynamic analysis, each component in the system was modeled. The mass, energy and entropy balance equations were formulated to determine the properties of each state in the systems. Each stage was described by the input and output conditions. In this systems, the influence of key operating variables such as ambient temperature, pressure ratio and turbine inlet temperature (TIT) on specific work output (SWO), specific fuel consumption (SFC), energy and exergy efficiencies were investigated. In the exergy analysis, component wise exergy destruction/losses were evaluated to determine distribution of the exergy destruction in the systems. This chapter presents the details explanation of the findings of the variables described above in a chronological order.

5.1 Simple gas turbine cycle and ABC (Without fogging)

The basic gas turbine system comprises a compressor, a combustion chamber, a turbine; in the air bottoming combined cycle main component is as same as simple cycle, but an extra regenerator and a pair of compressor-turbine needed for the bottoming cycle. In the plant analyses, effect of most important parameters, ambient temperature and pressure ratio & TIT were considered for details thermodynamic investigation.

Table 5.1: Specific fuel exergy and the percentage of specific work and components exergy destruction for simple gas turbine cycle, without fogging at operating condition (R_P =20)

TIT(°C)	T_{amb} (°C)	$EX_{CH,f}$ (kJ/kg)	W(%)	$E_{d,comp}$(%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
900	5	575.27	30.26	5.76	33.23	9.10	21.65
	10	554.83	29.29	6.01	33.91	9.44	21.35
	15	540.78	28.57	6.18	34.69	9.68	20.88
	20	526.75	27.81	6.37	35.46	9.94	20.42
	25	512.72	27.01	6.57	36.24	10.21	19.97
	30	498.71	26.15	6.77	37.01	10.50	19.57
	35	484.71	25.25	6.99	37.78	10.80	19.18
1000	5	709.95	32.77	4.66	31.90	7.43	23.24
	10	689.39	32.06	4.82	32.61	7.65	22.86
	15	675.25	31.54	4.94	33.40	7.81	22.31
	20	661.16	31.01	5.06	34.20	7.98	21.75
	25	646.99	30.43	5.19	34.99	8.16	21.23
	30	632.88	29.74	5.32	35.79	8.34	20.81
	35	618.79	29.21	5.46	36.58	8.52	20.23
1100	5	848.34	34.39	3.89	30.67	6.27	24.78
	10	827.65	33.85	4.01	31.40	6.42	24.32
	15	813.41	33.44	4.09	32.21	6.54	23.76
	20	799.17	33.23	4.18	33.02	6.65	22.92
	25	784.96	32.62	4.27	33.83	6.77	22.51
	30	770.75	32.18	4.36	34.65	6.90	21.91
	35	756.54	31.71	4.46	35.46	7.03	21.34
1200	5	998.72	35.46	3.35	29.53	5.41	26.25

	10	969.66	35.07	3.41	30.28	5.53	25.71
	15	955.31	34.77	3.48	31.11	5.61	25.03
	20	940.97	34.04	3.54	31.93	5.70	24.79
	25	926.65	33.46	3.61	32.76	5.78	24.39
	30	912.33	33.13	3.67	33.58	5.87	23.75
	35	898.03	33.03	3.74	34.41	5.97	23.12
1300	5	1136.45	36.27	2.89	28.49	4.76	27.49
	10	1115.48	35.91	2.96	29.25	4.85	27.03
	15	1101.02	35.66	3.01	30.09	4.91	26.33
	20	1086.57	35.40	3.06	30.92	4.98	25.64
	25	1072.13	35.12	3.11	31.76	5.04	24.97
	30	1057.70	34.84	3.16	32.60	5.11	24.29
	35	1043.28	34.55	3.21	33.44	5.18	23.62
1400	5	1285.51	36.78	2.57	27.51	4.24	28.90
	10	1265.17	36.51	2.60	28.30	4.31	28.28
	15	1250.58	36.29	2.64	29.14	4.36	27.57
	20	1236.03	36.08	2.68	29.99	4.41	26.84
	25	1221.46	35.84	2.72	30.84	4.46	26.14
	30	1206.93	35.61	2.76	31.68	4.52	25.43
	35	1192.39	35.36	2.80	32.53	4.57	24.74

Table 5.2: Specific fuel exergy and the percentage of specific work and components exergy destruction for ABC, without fogging at operating condition (R_P = 20 & r_P = 6)

TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
900	5	575.27	27.80	5.75	3.29	33.22	7.91	3.80	1.47	12.89	3.87
	10	554.83	26.15	6.00	3.43	32.93	8.21	3.94	1.41	14.19	4.01
	15	540.78	24.47	6.18	3.52	32.71	8.43	4.05	1.38	15.14	4.11
	20	526.75	22.97	6.36	3.63	32.50	8.66	4.16	1.35	16.15	4.21
	25	512.72	19.38	6.56	3.74	32.27	8.90	4.28	1.32	17.23	4.32
	30	498.71	18.98	6.76	3.85	32.04	9.14	4.40	1.29	18.36	4.44
	35	484.71	17.94	6.97	3.97	31.81	9.40	4.52	1.27	19.57	4.56
1000	5	709.95	32.83	4.65	2.66	31.89	6.47	3.09	1.54	11.81	5.06
	10	689.39	31.44	4.82	2.75	31.62	6.67	3.19	1.47	12.83	5.21
	15	675.25	30.42	4.94	2.82	31.43	6.81	3.26	1.43	13.57	5.32
	20	661.16	29.37	5.06	2.89	31.23	6.96	3.33	1.39	14.34	5.43
	25	646.99	28.24	5.19	2.95	31.03	7.11	3.40	1.36	15.16	5.54
	30	632.88	27.08	5.32	3.03	30.82	7.27	3.48	1.32	16.01	5.66
	35	618.79	25.85	5.45	3.10	30.61	7.43	3.56	1.29	16.91	5.78
1100	5	848.34	36.18	3.88	2.22	30.67	5.47	2.60	1.62	11.18	6.17
	10	827.65	35.91	4.00	2.29	30.41	5.61	2.67	1.55	12.01	6.32
	15	813.41	34.37	4.09	2.33	30.23	5.71	2.72	1.51	12.62	6.43
	20	799.17	33.57	4.18	2.38	30.05	5.81	2.77	1.46	13.25	6.54
	25	784.96	32.72	4.26	2.43	29.86	5.92	2.82	1.42	13.91	6.66
	30	770.75	31.87	4.36	2.48	29.67	6.02	2.87	1.38	14.59	6.77
	35	756.54	30.93	4.45	2.53	29.48	6.13	2.93	1.35	15.30	6.89
1200	5	998.72	38.54	3.32	1.90	29.54	4.73	2.24	1.72	10.83	7.19
	10	969.66	37.70	3.41	1.95	29.30	4.83	2.29	1.64	11.54	7.34
	15	955.31	37.09	3.47	1.98	29.13	4.91	2.32	1.59	12.05	7.45
	20	940.97	36.45	3.54	2.02	28.95	4.98	2.36	1.55	12.58	7.56
	25	926.65	35.79	3.60	2.05	28.78	5.06	2.40	1.50	13.13	7.67
	30	912.33	35.12	3.67	2.09	28.61	5.14	2.44	1.46	13.70	7.79
	35	898.03	34.40	3.74	2.13	28.43	5.22	2.48	1.42	14.29	7.90
1300	5	1136.45	40.26	2.89	1.65	28.49	4.16	1.96	1.82	10.67	8.12
	10	1115.48	39.55	2.96	1.69	28.26	4.24	2.00	1.74	11.29	8.27
	15	1101.02	39.04	3.01	1.72	28.10	4.30	2.03	1.69	11.74	8.38
	20	1086.57	38.52	3.06	1.74	27.94	4.36	2.05	1.64	12.19	8.49
	25	1072.13	37.99	3.11	.177	27.78	4.42	2.08	1.59	12.67	8.60
	30	1057.70	37.44	3.16	1.80	27.62	4.47	2.11	1.54	13.15	8.71
	35	1043.28	36.86	3.21	1.83	27.46	4.53	2.14	1.50	13.65	8.82
1400	5	1285.51	41.49	2.54	1.45	27.52	3.71	1.74	1.91	10.65	8.98
	10	1265.17	40.90	2.60	1.48	27.31	3.78	1.77	1.83	11.20	9.12
	15	1250.58	40.47	2.64	1.51	27.16	3.82	1.79	1.78	11.59	9.23
	20	1236.03	40.05	2.68	1.53	27.01	3.87	1.81	1.73	12.00	9.33
	25	1221.46	39.60	2.72	1.55	26.85	3.91	1.83	1.68	12.41	9.44
	30	1206.93	39.14	2.76	1.57	26.70	3.96	1.86	1.63	12.83	9.55
	35	1192.39	38.65	2.80	1.59	26.55	4.01	1.88	1.58	13.27	9.66

5.1.1 Effect of independent parameters on the key components

Exergy destruction dependency of the main turbine and compressor of the ABC and simple gas turbine cycle on ambient temperature and pressure ratio are shown in the Fig.5.1 & Fig.5.2 respectively. When the ambient temperature is increased the exergy destruction of both the main turbine and compressor increases, this is also true for the pressure ratio increment. So, for the explanation, as the turbine and compressor is adiabatic, for constant specific heat we have [11]:

$$EX_{turb} = T_0\, c_p \ln\left[(1 - \eta_{turb})(R_P)^{\frac{K-1}{K}} + \eta_{turb}\right] \tag{5.1}$$

and

$$EX_{comp} = T_0\, c_p \ln\left[\frac{1}{\eta_{comp}} - \left(\frac{1}{\eta_{comp}} - 1\right)(R_P)^{\frac{K-1}{K}}\right] \tag{5.2}$$

Respectively, where EX_{turb} and EX_{comp} are the exergy destruction of the turbine and compressor, and η_{turb} and η_{comp} are the turbine and compressor isentropic efficiency.

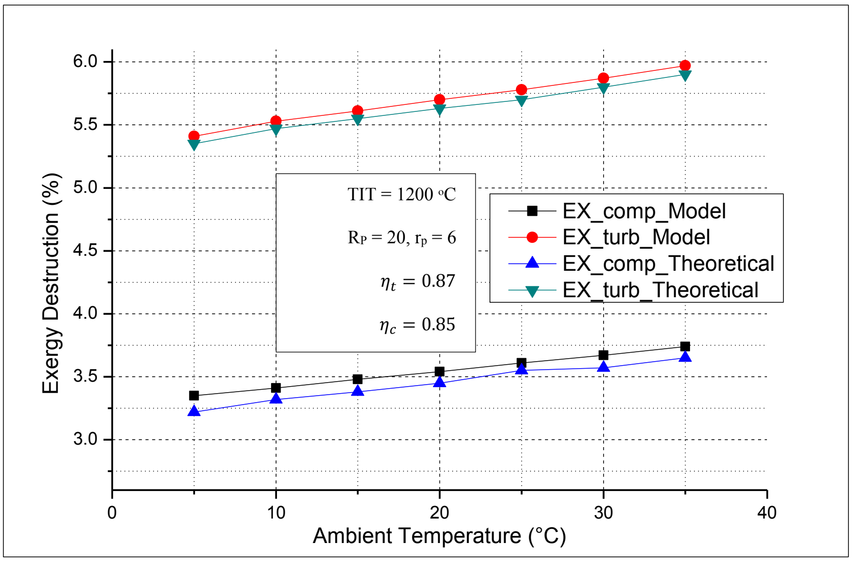


Fig.5.1. Exergy destruction of the main turbine and compressor in simple gas turbine cycle & ABC

Stated equations show that the internal irreversibilities of both the turbine and compressor are only functions of the pressure ratio and isentropic efficiency for given values of c_p , K and T_0 . Therefore, for a particular value of ambient temperature and isentropic efficiency, as the pressure ratio increased, the exergy destruction of both the turbine and compressor increases as the Fig.5.2 illustrated. Similarly, increasing the ambient temperature, c_p increases, which also leads to an increase in the amount of the above mentioned irreversibilities as shown in Fig.5.1 and it shows a good agreement with the theoretical values.

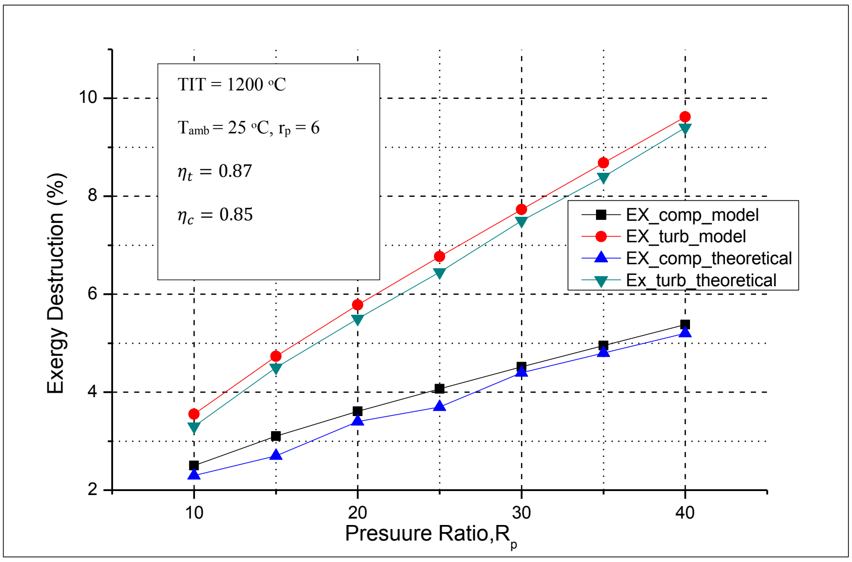


Fig.5.2. Exergy destruction of the main turbine and compressor in simple gas turbine cycle & ABC

Chemical reaction during the combustion is responsible for the exergy destruction of the combustion chamber. Fig.5.3 shows the exregy destruction of the combustion chamber for both ABC and simple gas turbine cycle. Since the amount of air/fuel ratio and injected fuel into the combustion chamber for both cycles is identical, consequently the combustion chamber exergy destruction of both cycles for a given ambient temperature is same.

As Fig.5.3 shows, increasing the ambient temperature reduces the exergy destruction of the combustion chamber. Possible accounts of this embedded in the phenomena of the exergy destruction of the combustion chamber. Actually combustion chamber exergy destruction comprises of two phenomena: the difference between the temperature of fuel and inlet air during mixing process and the temperature difference of the reactants and products in the combustion chamber. The exergy destruction in the combustion chamber is high at the low ambient chamber as shown in the Fig.5.3, this is due to the increased difference between the compressor discharge and the reaction zone property. And for the higher ambient temperature this differences reduced in prominent amount and consequently combustion chamber exergy destruction start to decrease.

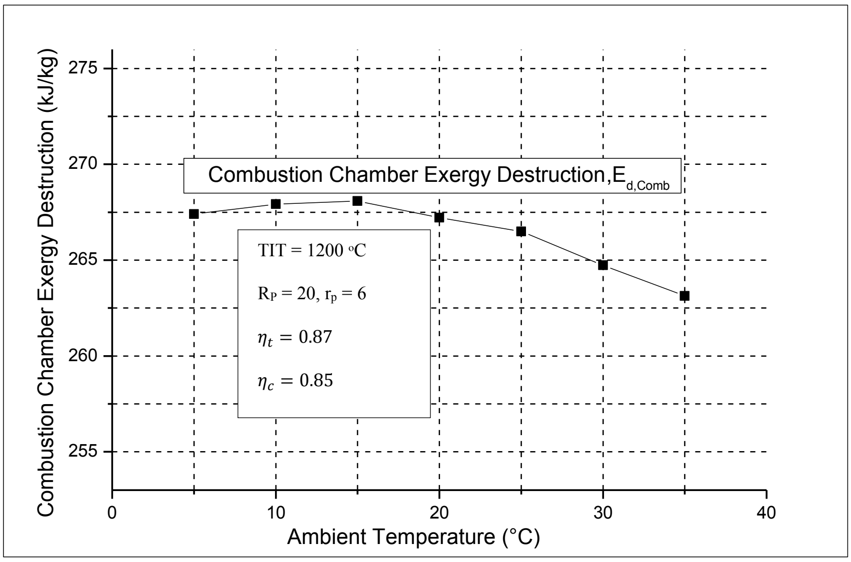


Fig.5.3. Exergy destruction of the combustion chamber in simple gas turbine cycle & ABC

5.1.2 Potential benefits of ABC over simple gas turbine cycle

Fig.5.4 shows the energy & exergy efficiency of components of both the simple gas turbine cycle & ABC and exergetic efficiency of the total plant. It is shown that for both simple and combined cycle the exergetic efficiency of the combustion chamber is much lower than that of the other components, this is because of the higher irreversibilities in the combustion chamber compared with the others. It is also noticeable that the exergetic efficiency of the ABC is higher in comparison with simple gas turbine cycle, this is due to the provision of the exhaust exergy recovery in the ABC.

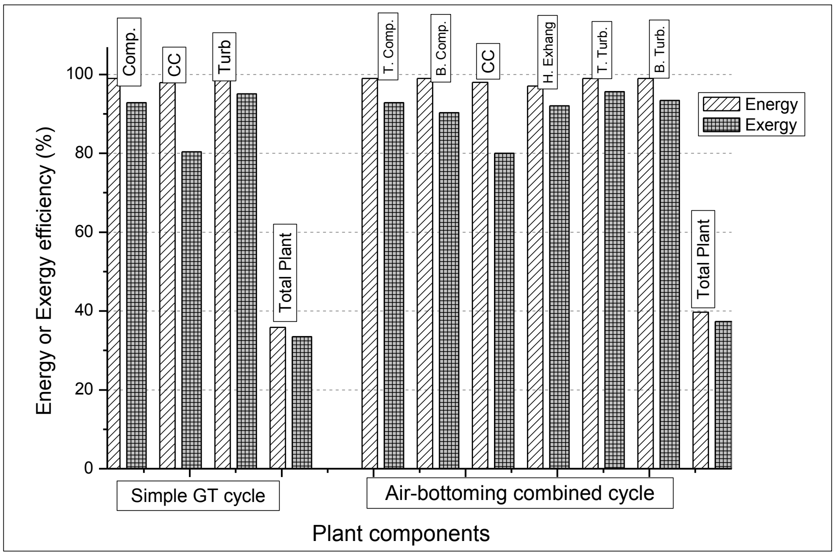


Fig.5.4. Energy & Exergy efficiency of the plant components in simple gas turbine cycle & ABC (R_P = 20, r_P = 6 and TIT = 1200 °C, T_{amb} = 25 °C)

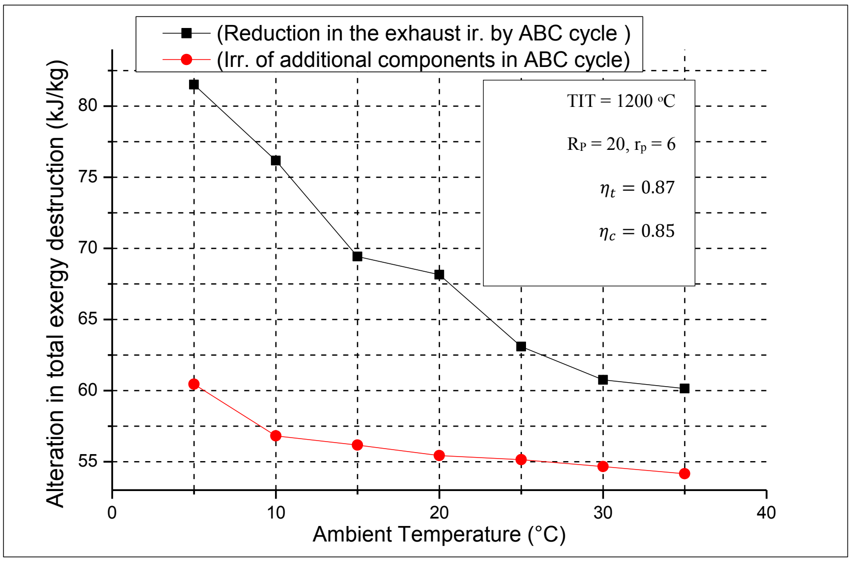


Fig.5.5. Comparison between exhaust exergy destruction reduction by ABC cycle and the exergy destruction created by additional components in ABC cycle

Fig.5.5 shows the comparison between the exergy destruction recovery due to the ABC over simple gas turbine cycle and additional exergy destruction for the extra components in ABC. As Fig.5.5 shows, the exergy destruction following the addition of the new components is much lower than the amount of the exergy recovery in the ABC. This explains why the SFC is lower in ABC compared with the simple gas turbine cycle.

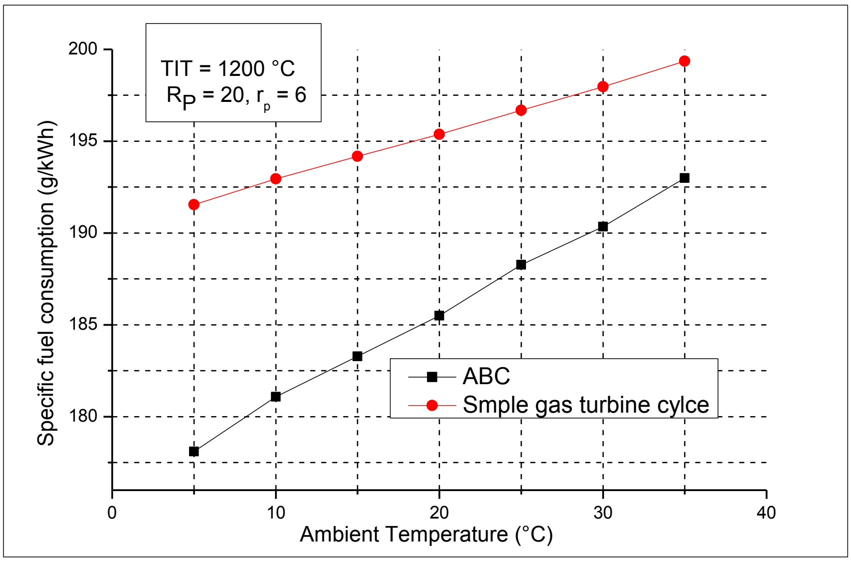


Fig.5.6. SFC of simple gas turbine cycle and ABC cycle

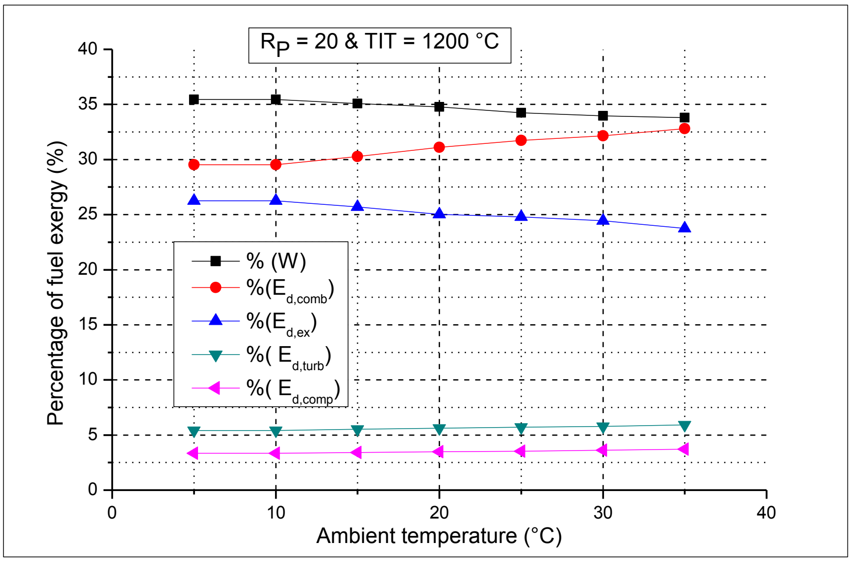


Fig.5.7. Work output, exergy destruction of components as a percentage of fuel exergy of simple gas turbine cycle

Recalling the previous Fig.5.5, that originated why the SFC of ABC is lower than the simple gas turbine cycle. This Fig.5.6 confirms that the SFC for this configuration of ABC is averagely around 9% less than that of the simple gas turbine cycle. As indicated in the Fig.5.6 this improvement is noticeably greater at lower ambient temperatures. In fact a lower ambient temperature leads to a higher temperature difference inside the regenerator, which intern affects the SFC by augmenting the exergy recovery as well as the exergy destruction, nevertheless, the exergy recovery is dominant.

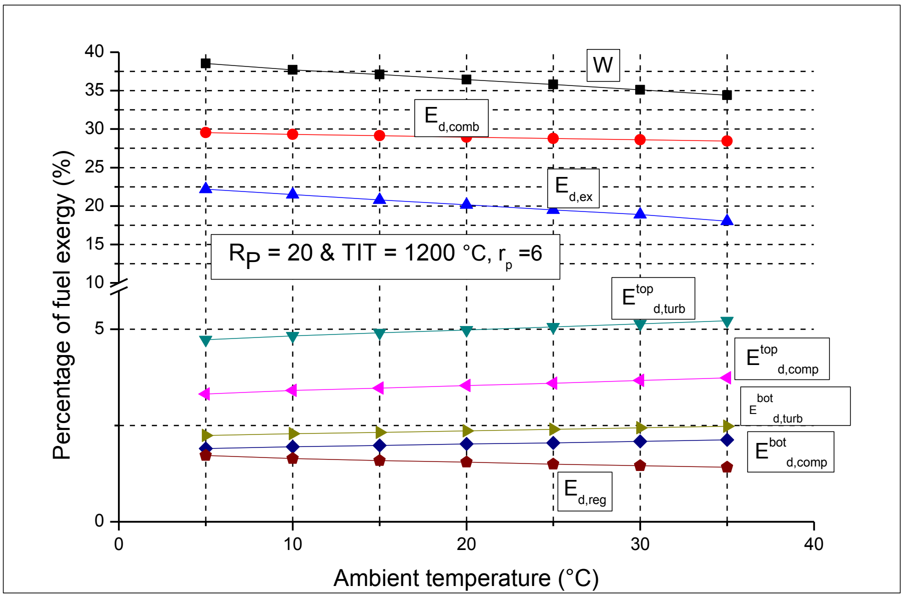


Fig.5.8. Gas turbine with ABC: Work output of the cycle, exergy destruction (irreversibility) of components as a percentage of fuel exergy

Fig.5.7 shows that in the simple gas turbine cycle, averagely 57.5% of the fuel exergy has been lost in the combustion chamber and exhaust; the figure also indicates that around 7.5% of the fuel exergy is associated with turbine and compressor exergy destruction, and the remainder of the fuel exergy contributes to the work output of the cycle.

The percentage of work output and exergy destruction in each component from fuel exergy in the gas turbine with air bottoming cycle shown in Fig.5.8. Compared with the simple gas turbine cycle, decrease in the exhaust exergy destruction and increase in the work output is the only significant change in ABC. With the exhaust exergy recovery in the ABC, approximately 8.5% of fuel exergy is recovered; 3.4% accounts for the exergy destruction of the additional components in the ABC, while 5.1% results in the increase of the work output.

5.2 Effect of inlet fogging on simple gas turbine cycle and ABC

In the following paragraphs, we will present the results of the study on the comparative performance parameters of simple & combined cycle power augmentation by inlet fogging.

Table 5.3: Specific fuel exergy and the percentage of specific work and components exergy destruction for simple gas turbine cycle, with fogging at operating condition (R_P = 20)

TIT(°C)	T_{amb} (°C)	$EX_{CH,f}$ (kJ/kg)	W(%)	$E_{d,comp}$(%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
900	5	569.88	29.82	5.82	33.46	9.17	21.73
	10	556.78	29.18	5.98	33.17	9.40	22.27
	15	544.19	28.49	6.16	32.88	9.64	22.84
	20	531.84	27.77	6.33	32.58	9.88	23.44
	25	520.01	27.01	6.52	32.27	10.12	24.08
	30	508.92	26.21	6.70	31.95	10.37	24.78
	35	498.57	25.38	6.88	31.60	10.61	25.54
1000	5	704.26	32.42	4.70	32.09	7.48	23.32
	10	691.29	31.96	4.81	31.82	7.63	23.79
	15	678.91	31.46	4.92	31.56	7.78	24.28
	20	666.84	30.96	5.04	31.28	7.94	24.80
	25	655.44	30.41	5.16	31.00	8.09	25.35
	30	644.79	29.85	5.27	30.70	8.24	25.94
	35	635.12	29.25	5.39	30.39	8.39	26.58
1100	5	842.34	34.32	3.92	30.83	6.30	24.84
	10	829.50	33.76	4.00	30.58	6.41	25.25
	15	817.34	33.39	4.08	30.34	6.51	25.69
	20	805.55	33.00	4.16	30.08	6.62	26.15
	25	794.54	32.58	4.24	29.82	6.72	26.64
	30	784.42	32.15	4.32	29.55	6.83	27.16
	35	775.49	31.70	4.40	29.26	6.92	27.72
1200	5	984.16	36.28	3.34	29.67	5.44	25.27
	10	971.47	35.99	3.40	29.44	5.52	25.65
	15	959.53	35.69	3.46	29.21	5.59	26.04
	20	948.03	35.38	3.53	28.97	5.67	26.46
	25	937.58	35.04	3.59	28.73	5.74	26.90
	30	927.87	34.69	3.64	28.48	5.82	27.37
	35	919.68	34.34	3.70	28.21	5.88	27.88
1300	5	1129.79	36.09	2.91	28.61	4.78	27.62
	10	1117.23	35.85	2.95	28.39	4.84	27.97
	15	11055.2	35.59	3.00	28.18	4.90	28.33
	20	1094.34	35.34	3.05	27.95	4.95	28.72
	25	1084.16	35.06	3.09	27.72	5.01	29.12
	30	1075.18	34.77	3.14	27.49	5.06	29.55
	35	1067.78	34.46	3.18	27.23	5.11	30.02
1400	5	1279.26	36.84	2.56	27.63	4.26	28.91
	10	1266.87	36.45	2.60	27.42	4.30	29.23
	15	1255.40	36.23	2.63	27.22	4.35	29.56
	20	1244.54	36.02	2.67	27.01	4.39	29.92
	25	1234.80	35.78	2.71	26.79	4.44	30.29
	30	1226.42	35.53	2.74	26.57	4.48	30.69
	35	1219.84	35.26	2.77	26.33	4.51	31.12

Table 5.4: Specific fuel exergy and the percentage of specific work and components exergy destruction for ABC, with fogging at operating condition ($R_P = 20$ & $r_P = 6$)

$TIT(°C)$	T_{amb} (°C)	EX_{CH} (kJ/kg)	$W(\%)$	$E^{top}_{d,comp}$ (%)	$E^{bot}_{d,comp}$ (%)	$E_{d,comb}$ (%)	$E^{top}_{d,turb}$ (%)	E^{bot}_{dturb} (%)	$E_{d,reg}$ (%)	$E^{top}_{d,ex}$ (%)	$E^{bot}_{d,ex}$ (%)
900	5	569.88	27.13	5.80	2.54	33.47	7.98	2.94	1.46	15.70	2.98
	10	556.78	25.77	5.98	2.71	33.19	8.19	3.12	1.39	16.50	3.16
	15	544.19	24.52	6.15	2.82	32.92	8.39	3.24	1.35	17.31	3.30
	20	531.85	23.18	6.33	2.98	32.62	8.61	3.41	1.31	18.09	3.47
	25	520.08	21.77	6.51	3.10	32.32	8.82	3.54	1.28	19.04	3.62
	30	508.92	20.28	6.69	3.24	31.99	9.03	3.70	1.25	20.03	3.79
	35	498.57	18.68	6.87	3.40	31.64	9.24	3.88	1.23	21.08	3.99
1000	5	704.26	31.68	4.96	2.05	32.10	6.52	2.39	1.60	15.07	3.90
	10	691.29	30.75	4.80	2.18	31.84	6.65	2.52	1.52	15.61	4.12
	15	678.91	29.89	4.92	2.26	31.59	6.79	2.61	1.47	16.20	4.27
	20	666.84	29.01	5.03	2.37	31.31	6.92	2.73	1.42	16.73	4.48
	25	655.44	28.03	5.15	2.45	31.04	7.06	2.83	1.38	17.43	4.64
	30	644.79	27.02	5.27	2.55	30.74	7.19	2.93	1.34	18.13	4.83
	35	635.13	25.95	5.38	2.66	30.42	7.32	3.06	1.30	18.85	5.05
1100	5	842.34	34.72	3.91	1.71	30.84	5.50	2.01	1.74	14.81	4.75
	10	829.50	34.07	3.99	1.81	30.60	5.60	2.11	1.65	15.17	5.00
	15	817.34	33.45	4.08	1.87	30.36	5.69	2.18	1.60	15.62	5.17
	20	805.55	32.82	4.16	1.96	30.11	5.78	2.27	1.55	15.97	5.39
	25	794.54	32.10	4.24	2.02	29.85	5.88	2.34	1.50	16.51	5.57
	30	784.42	31.38	4.32	2.09	29.58	5.96	2.42	1.45	17.03	5.77
	35	775.49	30.62	4.40	2.18	29.28	6.05	2.52	1.40	17.54	6.02
1200	5	984.16	35.83	3.34	1.46	29.68	4.75	1.73	1.87	14.78	5.53
	10	971.47	36.38	3.40	1.54	29.46	4.82	1.81	1.78	15.00	5.81
	15	959.53	35.89	3.46	1.59	29.23	4.89	1.86	1.72	15.35	5.99
	20	948.03	35.45	3.52	1.66	29.00	4.96	1.94	1.67	15.58	6.23
	25	937.43	34.90	3.58	1.71	28.76	5.03	1.99	1.61	16.01	6.41
	30	927.87	34.35	3.64	1.76	28.50	5.09	2.06	1.56	16.40	6.63
	35	919.68	33.81	3.70	1.83	28.23	5.15	2.13	1.51	16.76	6.90
1300	5	1129.79	38.38	2.90	1.27	28.62	4.18	1.51	1.99	14.91	6.25
	10	1117.27	38.01	2.95	1.33	28.41	4.24	15.8	1.90	15.07	6.52
	15	1105.52	37.61	3.00	1.38	28.20	4.29	1.63	1.84	15.29	6.73
	20	1094.34	37.33	3.04	1.43	27.97	4.34	1.69	1.78	15.42	7.00
	25	1084.16	36.91	3.09	1.47	27.75	4.39	1.73	1.73	15.76	7.19
	30	1075.18	36.47	3.13	1.52	27.51	4.43	1.76	1.67	16.06	7.42
	35	1067.78	36.05	3.18	1.57	27.25	4.47	1.84	1.62	16.31	7.69
1400	5	1279.26	39.50	2.56	1.12	27.63	3.73	1.34	2.10	15.13	6.90
	10	1266.91	39.22	2.59	1.17	27.44	3.77	1.39	2.00	15.22	7.19
	15	1255.40	38.94	2.63	1.21	27.24	3.81	1.44	1.95	15.37	7.42
	20	1244.55	38.70	2.67	1.26	27.03	3.85	1.49	1.89	15.43	7.69
	25	1234.80	38.36	2.70	1.29	26.81	3.89	1.52	1.83	15.70	7.89
	30	1226.42	38.03	2.74	1.33	26.59	3.92	1.57	1.78	15.92	8.13
	35	1219.84	37.69	2.77	1.37	26.35	3.96	1.62	1.72	16.09	8.42

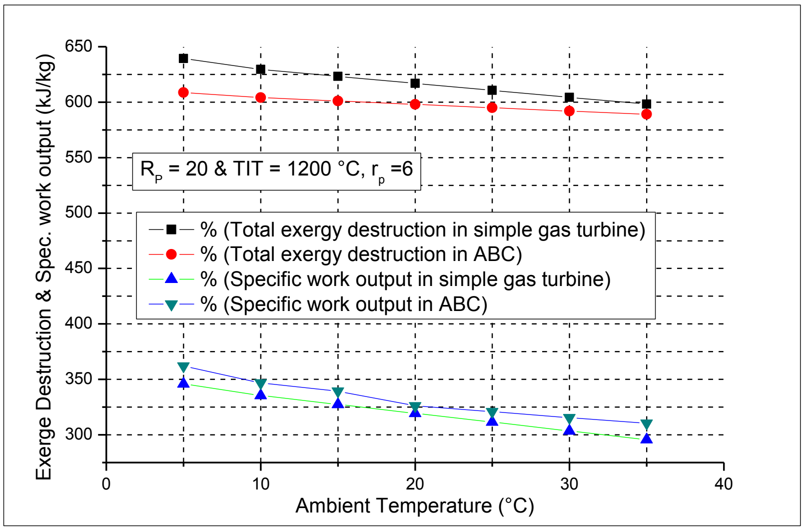


Fig.5.9. Comparison between work output and total exergy destruction variations in ABC & simple gas turbine without inlet fogging

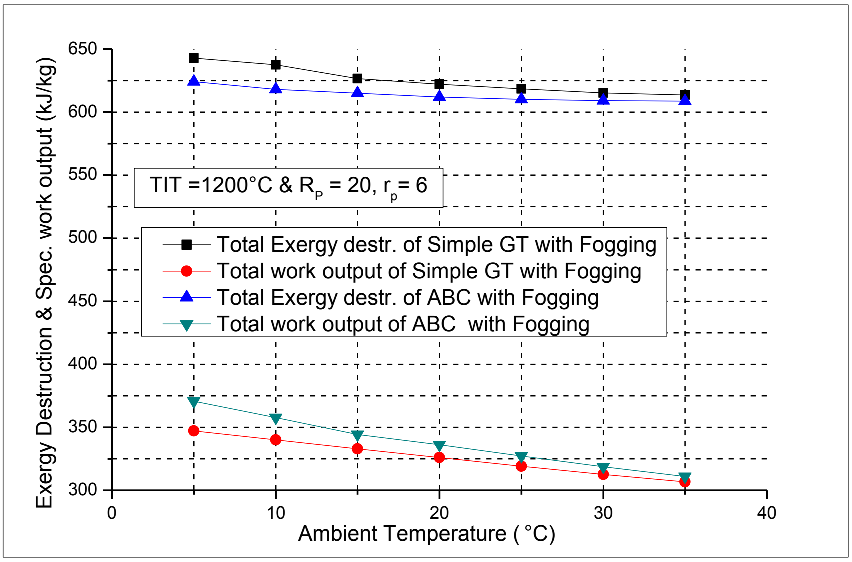


Fig.5.10. Comparison between work output and total exergy destruction variations in ABC & simple gas turbine with inlet fogging

In ABC cycle total amount of exergy destruction is lesser than that of simple gas turbine cycle as Fig. 5.9 shows. This is because of the exhaust exergy recovery in the ABC cycle. The exhaust exergy in a simple gas turbine cycle is usually wasted by the mixing of the combustion products with the atmosphere. Installing a combined cycle like ABC, the total exergy destruction is decreased by the exhaust exergy recovery and increased by the addition of new components. So, because of the lower total exergy destruction in the ABC, a greater amount of fuel exrergy will be converted into work compared to the simple gas turbine cycle as shown in the Fig.5.9.

In case of inlet fogging, comparing with the without fogging condition, the total amount of exergy destruction increases, this is due to the fact of differences in the property due to the inlet cooling with that of without fogging condition. As the Fig.5.10 also shows that the noticeable amount work output increment in ABC due to the fogging, this is because of the exhaust exergy recovery and the amount of mass flow increment due to fogging in ABC. Even the power output increases in case of inlet fogging, combustion chamber still responsible for the major exergy destruction of the plant, as shown in the Fig.5.11. Fig.5.11 shows that, in comparison with other plant components, the combustion chamber destructs the largest amount of total inlet exergy of the plant, this is true for both cases with and without fogging. This figure also shows that approximately 60% of the total inlet exergy is annihilated in the plant.

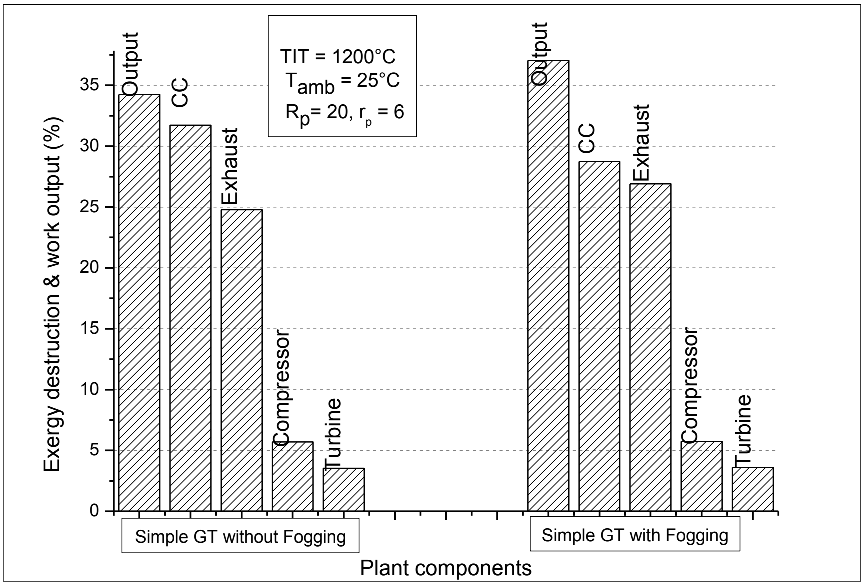


Fig.5.11. Work output and components exergy destruction of simple GT cycle without & with inlet fogging

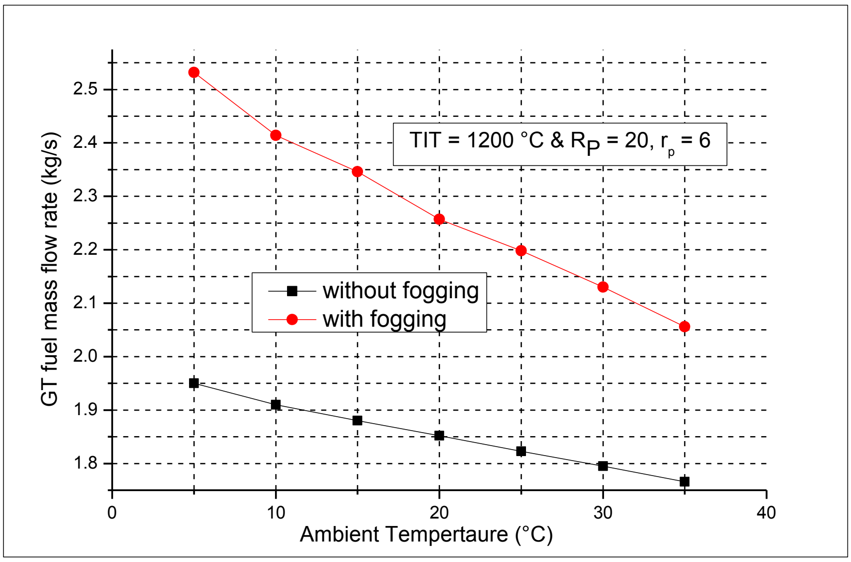


Fig.5.12. Gas turbine fuel mass flow rate under various ambient condition

As shown in Fig.5.12, the differences in fuel flow rates of the gas turbine with and without an inlet fogging system are inversely proportional to the ambient temperature. For a gas turbine with an inlet fogging system, the mass flow rate of fuel is proportional to the consumption of fogging water. It implies that the differences in the mass flow rates of fuel will have a higher value under lower ambient temperature for a given relative humidity a shown in Fig.5.12.

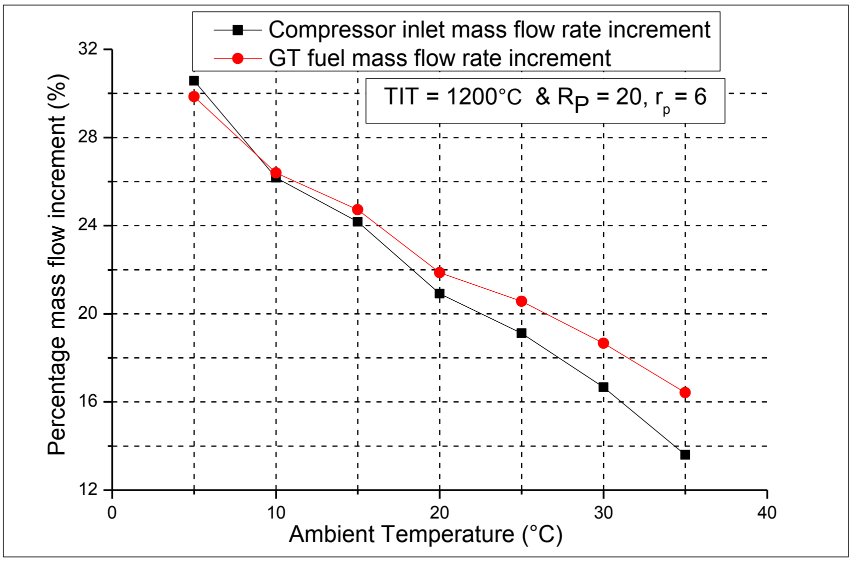


Fig.5.13. Gas turbine fuel mass flow rate & compressor inlet flow rate increment by inlet fogging

From the Fig.5.13, it is obvious that both the compressor inlet flow rate and fuel flow rate of the gas turbine increased with the inlet fogging system. Compressor mass flow increases averagely 21.6% and GT fuel flow rate experiences approximately 22.6% increment due to the installation of the inlet fogging system in the cycle, as shown in the Fig.5.13.

Since inlet fogging can increase the mass flow rate of the compressor and the fuel flow rate of the gas turbine for a given ambient temperature and relative humidity, as shown in Fig.5.12 and Fig.5.13, the net result will be increased gas turbine power output.

AS shown in the Fig.5.14, significant improvement of the power output of ABC over simple gas turbine cycle, due to the exhaust heat recovery in the bottoming cycle of the ABC combined cycle. As the ambient temperature increases the power output of both cycle start to fall, due to the lesser capacity of giving work potential at higher temperature. Inlet fogging gives tremendous increment of power output of both cycle as shown in Fig.5.15. From the Fig.5.16, it could be found that power output of simple gas turbine cycle increases averagely 21.9%, due to inlet fogging and for ABC this value is around 25.2 %. ABC gives higher value, because of its two benefit, one is fogging like the simple gas turbine cycle and other one is exhaust exergy recovery over the simple gas turbine cycle.

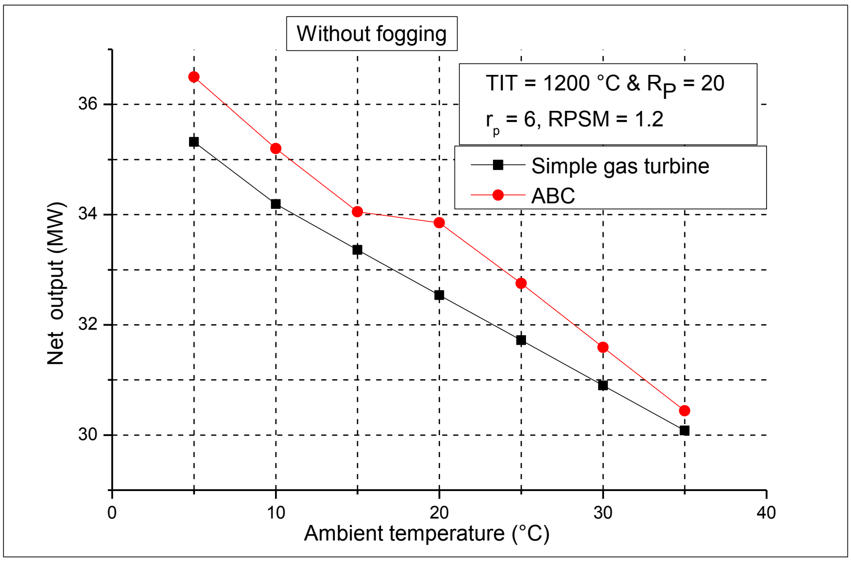


Fig.5.14. Comparison of Net output of simple gas turbine cycle & ABC without the inlet fogging system

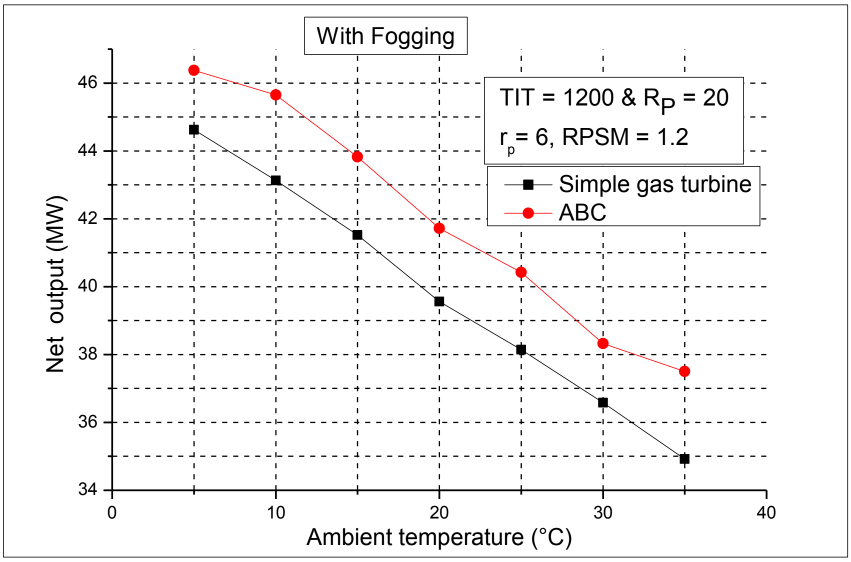


Fig.5.15. Comparison of Net output of simple gas turbine cycle & ABC with the inlet fogging system

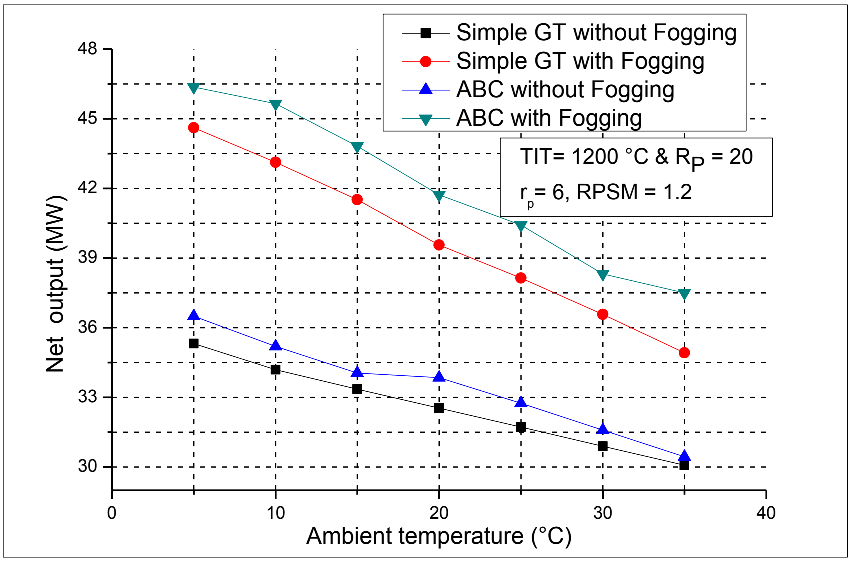


Fig.5.16. Comparison of Net output of simple gas turbine cycle & ABC, with & without the inlet fogging system

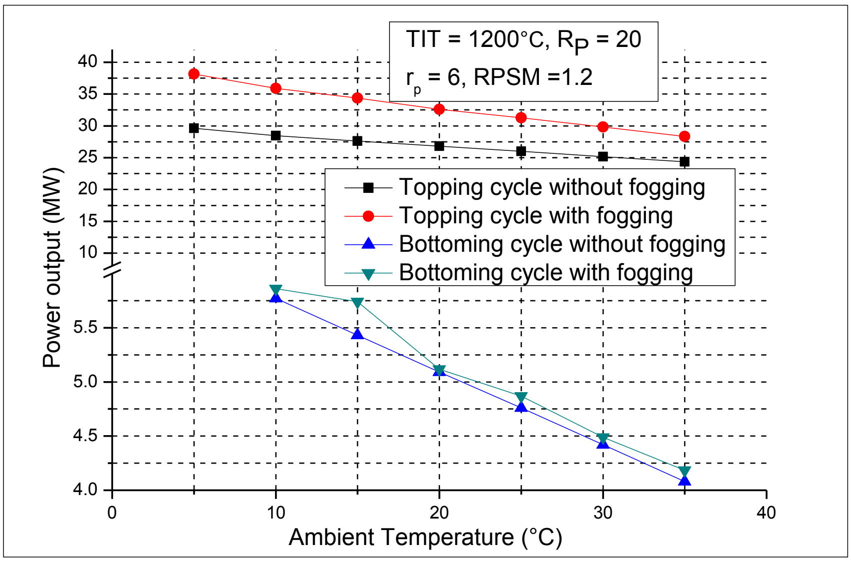


Fig.5.17. Comparison of power output of topping & bottoming cycle, with & without the inlet fogging system

As previously shown, the mass flow rate at the compressor inlet with an inlet fogging is always higher than no fogging case, which is due to the additional fogging water as well as an increase in mass flow rate at the compressor inlet with the reduction in air temperature. Also shown in previous figure, that the fuel flow of gas turbine with an inlet fogging system is greater than the no fogging case under the same ambient conditions. Therefore, both the dry flue gas and vapor carry additional energy into the regenerator in the combined cycle. From the above discussion, it is demonstrated that the power output of the bottoming cycle of the combined cycle is also augmented with inlet fogging system, though it is marginal as shown in the Fig.5.17. It is interesting to note that the power augmentation due to inlet fogging in the topping cycle is five times higher than that of bottoming cycle, as we can see from the Fig.5.17. Therefore, topping gas turbine has the major contribution in the power augmentation of the combined ABC cycle.

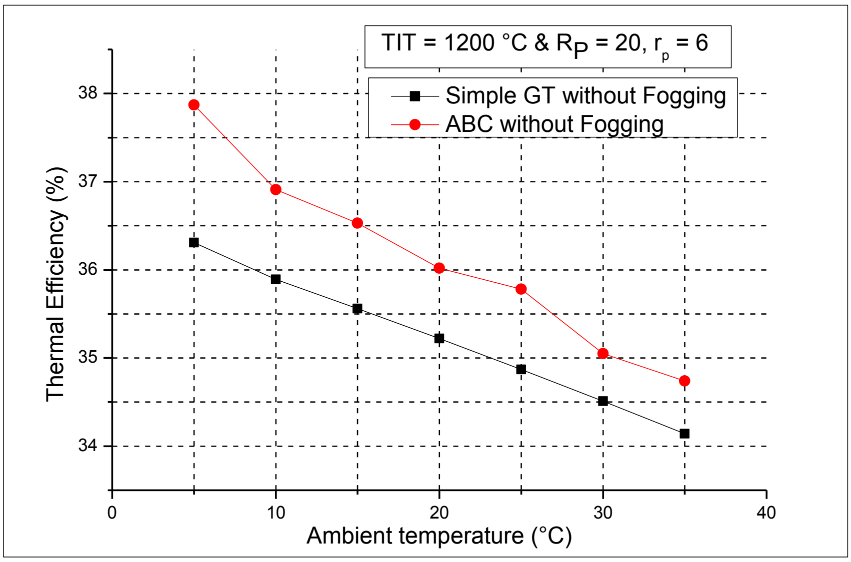


Fig.5.18. Comparison of thermal efficiency of ABC & simple gas turbine cycle, without the inlet fogging system

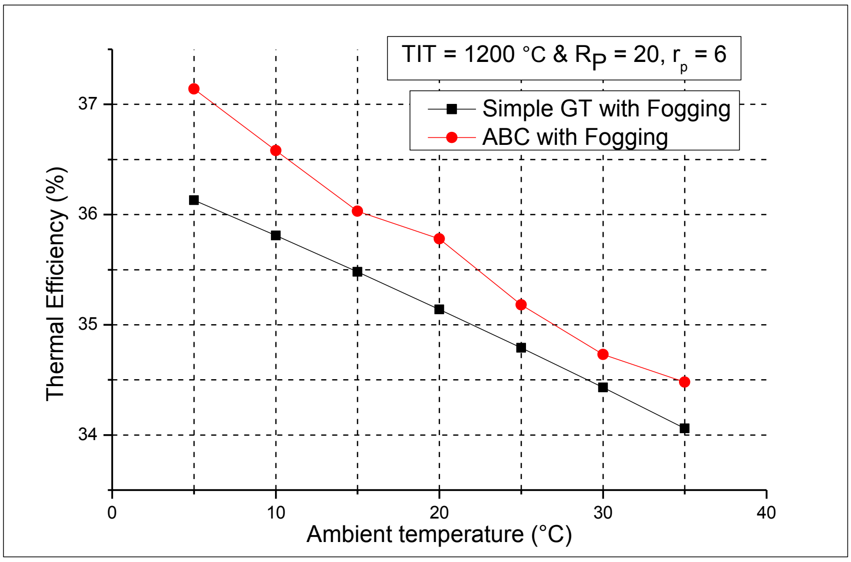


Fig.5.19. Comparison of thermal efficiency of ABC & simple gas turbine cycle, with the inlet fogging system

Fig.5.18 shows the thermal efficiency of the ABC and simple gas turbine cycle without fogging system, here the due to the recovery of the exhaust energy in the ABC cycle over the simple GT cycle, ABC has the higher thermal efficiency. But with the increment of the ambient temperature thermal efficiency decreases, because of the less power output with higher temperature. With the initiation of the inlet fogging thermal efficiency of both cycle increases as shown in the Fig.5.19.

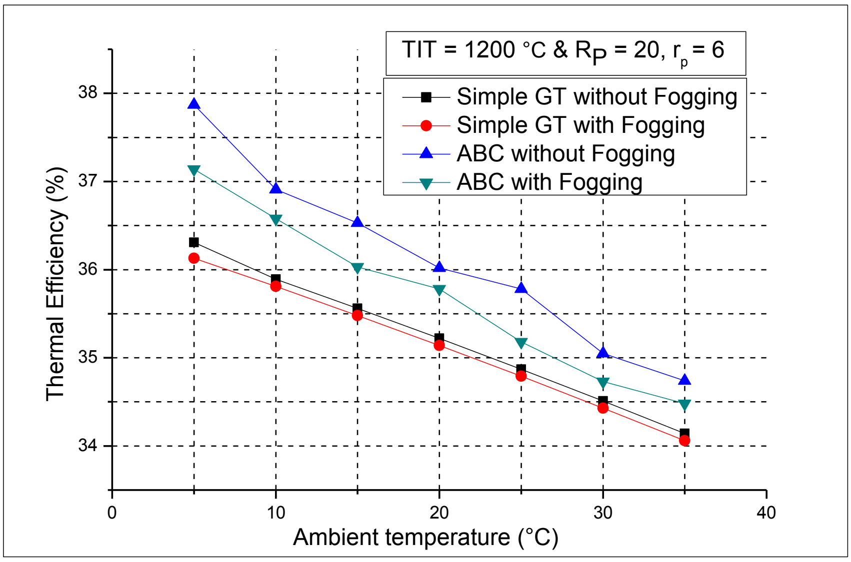


Fig.5.20. Comparison of thermal efficiency of ABC & simple gas turbine cycle, with & without the inlet fogging system

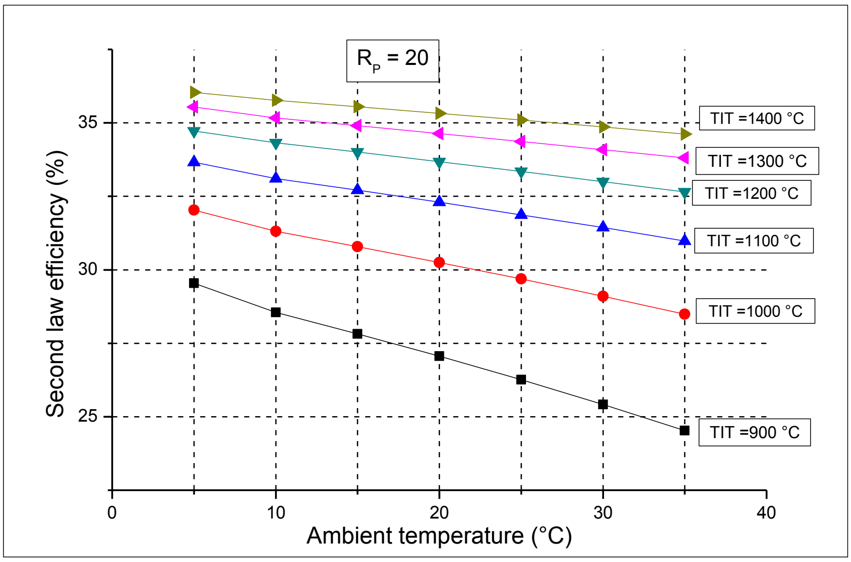


Fig.5.21. Second law efficiency of simple gas turbine cycle with the variation of TIT & ambient temperature

In the Fig.5.20, if we compare each cycle's thermal efficiency with and without fogging condition, it is seen that the thermal efficiency improvement of respective cycle is marginal. This is because of the additional power consumption by the plant with an inlet fogging installation.

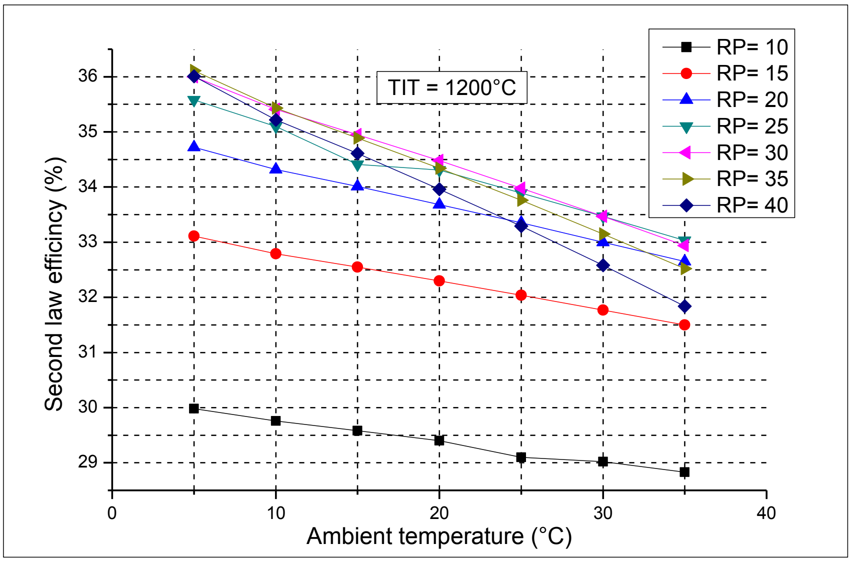


Fig.5.22. Second law efficiency of simple gas turbine cycle with the variation of pressure ratio & ambient temperature

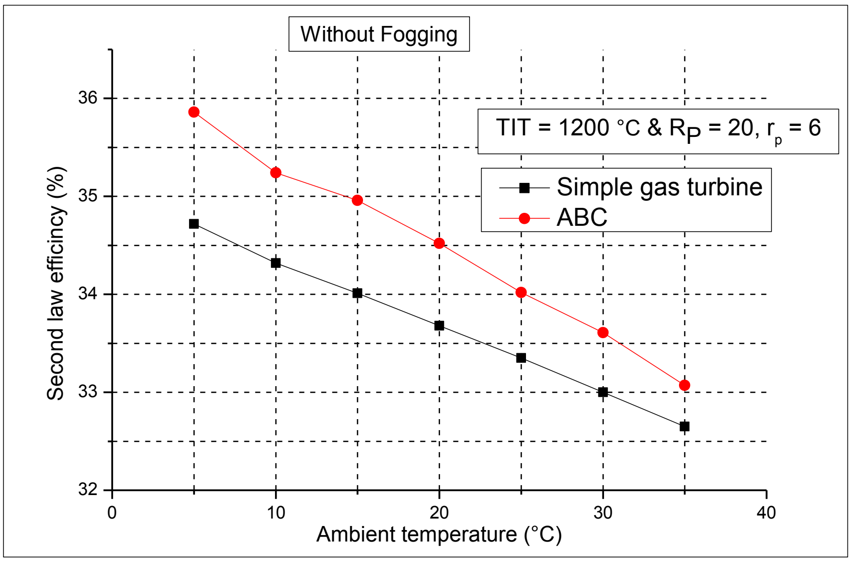


Fig.5.23. Second law efficiency of simple gas turbine cycle & ABC without inlet fogging system

Fig.5.21 and Fig.5.22, show that the second law efficiency of simple gas turbine cycle decreases with the increase of the ambient temperature, irrespective of turbine inlet temperature and compression ratio, this is due to the higher exergy destruction of the plant components with ambient condition change.

From the Fig.5.23 and Fig.5.24, it is seen that the second law efficiency of the combined cycle (ABC) is higher than that of simple GT cycle, due to the substantial exergy recovery in the air bottoming combined cycle over the simple gas turbine cycle.

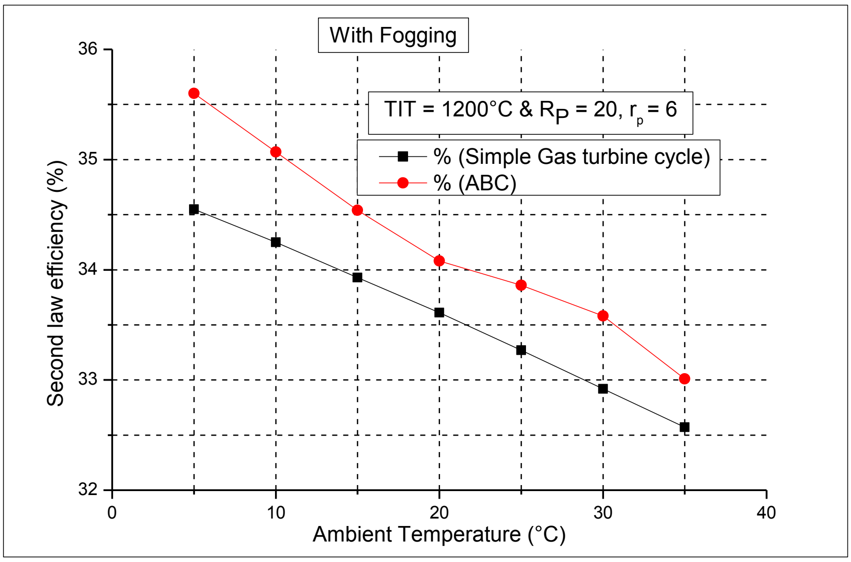


Fig.5.24. Second law efficiency of simple gas turbine cycle & ABC with inlet fogging system

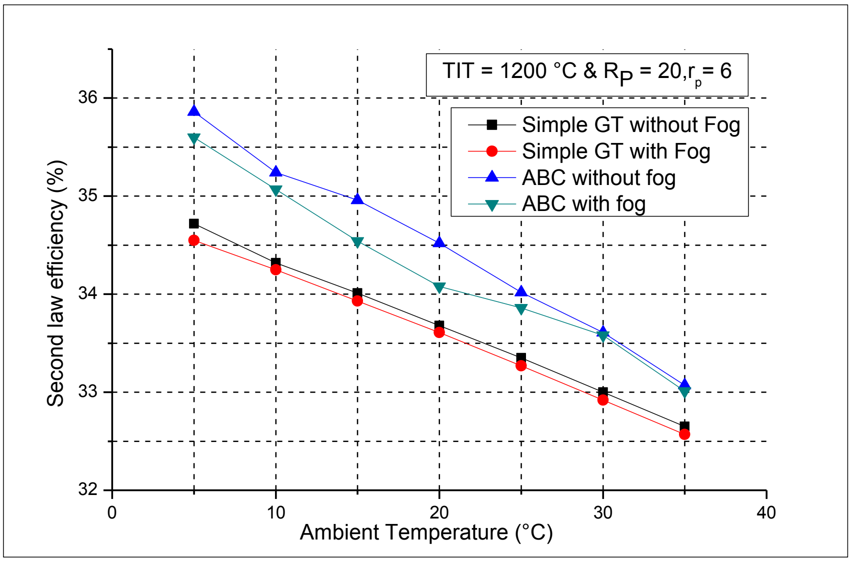


Fig.5.25. Comparison of second law efficiency of simple gas turbine cycle & ABC, with & without inlet fogging system

Fig.5.25 draws a comparison of the second law efficiency of ABC and simple GT cycle with & without inlet fogging system. In both cases the ABC cycle hold the leading position over the simple gas turbine cycle, but ABC itself shows a borderline change in the second law efficiency, without and with the inlet fogging. Because, the rate of power augmentation by the inlet fogging still cause an extra energy input to the gas turbine. This makes a small change in efficiency of the power plant as shown in Fig.5.25.

Therefore, combined cycle power augmentation with the inlet fogging is at the expense of marginal improvement of efficiency in order to boost power output.

Chapter 6

CONCLUSION AND RECOMMENDATION

Chapter 6

Conclusion

In the present work the effect of key operating variables such as the ambient temperature, pressure ratio and turbine inlet temperature on performance characteristics such as specific work, specific fuel consumption, exergy destruction, energy and exergy efficiencies of the simple gas turbine cycle & air bottoming cycle, without and with power augmenting inlet fogging systems are assessed. This chapter concludes with the summarized findings of the present work and recommendations for the further scope of continuation of the current research.

6.1 Summary of Results and Major Conclusions

The major conclusions of the study are:

- When the ambient temperature is increased the exergy destruction of both the main turbine and compressor increases, this is also true for the pressure ratio increment. The exergy destruction in the combustion chamber is high at the low ambient. And for the higher ambient temperature combustion chamber exergy destruction start to decrease.
- For both simple and combined cycle the exergetic efficiency of the combustion chamber is much lower than that of the other components, because of the higher irreversibilities in the combustion chamber.
- In the air bottoming combined cycle (ABC), exergy recovery is greater than the exergy loss due to additional components, approximately 8.5% of fuel exergy is recovered; 3.4% accounts for the exergy destruction of the additional components in the ABC, while 5.1% results in the increase of the work output. And this gives a boon of 9% less SFC in ABC than that of the simple gas turbine cycle.
- Due to the installation of the inlet fogging system in the cycle, compressor mass flow increases averagely 21.6% and GT fuel flow rate experiences approximately 22.6% increment and the net result is increment of cycle power output. Average Power augmentation of simple gas turbine cycle is around 21.9%, and of ABC approximately 25.2 %, due to inlet fogging.
- The mass flow rate at the compressor inlet and fuel flow of gas turbine with an inlet fogging is always higher than no fogging case, under the same ambient conditions, those are the potential reasons for power augmentation. In the combined ABC cycle, topping gas turbine has the major contribution in the power augmentation, cause power augmentation due to inlet fogging in the topping cycle is about five times higher than that of bottoming cycle.
- First law & second law efficiency of the combined cycle (ABC) is higher than that of simple GT cycle, irrespective of presence and absence of inlet fogging system, due to

the substantial exergy recovery in the air bottoming combined cycle over the simple gas turbine cycle.

- The rate of power augmentation by the inlet fogging still cause an extra energy input to the gas turbine. This makes a small change in efficiency of the power plant. Cycle power augmentation with the inlet fogging is at the expense of marginal improvement of efficiency in order to boost power output.

6.2 Contributions

In comparison with other relevant literature, in his study unique combination of performance parameters are chosen to assess the performance of power cycles. To the best of the author's knowledge, energy and exergy analysis of simple gas turbine cycle and a unique combined cycle (ABC), with power augmentation technique, inlet fogging has not been studied. This study shows how both power cycles comported under varying key parameters at the presence & absence of inlet fogging, which has not been addressed in the open literature.

To my knowledge, in the past nothing much has been written about the effects of inlet fogging on ABC. In this study the influence of inlet fogging on ABC is addressed. This study shows that the importance of considering the inlet fogging as a function of power augmentation for simple and combined cycle.

6.3 Recommendations for future work

Following points can be considered in future work:

- In this thermodynamic analysis calculations were performed based on simulated conditions. In order to simplify analysis, the state conditions were defined and the appropriate assumptions made. Due to the time and resources constraints it was not possible to analyze real power systems. This work can be further extended by analyzing actual gas turbine systems taking actual state conditions into account.
- This study considered fuel in the pure form. There is a growing interest in some specific blends of fuels. These can be studied further.
- In this study inlet fogging system was applied on the air bottoming combined cycle (ABC). This power augmentation technique can be applied to other combined cycle such as: Brayton-Rankine cycle; Brayton-ORC.
- Exergo-economic analyses can also be conducted further on the existing study, as well as on the different combination of the cycles.

APPENDICES

APPENDIX A

Apparatus models of Cycle-Tempo

A.1 TUBINE

The apparatus type 3, the turbine, is used to model an expansion process, irrespective of the medium expanding in the turbine. Each turbine can, in addition to an inlet and an outlet, have a maximum of 8 extractions, as indicated in Figure 3-1. The outlet pressure and the extraction pressures of a turbine cannot be specified with the parameter POUT, but must be calculated from data which are specified for apparatuses or pipes downstream. For off-design calculations the extraction pressures are calculated on the basis of Traupel's formulae [65] (a refinement of Stodola's cone law), provided the following data are known for the turbine, which means specified or calculated by other apparatuses:

- the outlet pressure; this will in general be calculated in off-design situations from data for the condenser;
- a number of results from the design case; these must be specified as "Off-design input data" for the relevant apparatuses. These design data can also be found at the end of the output file (under option View | Text Output).

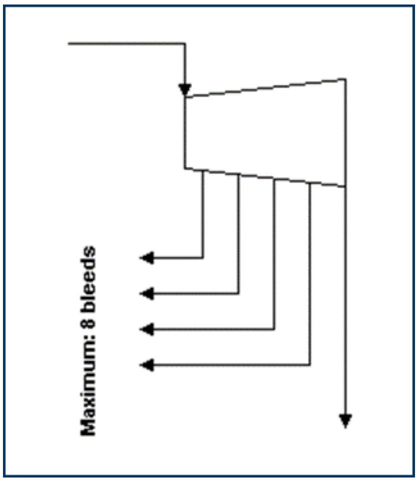


Figure A. 1: Diagram of apparatus type 3, the turbine

The turbines and turbine sections distinguished by the program can be classified in two categories, distinguished from each other by the turbine code TUCODE:

- general turbines TUCODE = 0
- specific steam turbines TUCODE = 10000 and higher

The general turbine type can where necessary also be used as a steam turbine, but is intended more as an expansion section of a gas turbine installation, and as turbine type for various media. The user will have to specify the internal efficiency of the turbine himself, or this must be calculated from the conditions at the inlet and outlet of the turbine.

Input parameters

PIN, TIN, TOUT and DELT are standard.
(N.B. it is not possible to specify POUT and DELP).

TUCODE = five digit turbine code, t_1 t_2 t_3 t_4 t_5. The digit furthest on the left, (t_1) indicates the turbine type (default = 0).

GDCODE = code which indicates the presence (GDCODE = 2) or absence (GDCODE = 1) of a governing stage (default = UNKNOWN).

ETHAI = isentropic efficiency (default = UNKNOWN for TUCODE = 0).

ETHAM = mechanical efficiency (default = 1).

Depending on the type of turbine, indicated by t_1 of TUCODE, a few geometric data have to be specified. A summary of the input variables is given in Table 2-2. For a detailed description see part "Technical Notes" of the manual.

Number of equations for system matrix

This apparatus type adds 1 mass equation to the system matrix.

Pressure calculation

1. Design load: No relations are available to calculate pressures: the outlet pressure and the pressures at the extraction points have to be specified with data for apparatus downstream of the turbine (or with the help of extra conditions for pipes). The turbine inlet pressure can be specified for the turbine or for apparatus upstream of the turbine.

2. Off-design: The pressures at extraction points are calculated using Traupel formula, provided the pressure of the outlet is known, and the design extraction point pressures are specified in the input. The calculation of the turbine inlet pressure using Traupel's formula is only output when the relevant turbine section does not have a governing stage (GDCODE = 1).

Temperature, specific enthalpy and vapor fraction
(for design load and off-design calculation)

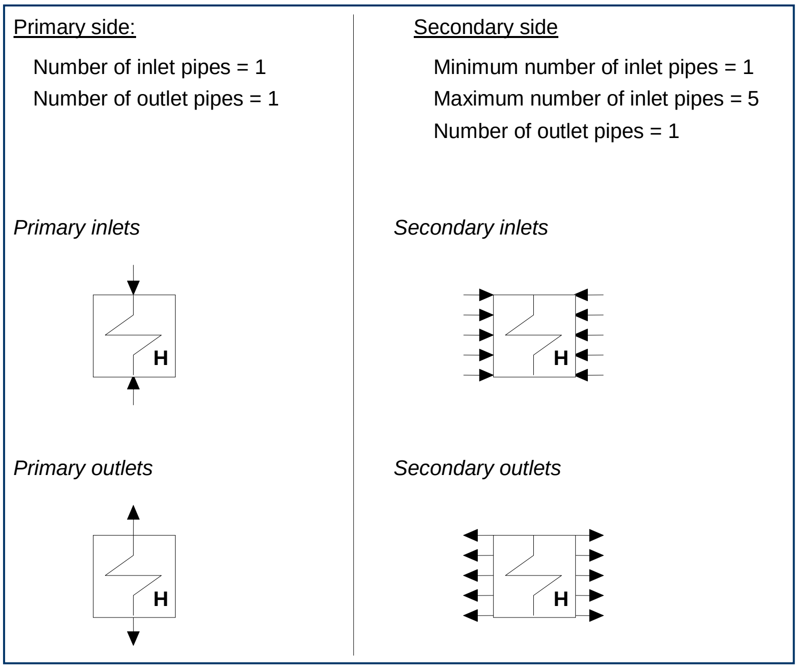
3. $T_{out} = T_{in} + DELT$

4. $h_{out} = f(h_{in}, ETHAI)$

a straight or curved expansion line is assumed and pressures have to be known.

5. Thermodynamic variables at extraction points are computable from turbine inlet and outlet conditions and the pressure of the extraction point. The isentropic efficiency (η_i) can be specified in the input (as $t_1 = 0$), or is computable from user defined turbine data, using polynomials suggested by General Electric (t_1 = 1 to 5, 8 and 9) or VMF Stork (nowadays NEM Hengelo, the Netherlands) (t_1 = 6 and 7). In addition the enthalpy at the extraction points is also influenced by the shape of the expansion line. In the h,s-diagram this is a straight line for $t_5 = 0$. For turbine sections with t_1 = 5, 8 or 9 a curved expansion line may be chosen with $t_5 = 1$.

A.2 HEAT EXCHANGER



This apparatus is used as a general heat exchanger, evaporator or furnace. The former two are represented by the subtype “General”, the latter by subtype “Furnace”.

For the furnace, the radiation constant is calculated at design using, among other, the furnace outlet temperature. This temperature is calculated at off-design using the Ter Linden method. For furnaces EEQCOD = 1 should be chosen. Additional input for furnaces is described at the end of this paragraph.

The energy equation code (EEQCOD) determines the usage of the energy equation:

- **EEQCOD = 1:** the energy equation of the apparatus is used to calculate a mass flow. An energy equation, defined by the user (possibly in combination with other apparatuses), can be specified as a production function. If this is not the case, the program will automatically define the production function. The value of this function represents the energy release to the environment, i.e. a thermal loss. The energy equation will be added to the system matrix.

- **EEQCOD = 2:** the energy equation of the apparatus is used to calculate an enthalpy in one of the inlets or outlets. The energy equation will not be added to the system matrix.

If the EEQCOD is not specified the default value 2 is used.

For off-design calculations the heat transfer equation is used. For this the heat transfer capacity rate (UA-value) must be specified in the input. The primary and secondary medium may in that case only have 1 inlet and 1 outlet.

Input parameters

PIN1, POUT1, DELP1, TIN1, TOUT1, DELT1 are standard
PIN2, POUT2, DELP2, TIN2, TOUT2, DELT2[1)] are standard

EEQCOD	=	code which indicates whether the energy balance is used to calculate a mass flow (EEQCOD=1) or a temperature (EEQCOD=2) (default=2)
DELTH	=	high terminal temperature difference (°C) see Figure 2-4. (default = UNKNOWN)
DELTL	=	low terminal temperature difference (°C) see Figure 2-4. (default = UNKNOWN)
RPSM	=	initial estimate for the ratio of the primary/secondary mass flow for EEQCOD = 2. A negative value indicates a parallel flow heat exchanger and a positive value gives a counter current heat exchanger (default = 1.0). Specification of RPSM is recommended if it is anticipated that the mass flow ratio between primary and secondary medium will differ appreciably from 1. This can prevent fluctuations in the mass flows during the first iteration steps. For EEQCOD = 1 only the sign of RPSM is used to determine the flow directions.

[1)] DELT2 is defined as temperature rise, so this value normally has a negative value for the secondary medium.

DELE = energy flow to the environment (kW) for EEQCOD = 2

(default = 0.0). DELE > 0 is energy flow to the environment, for example radiation loss. This value, which is used in a local energy balance, can be altered in a user subroutine (APSUB). DELE should differ by at least EPS from -8888.8

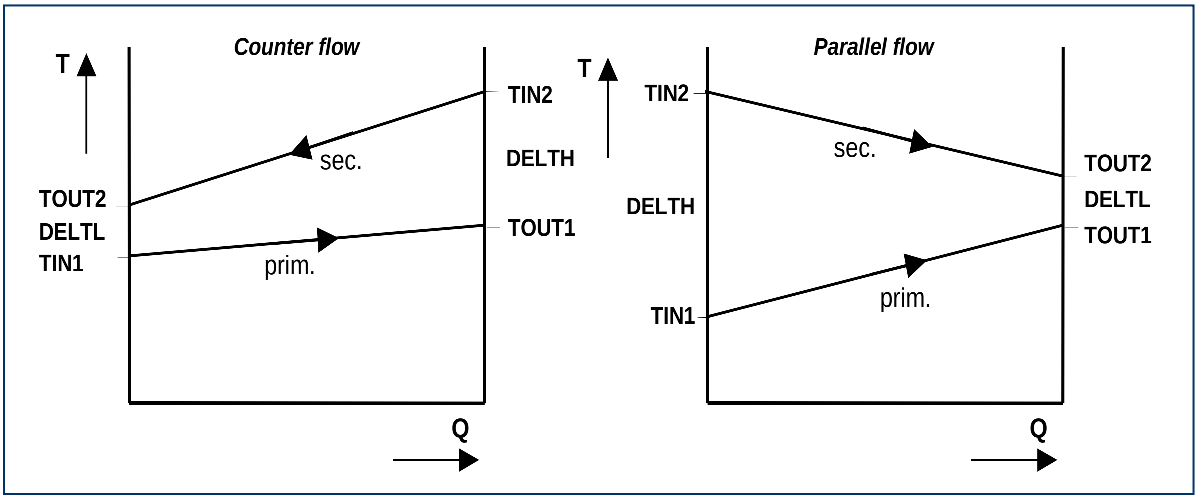


Figure A.2: temperature determination heat exchanger

Number of equations for system matrix

This apparatus type adds 2 mass equations to the system matrix. If EEQCOD = 1 an energy equations is added also, in the form of a production function. The program will automatically generate a production function if it detects that the apparatus has not been defined in another production function.

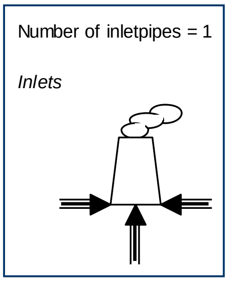
Summarizing:

EEQCOD = 1: 2 mass equations + 1 production function = 3 equations

EEQCOD = 2: 2 mass equations

A.3 STACK

The stack is used as a sink for flue gases.



Input parameters

PIN and TIN are standard.

HIN = specific inlet enthalpy (kJ/kg) (default = UNKNOWN)

DELM = mass flow from the system (kg/s) or (-) (default = UNKNOWN)

DELV = volume flow from the system (m^3/s) or (-) (default = UNKNOWN)

DELVN = volume flow at normal conditions (1.01325 bar, 0 °C) from the system (m_n^3/s) or (-) (default = UNKNOWN)

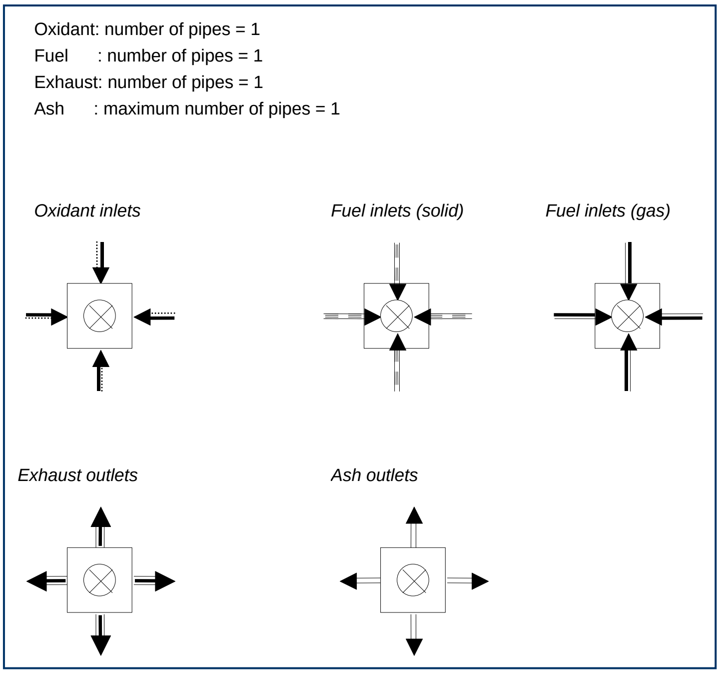
- Either DELM, DELV or DELVN may be specified.
- If DELM, DELV or DELVN is specified then an extra mass equation will be added to the system matrix.
- The value of DELM, DELV or DELVN must differ by at least EPS from -8888.8, and may only be altered in a user subroutine if this is specified relative to PIPE.

PIPE = pipe number, if given then DELM, DELV or DELVN is considered to be relative to the pipe mentioned.

Number of equations for system matrix

Only if DELM, DELV or DELVN is specified, 1 mass equation will be added to the system matrix.

A.4 COMPRESSOR



In the combustor an oxidant and a fuel flow react. The composition of the product gas is determined by the chemical equilibrium at the specified or calculated conditions, which may deviate from the prevailing conditions, if so specified by the user. In the combustor no heat transferring area is modeled; the heat, which is released, is used to increase the temperature of the product gas and ash. The reaction enthalpy is calculated and used in the energy balance. Depending on the energy equation code (EEQCOD) there are two possible ways of using the energy balance:

- **EEQCOD = 1**: The energy balance can be used to define a mass flow. In this model there are 3 unknown mass flows (the mass flow in the ash pipe is defined separately). Two mass flows are defined by adding equations to the system matrix (energy balance and total mass balance). The mass flow missing must be specified or calculated elsewhere.

- **EEQCOD = 2 (default)**: The energy balance can be used to determine the temperature of the outgoing product gas. In this case only the total mass balance is added to the system matrix for calculating one of the unknown mass flows. The two missing mass flows can be determined in 2 ways:

- both mass flows can be specified or calculated elsewhere;
- the air factor (LAMBDA) can be specified in combination with the specification or calculation elsewhere of a mass flow.

Where an ash pipe is specified, composition and mass flow are defined by:

- Automatic discharge of a number of solid or liquid components to the ash pipe. These components are Al_2O_3(s), Al_2O_3(l), Fe_2O_3(s), SiO_2(s), SiO_2(l).
- Specification of a mass or molar percentage per component with respect to the mass or mole flow in the fuel pipe (see input of **Reaction data** in paragraph 4.2 of part “Cycle-Tempo Operation”).

The composition in the incoming lines (fuel and oxidant) must always be specified, or calculated in the apparatuses upstream. The composition in the product gas pipe is calculated according to chemical equilibrium. It is however possible to keep parts of the reactants outside the reaction (see input of **Reaction data** in paragraph 4.2 of part “Cycle-Tempo Operation”).

The temperature at which chemical equilibrium is calculated (TREACT) can be specified. Where this is not specified, the outlet temperature is used as equilibrium temperature. It is then however possible to specify a temperature difference (DTREAC) between equilibrium temperature and outlet temperature (TREACT=TOUT + DTREAC). The equilibrium pressure can also be specified (PREACT). If this is not specified the pressure at the outlet is used. If the pressure difference (DPREAC) is specified the equilibrium pressure becomes PREACT=POUT + DPREAC.

Symbols for connections and medium types

Symbol flue gas pipe :“Flue gas”
Symbol ash pipe : “Ash”

The symbols for the remaining pipes connected may be chosen freely.

The medium type of all pipes connected should be GASMIX. The only exception is the fuel pipe, which may also be of type FUEL.

Input parameters

The following apparatus data can be specified:

PIN, POUT, DELP, TIN and TOUT are standard

EEQCOD = code which indicates whether the energy balance is used to calculate a mass flow (EEQCOD = 1) or a temperature (EEQCOD = 2) (default = 2)

LAMBDA = air factor (actual oxidant-fuel ratio/stoichiometric oxidant-fuel ratio) (-) (default = UNKNOWN)

ESTOFR = estimate of the oxidant-fuel ratio for the first iteration where LAMBDA= UNKNOWN (kg/kg) (default = 15)

DELE = energy flow to the environment (kW) (default=0)

PREACT = pressure at which equilibrium is calculated (bar) (default = POUT + DPREAC)

DPREAC = difference between equilibrium pressure and outlet pressure (only to be specified if PREACT is not specified (bar) (default = 0)

TREACT = temperature at which the chemical equilibrium is calculated (°C) (default = TOUT + DTREAC)

DTREAC = difference between equilibrium temperature and outlet temperature (only to be specified if TREACT is not specified (°C) (default = 0)

ESTPOU = estimate for the outlet pressure if PREACT and POUT are not specified (bar) (default = 4)

PASH = pressure in ash pipe (bar) (default = PREACT-DPASH)

DPASH = difference between equilibrium pressure and pressure in ash pipe, only to be specified if PASH is not specified (bar) (default = 0)

TASH = temperature of the ash discharged (°C) (default = TREACT-DTASH)

DTASH = difference between equilibrium temperature and temperature in ash pipe, only to be specified if TASH is not specified (default = 0).

Number of equations for system matrix

As default (EEQCOD = 2), 1 mass equation is added to the system matrix. If either EEQCOD = 1 is specified, or EEQCOD = 2 together with parameter LAMBDA, an extra equation is added. If an ash pipe is connected, again an extra mass equation is added to the system matrix.

Summarizing:

Without ash pipe:

EEQCOD = 1: 1 mass equation + 1 energy equation

EEQCOD = 2: 1 mass equation

EEQCOD = 2 + LAMBDA specified: 2 mass equations

With ash pipe:

EEQCOD = 1: 2 mass equations + 1 energy equation

EEQCOD = 2: 2 mass equations

EEQCOD = 2 + LAMBDA specified: 3 mass equations

APPENDIX B

Simulation approaches & methodology

The process scheme may consist of a closed or an open system or of a combination of these systems. The calculation procedure is broken down into twelve steps. The calculation run for Cycle-Tempo is set out in Figure B.2

Step 1 Reading in

The order for reading in is:

a. Parameters which determine the size of the system, such as number of apparatuses, pipes, turbines etc.

b. Apparatus data. Data may be specified which may differ for each apparatus. The apparatus number and apparatus type are compulsory.

c. Topology of the system. It is made clear to the program how the pipes are linked between the apparatuses.

d. Medium data per pipe.

e. Reading in the optional data.

In each step the input data are where possible checked for accuracy. For each error which is discovered, an error message is given. The program stops in that case after the whole input phase has been completed.

Step 2 Creation of system matrix

The calculation starts with the creation of the system matrix for the mass flow calculation. A check is made that the number of equations corresponds with the number of pipes. If this is not the case, then an error message follows and the program stops.

Step 3 Calculating compositions

In this step the medium types and gas compositions in the pipes are determined. There are several apparatus routines for this, depending on the apparatus types used.

Step 4 Difference in compositions

If the main iteration has been carried out a minimum of twice *and* medium types occur in the system which consist of a mixture, then it is determined in which pipe the largest molar fraction change occurs in the succeeding main iterations. It is also determined how many pipes do not meet the break-off criterion. The break-off criterion is:

$$| C_j(i) - C_j(i-1) | < \in$$

The result of this test is always printed out in the "Text Output" and during the calculation process on the screen.

Step 5 Calculating p, T, h

The pressures, temperatures and enthalpies are calculated with the help of apparatus routines. The next order is followed:

1. Turbines (type 3) in order of increasing apparatus number
2. Condensers (type 4) in order of increasing apparatus number
3. Flashed heaters (type 5) in order of increasing apparatus number
4. Heat exchangers (EEQCOD=2, type 6) in order of increasing apparatus number
5. Heat exchangers (EEQCOD=1, type 12) in order of increasing apparatus number
6. Moisture separators (type 22) in order of increasing apparatus number
7. Other apparatus types in order of increasing apparatus number

If after such a passage not all properties are known, the apparatus routines are called again, but then in reversed order. This procedure is repeated until the number of known properties doesn't increase any more. Either the properties in all pipes are known, or not enough input data are specified by the user to calculate these properties.

Step 6 Solving system matrix

In the system matrix, the enthalpies calculated in step 5 are substituted in the relevant energy equations. The solving of this system using the Gauss elimination method gives the mass flows for the system.

Step 7 Difference in mass flows

After the main iteration has been carried out a minimum of twice, for each pipe the relative and absolute difference is determined in the mass flows for the previous main iteration. *For each pipe* a check is made as to whether it meets the break-off criterion:

$$\left|\frac{\phi_m(\text{i})-\phi_m(\text{i-1})}{\phi_m(\text{i})}\right| < \in \quad \underline{\text{or}} \quad \left|\phi_\text{m}(\text{i})-\phi_m(\text{i-1})\right| < 0.001$$

For each pipe the printout shows how many pipes do <u>not</u> meet the criterion and in which pipe the maximum relative and in which the maximum absolute difference occurs.

Step 8 Break-off criterion compositions/mass flows

The break-off criterion for the main iteration is: All the pipes must meet both the criterion for the compositions and the criterion for the mass flows.

If both conditions are met, the required accuracy is reached and the last mass flows calculated are regarded as the solution of the system. If one or both of these conditions is not met, then there is a return to step 3.

Step 9 Calculating compositions

In the solution of the mass flows the relevant compositions are calculated. These compositions are then regarded as the solution of the system. The result is printed out in the table “Composition of fluids”.

Step 10 Calculating p, T, h

With the solution for the mass flows and compositions once again all the unknown pressures, temperatures and enthalpies are calculated. All the pipe data are printed out in the table “Data for all pipes” with for each pipe:

- Medium type.
- Mass flow.
- Molar flow.
- Volume flow at inlet and outlet.
- Pressure at inlet and outlet.
- Temperature at inlet and outlet.

- Enthalpy at inlet and outlet.
- Entropy at inlet and outlet.
- Vapor fraction at inlet and outlet (if fluids are present for which 2-phase states are allowed).
- Exergy at inlet and outlet (if an exergy calculation is made).
- Mass fraction (if binary mixtures are present).

Step 11 Output

As a control for each apparatus the energy balance is calculated with:

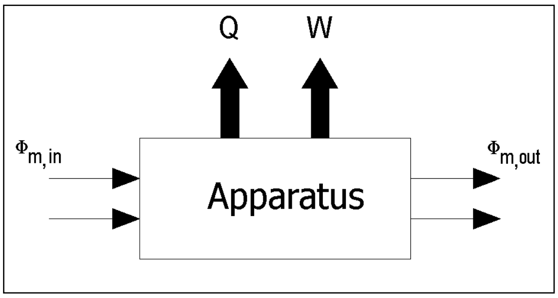


Figure B.1: Energy balance of an apparatus

$$\sum_{j=1}^{n} \phi_{m,in}(j)\, h_{in}(j) - \sum_{i=1}^{n} \phi_{m,out}(i)\, h_{out}(i) = Q + W$$

For apparatuses with streams exchanging heat the internal heat transfer is also calculated. The values are printed out in the table “Heat exchanging equipment” and give an idea of the accuracy of the solution.

Step 12 Exergy analysis

In this step, which is optional, an exergy analysis is given for each apparatus and for the whole system.

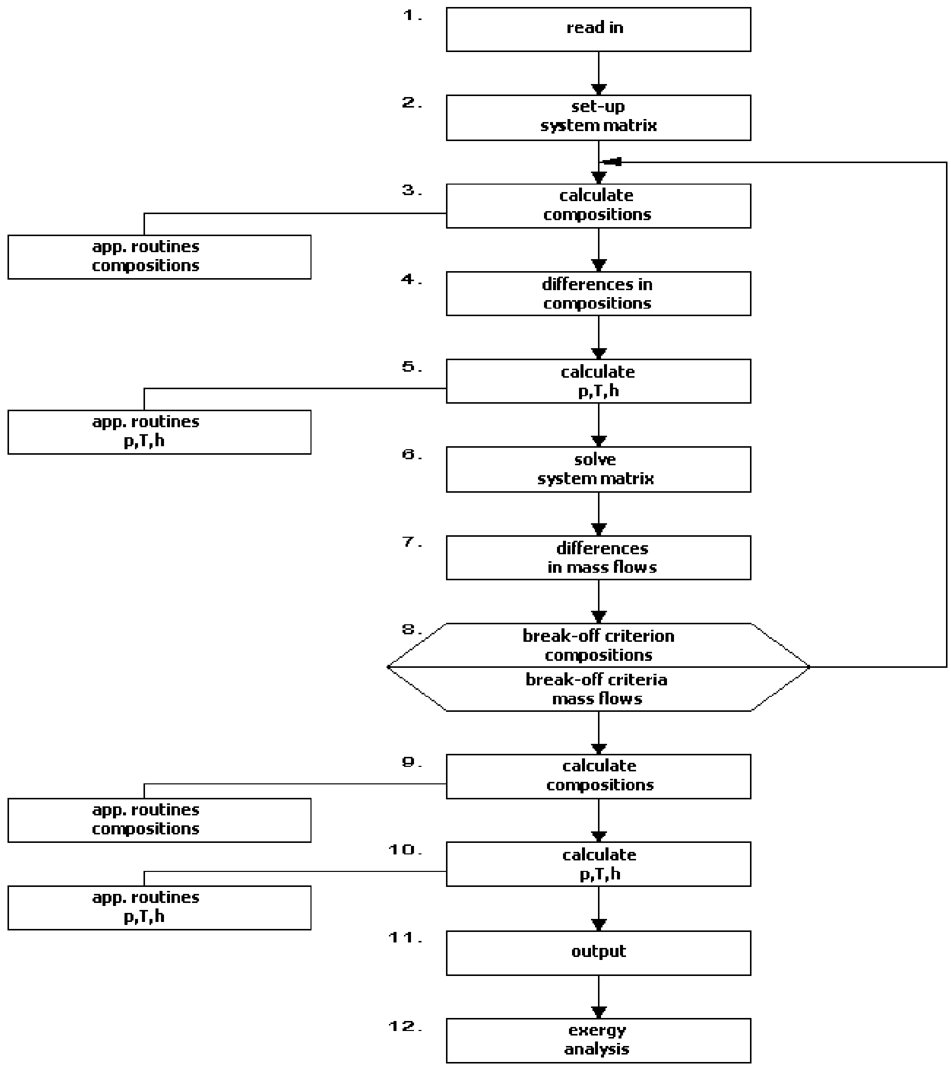


Figure B.2: Calculation run Cycle-Tempo [63].

Creating the system matrix

Mass flows are calculated from:

- mass balances of an apparatus
- energy balance of an apparatus

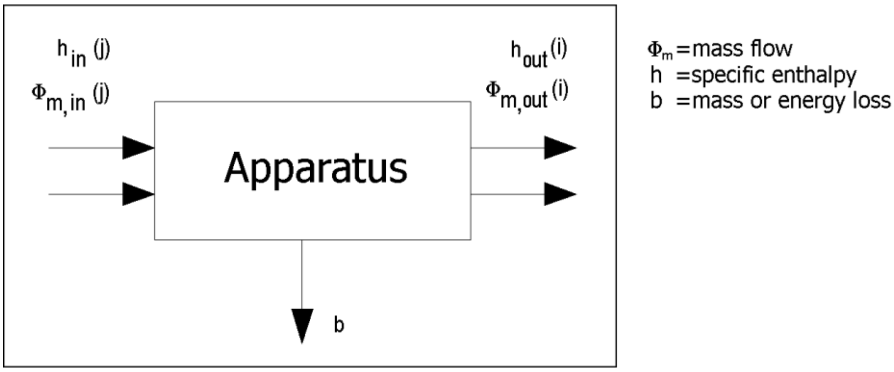


Figure B.3: Energy and mass balance of an apparatus

Mass balances are of the type:

$$\sum_{j=1}^{n_i} \phi_{m,in}(j) - \sum_{i=1}^{n_o} \phi_{m,out}(i) \quad = \quad b(k)$$

(k = number of equations)

Energy balances are of the type:

$$\sum_{j=1}^{n_i} \phi_{m,in}(j) \times h_{in}(j) - \sum_{i=1}^{n_o} \phi_{m,out}(i) \times h_{out}(j) \quad = \quad b(l)$$

(l = number of equations)

The mass balances can also be prepared from:

- atomic balance of an apparatus
- prescribed mass flows
- prescribed mass flow ratios

The equations drawn up (mass and energy balances) are written in matrix form:

$$A \, \underline{m} = \underline{b}$$

The solution to this system gives the mass flow for each pipe in the system. The calculation must however meet three conditions:

1.	**The matrix must be square, which means that the number of equations must be equal to the number of pipes in the system.**
2.	**The matrix must be independent.**
3.	**If there are coefficients in the matrix which are dependent on the mass flows, an iterative calculation is necessary. This iteration process must be converging.**

Closed processes

To obtain an independent system of equations for a closed cycle for each closed cycle 1 mass balance of an apparatus must be eliminated. The reason is that 1 mass balance for an apparatus can always be deduced from the other mass balances. This is explained by the example in Figure 2-1.

If we leave out the cooling water cycle, equations 1, 2, 3, 5 and 6 can also be written as:

Equation	1	$-m1 + m6$	$= 0$
Equation	2	$m1 - m2 - m7$	$= 0$
Equation	3	$m2 - m3$	$= 0$
Equation	5	$m4 - m5 + m7$	$= 0$
Equation	6	$m5 - m6$	$= 0$
		$m4 - m3$	$= 0$

The resulting equation is the same as the mass balance of pump number 4.

Thus, adding this mass balance would cause a dependent matrix. For the same reason the mass balance of sink number 7 is left out of the matrix. The program itself eliminates 1 mass balance per closed cycle.

The user is free to specify the energy equations with a right hand side. These are the so-called production functions. It is important to choose these equations such that they are not dependent on the mass balances.

Open processes

For an open process several possibilities are available for selecting mass balances. This is illustrated from an example, see Figure 5.12.

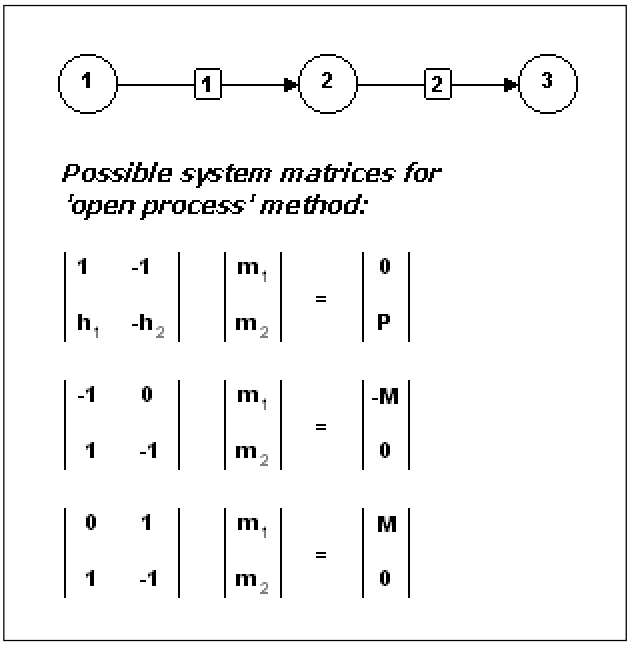


Figure B.4: Example 'open process' method

For an open process *no* mass balance of an apparatus is eliminated in the chain. All the mass balances are necessary in the system matrix so that the solution for the system will meet the boundary conditions for the apparatuses.
The following possibilities are available for preparing the system matrix (worked out for Figure 5.12 but this is to be extended to larger systems):

1. Specify the power for an apparatus in the chain and calculate the mass flows (1 mass balance and 1 energy balance).
2. Specify the incoming mass flow of the system and calculate the outgoing mass flow of the system (2 mass balances).
3. Specify the outgoing mass flow of the system and calculate the incoming mass flow of the system (2 mass balances).

Also for open processes one must select energy equations to be specified with a right-hand side such that these are independent of the mass balances. In this example possibility 1 alone gives an independent system if $h_1 \neq h_2$.

APPENDIX C

SIMULATION DATA

C.1 Simple GT without Fogging

Table C.1: Simple gas turbine cycle without fogging (R_P = 10)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
10	900	5	723.06	28.62	3.75	36.15	5.17	26.31
		10	701.80	28.17	3.85	35.82	5.30	26.86
		15	694.98	27.83	3.93	35.59	5.39	27.26
		20	683.53	27.49	4.00	35.37	5.48	27.66
		25	672.09	27.13	4.08	35.14	5.57	28.08
		30	660.66	26.75	4.16	34.91	5.66	28.51
		35	649.22	26.36	4.25	34.69	5.76	28.94
	1000	5	858.40	29.68	3.15	34.54	4.40	28.23
		10	841.68	29.32	3.23	34.24	4.49	28.73
		15	830.14	29.05	3.28	34.02	4.56	29.08
		20	818.61	28.76	3.34	33.81	4.62	29.44
		25	807.09	28.47	3.39	33.60	4.69	29.81
		30	795.56	28.21	3.45	33.40	4.75	30.18
		35	784.04	27.93	3.51	33.19	4.82	30.56
	1100	5	997.50	30.95	2.70	33.09	3.83	30.00
		10	980.66	30.03	2.76	32.80	3.90	30.45
		15	969.04	29.87	2.80	32.60	3.94	30.77
		20	957.42	29.66	2.84	32.41	3.99	31.10
		25	945.81	29.43	2.89	32.21	4.04	31.42
		30	934.20	29.20	2.93	32.02	4.09	31.76
		35	922.60	28.95	2.97	31.83	4.14	32.10
	1200	5	1139.79	30.82	2.38	31.75	3.39	31.66
		10	1123.44	30.60	2.40	31.50	3.44	32.06
		15	1111.72	30.42	2.44	31.31	3.48	32.35
		20	1100.01	30.24	2.47	31.13	3.51	32.64
		25	1088.31	30.06	2.50	30.95	3.55	32.94
		30	1076.60	29.87	2.54	30.77	3.59	33.24
		35	1064.91	29.67	2.57	30.59	3.63	33.55
	1300	5	1287.15	31.15	2.08	30.55	3.03	33.17
		10	1270.06	30.95	2.12	30.30	3.08	33.55
		15	1258.25	30.79	2.15	30.13	3.10	33.82
		20	1246.45	30.64	2.17	29.96	3.13	34.09
		25	1234.64	30.49	2.20	29.79	3.16	34.36
		30	1222.85	30.32	2.23	29.62	3.19	34.64
		35	1211.04	30.16	2.25	29.45	3.22	34.92
	1400	5	1437.19	31.34	1.88	29.43	2.75	34.61
		10	1420.59	31.18	1.89	29.21	2.78	34.95
		15	1408.68	31.04	1.91	29.04	2.80	35.20
		20	1396.78	30.91	1.93	28.88	2.83	35.45
		25	1384.87	30.77	1.96	28.72	2.85	35.70
		30	1372.97	30.63	1.98	28.56	2.88	35.95
		35	1361.08	30.48	2.00	28.40	2.90	36.21

Table C.2: Simple gas turbine cycle without fogging (R_P = 15)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
15	900	5	640.12	30.26	4.80	34.42	7.17	23.34
		10	621.35	29.57	4.97	34.10	7.40	23.97
		15	608.44	29.06	5.09	33.87	7.55	24.43
		20	595.53	28.53	5.21	33.65	7.72	24.89
		25	582.64	27.96	5.34	33.42	7.89	25.38
		30	569.75	27.37	5.48	33.20	8.07	25.88
		35	556.87	26.75	5.62	32.97	8.25	26.41
	1000	5	775.10	32.00	3.95	32.97	5.98	25.10
		10	756.21	31.46	4.07	32.67	6.13	25.66
		15	743.21	31.09	4.15	32.47	6.24	26.05
		20	730.22	30.69	4.24	32.26	6.35	26.45
		25	717.22	30.28	4.33	32.06	6.46	26.87
		30	704.25	29.85	4.42	31.85	6.58	27.30
		35	691.28	29.40	4.52	31.64	6.70	27.74
	1100	5	913.80	33.14	3.34	31.65	5.12	26.75
		10	894.79	32.73	3.43	31.37	5.23	27.24

		15	881.70	30.43	3.49	31.18	5.31	27.59
		20	868.61	32.10	3.56	30.99	5.39	27.95
		25	855.52	31.80	3.62	30.80	5.47	28.31
		30	842.45	31.46	3.69	30.61	5.55	28.69
		35	829.38	31.11	3.76	30.42	5.64	29.07
	1200	5	1055.59	33.89	2.91	30.43	4.47	28.30
		10	1037.14	33.58	2.95	30.18	4.55	28.73
		15	1023.94	33.34	3.00	30.00	4.61	29.04
		20	1010.75	33.10	3.05	29.82	4.67	29.37
		25	997.57	32.83	3.10	29.64	4.73	29.69
		30	984.39	32.56	3.15	29.47	4.79	30.03
		35	971.23	32.28	3.20	29.29	4.86	30.37
	1300	5	1202.60	34.46	2.53	29.32	3.96	29.72
		10	1183.32	`34.18	2.58	29.08	4.03	30.13
		15	1170.01	33.98	2.62	28.91	4.07	30.42
		20	1156.71	33.78	2.66	28.74	4.12	30.17
		25	1143.42	33.55	2.70	28.58	4.17	31.01
		30	1130.14	33.32	2.73	28.41	4.22	31.31
		35	1116.87	33.09	2.78	28.25	4.27	31.61
	1400	5	1352.09	34.81	2.26	28.29	3.56	31.09
		10	1333.37	34.59	2.28	28.07	3.61	31.45
		15	1319.96	34.42	2.31	27.91	3.65	31.71
		20	1306.56	34.24	2.35	27.75	3.68	31.98
		25	1293.16	34.05	2.38	27.59	3.72	32.25
		30	1279.77	33.86	2.41	27.44	3.76	32.53
		35	1266.38	33.66	2.44	27.29	3.80	32.81

Table C.3: Simple gas turbine cycle without fogging (R_P = 25)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
25	900	5	521.23	29.36	6.72	32.32	11.03	20.58
		10	499.42	28.05	7.05	32.00	11.52	21.38
		15	484.44	27.08	7.29	31.77	11.88	21.97
		20	469.47	26.05	7.55	31.54	12.26	22.60
		25	454.52	24.94	7.83	31.31	12.66	23.26
		30	439.58	23.76	8.12	31.07	13.09	23.96
		35	424.65	22.49	8.43	30.83	13.55	24.70
	1000	5	655.68	32.72	5.33	31.09	8.83	22.04
		10	633.73	31.81	5.54	30.80	9.14	22.71
		15	618.65	31.51	5.70	30.59	9.37	23.19
		20	603.58	30.45	5.86	30.39	9.60	23.70
		25	588.53	29.71	6.03	30.18	9.85	24.23
		30	573.48	28.93	6.21	29.98	10.10	24.78
		35	558.46	28.16	6.40	29.77	10.37	25.36
	1100	5	793.81	34.86	`4.39	29.93	7.35	23.46
		10	771.72	34.19	4.54	29.66	7.56	24.04
		15	756.54	33.70	4.65	29.48	7.71	24.45
		20	741.36	33.19	4.76	29.29	7.87	24.88
		25	726.21	32.65	4.88	29.10	8.04	25.33
		30	711.06	32.09	5.00	28.92	8.21	25.79
		35	695.93	31.50	5.12	28.73	8.38	26.27
	1200	5	934.86	36.27	3.75	28.85	6.28	24.84
		10	913.45	35.79	3.83	28.61	6.49	25.33
		15	898.16	35.41	3.91	28.44	6.54	25.70
		20	882.87	35.01	3.99	28.26	6.66	26.07
		25	867.60	34.60	4.07	28.09	6.77	26.46
		30	852.34	34.17	4.16	27.92	6.89	26.86
		35	837.10	33.71	4.25	27.75	7.02	27.27
	1300	5	1081.36	37.34	3.21	27.86	5.48	26.12
		10	1058.98	37.00	3.29	27.63	5.59	26.58
		15	1043.56	36.60	3.35	27.47	5.68	26.91
		20	1028.16	36.28	3.42	27.31	5.76	27.24
		25	1012.77	35.95	3.48	27.15	5.85	27.58
		30	993.35	35.73	3.56	26.72	5.96	28.03
		35	982.03	35.24	3.61	26.83	6.03	28.29
	1400	5	1230.06	38.02	2.83	26.93	4.85	27.37
		10	1208.35	37.69	2.88	26.72	4.94	27.77
		`15	1192.81	37.44	2.93	26.57	5.00	28.07
		20	1177.29	37.17	2.97	26.42	5.07	28.37
		25	1161.78	36.89	3.02	26.26	5.14	28.68
		30	1146.29	36.62	3.08	26.12	5.21	28.99
		35	113080	36.31	3.13	25.97	5.28	29.31

Table C.4: Simple gas turbine cycle without fogging (R_P = 30)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
30	900	5	474.54	27.81	7.69	31.57	13.04	19.90
		10	451.54	26.11	8.13	31.24	13.71	20.81
		15	435.76	24.84	8.46	31.01	14.22	21.48
		20	419.99	23.47	8.81	30.77	14.75	22.20
		25	404.24	21.99	9.19	30.53	15.33	22.97
		30	388.50	20.39	9.59	30.28	15.94	23.81
		35	372.77	18.65	10.02	30.03	16.61	24.70
	1000	5	608.76	32.17	5.98	30.43	10.23	21.20
		10	585.63	31.03	6.26	30.14	10.64	21.93
		15	569.74	30.21	6.46	29.93	10.94	22.47
		20	553.87	29.32	6.67	29.73	11.26	23.03
		25	538.01	28.39	6.89	29.52	11.59	23.63
		30	522.17	27.39	7.12	29.31	11.94	24.25
		35	506.35	26.33	7.37	29.10	12.30	24.91
	1100	5	746.67	34.89	4.87	29.34	8.40	22.51
		10	723.39	34.06	5.05	29.07	8.67	23.13
		15	707.40	33.47	5.19	28.89	8.87	23.58
		20	691.41	32.86	5.33	28.70	9.07	24.05
		25	675.44	32.19	5.47	28.51	9.29	24.54
		30	659.49	31.50	5.62	28.33	9.51	25.05
		35	643.56	30.76	5.78	28.14	9.74	25.58
	1200	5	887.44	36.65	4.12	28.31	7.11	23.81
		10	864.88	36.08	4.22	28.07	7.30	24.34
		15	848.86	35.62	4.31	27.90	7.44	24.73
		20	832.66	35.15	4.41	27.73	7.58	25.13
		25	816.59	34.65	4.52	27.56	7.73	25.55
		30	800.52	34.13	4.62	27.39	7.89	25.98
		35	784.47	33.59	4.73	27.21	8.05	26.42
	1300	5	1033.73	37.96	3.50	27.36	6.15	25.02
		10	1010.14	37.46	3.60	27.13	6.29	25.51
		15	993.91	37.10	3.67	26.97	6.40	25.86
		20	977.68	36.72	3.75	26.81	6.50	26.21
		25	961.48	36.34	3.82	26.65	6.61	26.58
		30	945.29	35.92	3.90	26.50	6.73	26.95
		35	929.12	35.50	3.98	26.34	6.84	27.34
	1400	5	1182.13	38.82	3.07	26.47	5.42	26.22
		10	1159.27	38.45	3.13	26.26	5.52	26.65
		15	1142.88	38.14	3.19	26.11	5.60	26.96
		20	1126.53	37.83	3.24	25.96	5.69	27.28
		25	1110.21	37.52	3.30	25.81	5.77	27.60
		30	1093.89	37.18	3.36	25.66	5.85	27.94
		35	110051.31	36.84	3.43	25.51	5.94	28.28

Table C.5: Simple gas turbine cycle without fogging (R_P = 35)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
35	900	5	433.18	25.71	8.71	30.92	15.16	19.48
		10	409.14	23.55	9.28	30.58	16.07	20.51
		15	392.65	21.91	9.71	30.34	16.75	21.29
		20	376.17	20.11	10.18	30.09	17.49	22.12
		25	359.72	18.18	10.68	29.84	18.28	23.03
		30	343.28	16.02	11.23	29.57	19.15	24.03
		35	326.86	13.65	11.83	29.29	20.10	25.11
	1000	5	567.21	31.23	6.64	29.87	11.65	20.61
		10	543.03	29.85	6.98	29.58	12.18	21.41
		15	526.43	28.82	7.23	29.37	12.57	22.01
		20	509.85	27.73	7.49	29.16	12.98	22.63
		25	493.29	26.56	7.77	28.95	13.41	23.30
		30	476.74	25.31	8.07	28.73	13.87	24.01
		35	460.22	23.96	8.39	28.51	14.37	24.77
	1100	5	704.92	34.58	5.33	28.84	9.43	21.81
		10	680.59	33.61	5.56	28.58	9.77	22.48
		15	663.88	32.90	5.72	28.39	10.02	22.97
		20	647.18	32.14	5.89	28.21	10.28	23.48
		25	630.50	31.35	6.07	28.02	10.55	24.01
		30	613.84	30.51	6.26	27.83	10.84	24.57
		35	597.20	29.61	6.45	27.64	11.14	25.16
	1200	5	845.44	36.72	4.47	27.86	7.91	23.03
		10	821.86	36.05	4.59	27.62	8.14	23.59
		15	805.03	35.52	4.71	27.45	8.32	24.01
		20	788.21	34.96	4.82	27.28	8.49	24.44
		25	771.42	34.37	4.95	27.11	8.68	24.89
		30	754.64	33.76	5.08	26.94	8.87	25.35

		35	737.87	33.12	5.21	26.77	9.07	25.84
	1300	5	991.54	38.30	3.77	26.95	6.79	24.18
		10	966.89	37.72	3.89	26.72	6.97	24.69
		15	949.94	37.31	3.98	26.56	7.09	25.06
		20	932.99	36.87	4.06	26.40	7.22	25.44
		25	916.08	36.41	4.16	26.25	7.35	25.83
		30	899.17	35.94	4.25	26.09	7.49	26.23
		35	882.28	35.45	4.35	25.93	7.63	26.64
	1400	5	1139.67	39.34	`3.30	26.08	5.95	25.33
		10	1115.76	38.90	3.36	25.88	6.08	25.78
		15	1098.68	38.56	3.43	25.73	6.17	26.10
		20	1081.60	38.22	3.50	25.58	6.27	26.44
		25	1064.54	37.84	3.57	25.43	6.37	26.78
		30	1047.52	37.47	3.64	25.29	6.47	27.14
		35	1030.50	37.07	3.71	25.14	6.58	27.50

Table C.6: Simple gas turbine cycle without fogging (R_P = 40)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
40	900	5	394.98	22.98	9.90	30.33	17.49	19.31
		10	370.94	20.39	10.53	29.99	18.64	20.44
		15	353.81	18.29	11.09	29.74	19.55	21.33
		20	336.70	15.96	11.70	29.47	20.54	22.31
		25	319.61	13.39	12.37	29.20	21.64	23.40
		30	302.55	10.52	13.12	28.90	22.85	24.59
		35	285.50	7.34	13.94	28.59	24.20	25.93
	1000	5	529.77	29.99	7.32	29.39	13.11	20.19
		10	504.66	28.33	7.73	29.09	13.78	21.08
		15	487.42	27.08	8.04	28.88	14.27	21.74
		20	470.20	25.74	8.36	28.66	14.79	22.44
		25	453.00	24.30	8.71	28.45	15.35	23.19
		30	435.83	22.73	9.09	28.22	15.95	24.00
		35	418.66	21.05	9.49	27.99	16.60	24.87
	1100	5	667.30	34.03	5.80	28.42	10.47	21.28
		10	642.03	32.89	6.06	28.15	10.89	22.00
		15	624.67	32.05	6.26	27.96	11.19	22.53
		20	607.33	31.17	6.46	27.77	11.51	23.08
		25	590.02	30.22	6.67	27.58	11.85	23.67
		30	572.73	`29.22	6.90	27.39	12.21	24.28
		35	555.45	28.14	7.14	27.20	12.58	24.94
	1200	5	807.59	36.59	4.81	27.47	8.70	22.42
		10	783.09	35.82	4.96	27.24	8.98	23.01
		15	765.62	35.20	5.09	27.07	9.18	23.46
		20	748.16	34.56	5.23	26.89	9.40	23.92
		25	730.73	33.87	5.38	26.72	9.62	24.40
		30	713.30	33.16	5.53	26.55	9.86	24.91
		35	695.91	32.40	5.69	26.38	10.10	25.43
	1300	5	953.53	38.45	4.04	26.60	7.42	23.51
		10	927.92	37.78	4.17	26.37	7.62	24.05
		15	910.31	37.31	4.27	26.21	7.77	24.44
		20	892.73	36.81	4.37	26.05	7.92	24.84
		25	875.17	36.29	4.48	25.89	8.08	25.25
		30	857.62	35.75	4.59	25.74	8.25	25.68
		35	840.10	35.18	4.70	25.58	8.42	26.12
	1400	5	1101.41	39.65	3.51	25.76	6.46	24.61
		10	1076.57	39.17	3.59	25.55	6.61	25.08
		15	1058.83	38.97	3.66	25.40	6.72	25.42
		20	1041.41	38.39	3.74	25.26	6.84	25.77
		25	1023.41	38.51	3.82	25.11	6.96	26.14
		30	1005.73	37.56	3.90	24.96	7.08	26.51
		35	988.07	37.14	3.98	24.82	7.20	26.90

B.2 ABC without Fogging

Table C.7: Simple gas turbine cycle without fogging (R_P = 10 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
10	900	5	723.06	31.42	3.74	2.61	36.08	5.11	3.04	1.50	11.61	4.89
		10	701.80	30.36	3.85	2.68	35.77	5.24	3.11	1.43	12.55	5.01
		15	694.98	29.60	3.92	2.74	35.55	5.32	3.17	1.38	13.23	5.09
		20	683.53	28.80	4.00	2.79	35.33	5.41	3.22	1.34	13.93	5.18
		25	672.09	27.97	4.08	2.84	35.10	5.51	3.28	1.30	14.66	5.26
		30	660.66	27.11	4.16	2.90	34.87	5.60	3.33	1.26	15.42	5.35
		35	649.22	26.20	4.24	2.95	34.94	5.70	3.39	1.22	16.21	5.44
	1000	5	858.40	34.39	3.14	2.20	34.48	4.35	2.57	1.61	11.10	6.15
		10	841.68	33.56	3.22	2.25	34.19	4.44	2.63	1.54	11.89	6.28
		15	830.14	32.96	3.28	2.29	33.99	4.50	2.66	1.49	12.46	6.36
		20	818.61	32.37	3.33	2.32	33.78	4.57	2.70	1.44	13.04	6.45
		25	807.09	31.72	3.39	2.36	33.58	4.63	2.74	1.40	13.64	6.54
		30	795.56	31.05	3.45	2.40	33.37	4.70	2.78	1.35	14.26	6.63
		35	784.04	30.37	3.50	2.44	33.15	4.77	2.82	1.31	14.90	6.72
	1100	5	997.50	36.46	2.70	1.89	33.04	3.79	2.22	1.73	10.85	7.31
		10	980.66	35.82	2.76	1.93	32.77	3.85	2.26	1.65	11.53	7.44
		15	969.04	35.33	2.80	1.95	32.58	3.90	2.29	1.60	12.01	7.53
		20	957.42	34.84	2.84	1.98	32.38	3.95	2.32	1.55	12.51	7.62
		25	945.81	34.34	2.88	2.01	32.19	4.00	2.35	1.50	13.02	7.71
		30	934.20	33.80	2.93	2.04	32.00	4.05	2.38	1.45	13.55	7.80
		35	922.60	33.26	2.97	2.07	31.80	4.10	2.41	1.41	14.09	7.90
	1200	5	1139.79	37.98	2.36	1.65	31.72	3.35	1.95	1.85	10.76	8.38
		10	1123.44	37.42	2.40	1.68	31.47	3.40	1.99	1.77	11.36	8.51
		15	1111.72	37.04	2.43	1.70	31.29	3.44	2.01	1.71	11.78	8.60
		20	1100.01	36.62	2.47	1.72	31.11	3.47	2.03	1.66	12.22	8.69
		25	1088.31	36.21	2.50	1.74	30.93	3.51	2.05	1.61	12.66	8.78
		30	1076.60	35.77	2.53	1.77	30.75	3.55	2.08	1.56	13.12	8.87
		35	1064.91	35.32	2.57	1.79	30.56	3.59	2.10	1.51	13.59	8.96
	1300	5	1287.15	`39.07	2.08	1.45	30.52	3.00	1.74	1.97	10.80	9.36
		10	1270.06	38.61	2.12	1.48	30.28	3.04	1.76	1.88	11.33	9.48
		15	1258.25	38.25	2.15	1.50	30.11	3.07	1.78	1.83	11.71	9.57
		20	1246.45	37.93	2.17	1.51	29.94	3.10	1.80	1.77	12.10	9.66
		25	1234.64	37.59	2.20	1.53	29.77	3.13	1.82	1.72	12.49	9.75
		30	1222.85	37.23	2.22	1.55	29.60	3.16	1.84	1.67	12.90	9.84
		35	1211.04	36.85	2.25	1.57	29.43	3.19	1.85	1.62	13.31	9.93
	1400	5	1437.19	39.89	1.86	1.30	29.41	2.72	1.56	2.08	10.93	10.24
		10	1420.59	39.49	1.89	1.32	29.19	2.75	1.59	1.99	11.42	10.37
		15	1408.68	39.18	1.91	1.33	29.03	2.78	1.60	1.94	11.76	10.46
		20	1396.78	38.91	1.93	1.35	28.87	2.80	1.61	1.88	12.11	10.55
		25	1384.87	38.60	1.95	1.36	28.71	2.82	1.63	1.83	12.46	10.63
		30	1372.97	38.29	1.98	1.38	28.55	2.85	1.64	1.77	12.83	10.72
		35	1361.08	37.96	2.00	1.39	28.39	2.87	1.66	1.72	13.20	10.81

Table C.8: Simple gas turbine cycle without fogging (R_P = 15 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
15	900	5	640.12	30.68	4.79	2.95	34.94	7.09	3.41	1.33	11.86	3.52
		10	621.35	29.25	4.96	3.06	34.04	7.32	3.52	1.28	12.95	3.63
		15	608.44	28.20	5.08	3.13	33.83	7.48	3.60	1.24	13.75	3.71
		20	595.53	27.09	5.21	3.21	33.61	7.64	3.68	1.21	14.59	3.78
		25	582.64	25.92	5.34	3.28	33.38	7.81	3.76	1.17	15.47	3.86
		30	569.75	26.93	5.53	3.40	32.50	8.07	3.89	1.16	16.54	3.98
		35	556.87	23.40	5.61	3.45	32.92	8.16	3.93	1.12	17.36	4.03
	1000	5	775.10	34.86	3.95	2.43	32.91	5.91	2.83	1.43	11.08	4.69
		10	756.21	33.69	4.06	2.51	32.63	6.07	2.91	1.36	11.97	4.81
		15	743.21	32.91	4.15	2.56	32.43	6.18	2.96	1.32	12.61	4.89
		20	730.22	32.09	4.24	2.61	32.23	6.29	3.01	1.28	13.28	4.97
		25	717.22	31.25	4.33	2.66	32.02	6.40	3.07	1.24	13.97	5.06
		30	704.25	30.35	4.42	2.72	31.82	6.52	3.13	1.20	14.70	5.15
		35	691.28	29.43	4.51	2.77	31.61	6.64	3.18	1.17	15.45	5.24
	1100	5	913.80	37.67	3.34	2.06	31.60	5.06	2.41	1.53	10.63	5.79
		10	894.79	36.74	3.43	2.11	31.34	5.17	2.47	1.46	11.38	5.91
		15	881.70	36.13	3.49	2.15	31.15	5.25	2.51	1.41	11.92	5.99
		20	868.61	35.50	3.55	2.19	30.96	5.33	2.54	1.36	12.47	6.08

		25	855.52	34.84	3.62	2.23	30.77	5.41	2.58	1.32	13.05	6.17
		30	842.45	34.15	3.69	2.27	30.58	5.50	2.62	1.28	13.65	6.26
		35	829.38	33.43	3.75	2.31	30.39	5.58	2.67	1.24	14.26	6.35
	1200	5	1055.59	39.68	2.88	1.78	30.39	4.42	2.10	1.63	10.41	6.80
		10	1037.14	38.89	2.95	1.82	30.15	4.51	2.14	1.56	11.06	6.93
		15	1023.94	38.40	3.00	1.85	29.97	4.57	2.17	1.51	11.52	7.01
		20	1010.75	37.91	3.05	1.88	29.80	4.63	2.20	1.46	11.99	7.10
		25	997.57	37.35	3.09	1.90	29.65	4.68	2.22	1.41	12.48	7.19
		30	984.39	36.83	3.15	1.93	29.44	4.75	2.26	1.37	12.99	7.28
		35	971.23	36.25	3.20	1.96	29.27	4.81	2.29	1.33	13.51	7.37
	1300	5	1202.60	41.04	2.52	1.56	29.29	3.92	1.85	1.74	10.33	7.74
		10	1183.32	40.47	2.58	1.59	29.06	3.99	1.88	1.66	10.91	7.86
		15	1170.01	40.04	2.62	1.61	28.89	4.03	1.90	1.61	11.31	7.95
		20	1156.71	39.66	2.65	1.63	28.73	4.08	1.93	1.56	11.73	8.04
		25	1143.42	39.22	2.69	1.66	28.56	4.13	1.95	1.51	12.16	8.13
		30	1130.14	38.76	2.73	1.68	28.40	4.18	1.97	1.46	12.60	8.22
		35	1116.87	38.29	2.77	1.70	28.23	4.22	2.00	1.42	13.05	8.31
	1400	5	1352.09	42.12	2.24	1.38	28.27	3.52	1.65	1.84	10.38	8.60
		10	1333.37	41.64	2.28	1.41	28.05	3.58	1.68	1.76	10.89	8.72
		15	1319.96	41.31	2.31	1.43	27.89	3.61	1.70	1.71	11.25	8.81
		20	1306.56	40.94	2.34	1.44	27.74	3.65	1.71	1.66	11.62	8.89
		25	1293.16	40.58	2.38	1.46	27.58	3.69	1.73	1.61	12.00	8.98
		30	1279.77	4018	2.41	1.48	27.42	3.72	1.75	1.56	12.39	9.07
		35	1266.38	39.79	2.44	1.50	27.27	3.76	1.77	1.51	12.79	9.16

Table C.9: Simple gas turbine cycle without fogging (R_P = 25 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E^{top}_{d,comp}$ (%)	$E^{bot}_{d,comp}$ (%)	$E_{d,comb}$ (%)	$E^{top}_{d,turb}$ (%)	E^{bot}_{dturb} (%)	$E_{d,reg}$ (%)	$E^{top}_{d,ex}$ (%)	$E^{bot}_{d,ex}$ (%)
25	900	5	521.23	24.56	6.76	3.63	32.36	8.73	4.19	1.61	13.98	4.24
		10	499.42	22.11	7.03	3.61	32.07	9.12	4.38	1.56	15.49	4.43
		15	484.44	20.28	7.28	3.94	31.85	9.41	4.52	1.53	16.63	4.56
		20	469.47	18.32	7.54	4.07	31.64	9.71	4.67	1.51	17.84	4.70
		25	454.52	16.24	7.82	4.22	31.41	10.03	4.83	1.48	19.13	4.85
		30	439.58	13.99	8.11	4.37	31.17	10.36	4.99	1.46	20.52	5.01
		35	424.65	11.63	8.42	4.53	30.93	10.72	5.16	1.44	22.01	5.18
	1000	5	655.68	30.66	5.32	2.88	31.12	7.00	3.35	1.65	12.55	5.46
		10	633.73	28.93	5.53	3.00	30.85	7.25	3.47	1.59	13.70	5.65
		15	618.65	27.68	5.69	3.08	30.66	7.43	3.56	1.55	14.55	5.78
		20	603.58	26.37	5.86	3.16	30.46	7.62	3.65	1.52	15.44	5.92
		25	588.53	24.96	6.03	3.25	30.26	7.81	3.75	1.48	16.39	6.07
		30	573.48	23.48	6.20	3.34	30.06	8.02	3.84	1.45	17.38	6.22
		35	558.46	21.91	6.39	3.44	29.85	8.23	3.95	1.42	18.44	6.38
	1100	5	793.81	34.63	4.38	2.38	29.96	5.84	2.78	1.72	11.72	6.57
		10	771.72	33.36	4.54	2.46	29.71	6.01	2.87	1.65	12.65	6.76
		15	756.54	32.43	4.64	2.51	29.54	6.13	2.93	1.61	13.32	6.89
		20	741.36	31.43	4.76	2.57	29.35	6.26	2.99	1.57	14.03	7.03
		25	726.21	30.41	4.87	2.63	29.17	6.39	3.05	1.53	14.77	7.17
		30	711.06	29.35	4.99	2.69	28.98	6.53	3.12	1.49	15.54	7.32
		35	695.93	28.22	5.12	2.75	28.79	6.66	3.18	1.45	16.35	7.47
	1200	5	934.86	37.38	3.71	2.01	28.89	5.00	2.37	1.80	11.24	7.59
		10	913.45	36.37	3.82	2.07	28.65	5.13	2.43	1.73	12.02	7.77
		15	898.16	35.66	3.90	2.11	28.49	5.22	2.47	1.68	12.58	7.90
		20	882.87	34.88	3.98	2.15	28.32	5.31	2.52	1.64	13.17	8.04
		25	867.60	34.10	4.07	2.20	28.15	5.40	2.56	1.59	13.77	8.17
		30	852.34	33.26	4.16	2.24	17.98	5.50	2.61	1.55	14.41	8.31
		35	837.10	32.39	4.24	2.28	27.80	5.59	2.66	1.51	15.06	8.45
	1300	5	1081.36	39.34	3.20	1.74	27.89	4.37	2.06	1.89	10.99	8.52
		10	1058.98	38.52	3.29	1.78	27.67	4.47	2.11	1.81	11.67	8.69
		15	1043.56	37.93	3.35	1.81	27.51	4.53	2.14	1.76	12.15	8.82
		20	1028.16	37.30	3.41	1.84	27.35	4.60	2.17	1.71	12.65	8.95
		25	1012.77	36.67	3.48	1.88	27.19	4.67	2.21	1.67	13.16	9.08
		30	993.35	36.00	3.54	1.91	27.03	4.74	2.24	1.62	13.69	9.21
		35	982.03	35.32	3.61	1.94	26.87	4.81	2.28	1.58	14.24	9.35
	1400	5	1230.06	40.78	2.81	1.52	26.96	3.88	1.82	1.98	10.91	9.36
		10	1208.35	40.07	2.87	1.56	26.75	3.95	1.85	1.90	11.50	9.53
		15	1192.81	39.58	2.92	1.58	26.51	4.01	1.88	1.85	11.92	9.65
		20	1177.29	39.07	2.97	1.61	26.46	4.06	1.91	1.80	12.36	9.78
		25	1161.78	38.54	3.02	1.63	26.31	4.11	1.93	1.75	12.81	9.90
		30	1146.29	38.00	3.07	1.66	26.16	4.17	1.96	1.70	13.27	10.03
		35	1130.80	37.43	3.13	1.68	26.01	4.22	1.98	1.65	13.74	10.16

Table C.10: Simple gas turbine cycle without fogging (R_P = 30 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E^{top}_{d,comp}$ (%)	$E^{bot}_{d,comp}$ (%)	$E_{d,comb}$ (%)	$E^{top}_{d,turb}$ (%)	E^{bot}_{dturb} (%)	$E_{d,reg}$ (%)	$E^{top}_{d,ex}$ (%)	$E^{bot}_{d,ex}$ (%)
30		5	474.54	20.99	7.67	3.99	31.65	9.57	4.61	1.76	15.12	4.64
		10	451.54	17.90	8.11	4.21	31.36	10.08	4.85	1.72	16.89	4.88
		15	435.76	15.58	8.44	4.38	31.14	10.45	5.03	1.70	18.23	5.05
	900	20	419.99	13.10	8.79	4.56	30.92	10.84	5.22	1.68	19.67	5.23
		25	404.24	10.37	9.17	4.75	30.69	11.27	5.43	1.66	21.23	5.43
		30	388.50	7.45	9.57	4.95	30.44	11.72	5.65	1.65	22.93	5.64
		35	372.77	4.29	10.00	5.16	30.19	12.20	5.88	1.64	24.77	5.87
		5	608.76	28.36	5.97	3.11	30.50	7.54	3.61	1.77	13.30	5.86
		10	585.63	26.28	6.25	3.24	30.23	7.84	3.76	1.71	14.60	6.09
		15	569.74	24.74	6.45	3.34	30.04	8.07	3.87	1.68	15.56	6.26
	1000	20	553.87	23.11	6.66	3.45	29.84	8.30	3.98	1.64	16.58	6.43
		25	538.01	21.39	6.88	3.56	29.64	8.54	4.10	1.61	17.67	6.61
		30	522.17	19.55	7.11	3.67	29.43	8.80	4.23	1.58	18.83	6.81
		35	506.35	17.60	7.35	3.80	29.22	9.07	4.36	1.56	20.06	7.01
		5	746.67	33.01	4.86	2.53	29.40	6.20	2.96	1.82	12.25	6.97
		10	723.39	31.49	5.05	2.62	29.15	6.41	3.06	1.75	13.28	7.19
		15	707.40	30.38	5.18	2.69	28.97	6.56	3.13	1.71	14.03	7.35
	1100	20	691.41	29.22	5.32	2.76	28.79	6.71	3.20	1.67	14.18	7.52
		25	675.44	27.98	5.47	2.83	28.61	6.87	3.28	1.63	15.64	7.69
		30	659.49	26.69	5.62	2.90	28.42	7.03	3.36	1.59	16.51	7.86
		35	643.56	25.32	5.78	2.98	28.23	7.20	3.44	1.56	17.43	8.05
		5	887.44	36.16	4.08	2.12	28.37	5.27	2.50	1.89	11.64	7.97
		10	864.88	35.00	4.21	2.19	28.14	5.41	2.57	1.81	12.49	8.19
		15	848.86	34.13	4.31	2.24	27.97	5.52	2.62	1.77	13.10	8.34
	1200	20	832.66	33.24	4.41	2.28	27.81	5.62	2.67	1.72	13.74	8.50
		25	816.59	32.32	4.51	2.33	27.64	5.73	2.73	1.68	14.41	8.66
		30	800.52	31.34	4.62	2.39	27.47	5.85	2.78	1.64	15.10	8.82
		35	784.47	30.31	4.73	2.44	27.29	5.97	2.84	1.60	15.83	8.99
		5	1033.73	38.39	3.49	1.82	27.41	4.57	2.16	1.96	11.31	8.89
		10	1010.14	37.44	3.60	1.87	27.19	4.68	2.21	1.89	12.03	9.09
		15	993.91	36.76	3.67	1.90	27.04	4.76	2.25	1.84	12.55	9.24
	1300	20	977.68	36.05	3.75	1.94	26.88	4.84	2.29	1.79	13.09	9.39
		25	961.48	35.32	3.82	1.98	26.72	4.92	2.33	1.74	13.64	9.54
		30	945.29	34.55	3.90	2.02	26.57	5.00	2.37	1.70	14.22	9.70
		35	929.12	33.74	3.98	2.06	26.41	5.09	2.41	1.65	14.82	9.85
		5	1182.13	40.00	3.05	1.58	26.52	4.03	1.89	2.05	11.16	9.72
		10	1159.27	39.20	3.13	1.62	26.31	4.12	1.93	1.97	11.79	9.92
		15	1142.88	38.65	3.18	1.65	26.16	4.18	1.96	1.91	12.24	10.05
	1400	20	1126.53	38.07	3.24	1.68	26.02	4.24	1.99	1.86	1.271	10.20
		25	1110.21	37.47	3.30	1.71	25.87	4.30	2.02	1.81	13.18	10.34
		30	1093.89	36.79	3.36	1.74	25.72	4.36	2.05	1.77	13.68	10.49
		35	1051.31	36.17	3.42	1.77	25.57	4.43	2.08	1.72	14.19	10.64

Table C.11: Simple gas turbine cycle without fogging (R_P = 35 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E^{top}_{d,comp}$ (%)	$E^{bot}_{d,comp}$ (%)	$E_{d,comb}$ (%)	$E^{top}_{d,turb}$ (%)	E^{bot}_{dturb} (%)	$E_{d,reg}$ (%)	$E^{top}_{d,ex}$ (%)	$E^{bot}_{d,ex}$ (%)
35		5	433.18	17.05	8.68	4.37	31.04	10.48	5.05	1.92	16.34	5.06
		10	409.14	15.22	9.26	4.65	30.75	11.11	5.35	1.89	18.41	5.36
		15	392.65	10.31	9.69	4.86	30.53	11.59	5.59	1.87	19.98	5.58
	900	20	376.17	7.14	10.16	5.09	30.29	12.10	5.83	1.86	21.71	5.82
		25	359.72	3.67	10.66	5.33	30.05	12.65	6.10	1.86	23.60	6.08
		30	343.28	0.13	11.21	5.60	29.79	13.25	6.39	1.86	25.67	6.36
		35	326.86	<<<1	11.80	5.89	29.52	13.90	6.71	1.86	27.95	6.66
		5	567.21	25.89	6.63	3.34	29.97	8.08	3.88	1.89	14.07	6.27
		10	543.03	23.40	6.97	3.50	29.70	8.45	4.06	1.84	15.53	6.55
		15	526.43	21.55	7.22	3.62	29.51	8.72	4.19	1.81	16.62	6.75
	1000	20	509.85	19.59	7.48	3.75	29.31	9.01	4.33	1.78	17.79	6.96
		25	493.29	17.47	7.76	3.88	29.11	9.31	4.47	1.75	19.04	7.19
		30	476.74	15.23	8.06	4.03	28.89	9.63	4.63	1.73	20.38	7.43
		35	460.22	12.80	8.38	4.18	28.67	9.97	4.80	1.71	21.81	7.68
		5	704.92	31.30	5.32	2.68	28.92	6.57	3.14	1.91	12.79	7.36
		10	680.59	29.54	5.55	2.79	28.68	6.81	3.25	1.85	13.91	7.62
		15	663.88	28.24	5.71	2.87	28.50	6.98	3.34	1.81	14.74	7.81
	1100	20	647.18	26.87	5.88	2.95	28.32	7.16	3.43	1.77	15.61	8.01
		25	630.50	25.41	6.06	3.03	28.14	7.35	3.52	1.74	16.54	8.21
		30	613.84	23.87	6.25	3.12	27.95	7.55	3.61	1.70	17.51	8.42
		35	597.20	22.24	6.44	3.21	17.76	7.76	3.71	1.67	18.55	8.65
		5	845.44	34.90	4.42	2.23	27.93	5.52	2.62	1.97	12.04	8.35
	1200	10	821.86	33.56	4.59	2.30	27.71	5.69	2.71	1.90	12.95	8.60
		15	805.03	32.58	4.70	2.36	27.54	5.81	2.77	1.85	13.62	8.77

		20	788.21	31.55	4.82	2.41	27.38	5.94	2.83	1.81	14.31	8.96
		25	771.42	30.46	4.94	2.47	27.21	6.07	2.89	1.76	15.04	9.14
		30	754.64	29.33	5.07	2.53	27.04	6.20	2.95	1.72	15.81	9.34
		35	737.87	28.15	5.20	2.60	26.87	6.34	3.02	1.69	16.61	9.54
	1300	5	991.54	37.41	3.77	1.90	27.01	4.76	2.25	2.03	11.61	9.25
		10	966.89	36.34	3.89	1.95	26.79	4.89	2.31	1.96	12.38	9.48
		15	949.94	35.57	3.97	1.99	26.64	4.98	2.35	1.91	12.94	9.65
		20	932.99	34.75	4.06	2.03	26.49	5.07	2.40	1.86	13.52	9.82
		25	916.08	33.90	4.15	2.08	26.33	5.16	2.44	1.82	14.12	9.99
		30	899.17	33.04	4.25	2.12	26.17	5.25	2.49	1.77	14.74	10.17
		35	882.28	32.11	4.34	2.17	16.02	5.35	2.54	1.73	15.39	10.35
	1400	5	1139.67	39.22	3.27	1.64	26.14	4.18	1.97	2.11	11.40	10.06
		10	1115.76	38.34	3.36	1.69	25.94	4.28	2.01	2.03	12.07	10.28
		15	1098.68	37.70	3.43	1.72	25.80	4.34	2.04	1.98	12.55	10.44
		20	1081.60	37.04	3.49	1.75	25.695	4.41	2.08	1.93	13.04	10.60
		25	1064.54	36.36	3.56	1.78	25.51	4.48	2.11	1.88	13.55	10.76
		30	1047.52	35.65	3.63	1.82	25.36	4.56	2.15	1.83	14.08	10.93
		35	1030.50	34.91	3.71	1.85	25.21	4.63	2.18	1.79	14.63	11.10

Table C.12: Simple gas turbine cycle without fogging (R_P = 40 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E^{top}_{d,comp}$ (%)	$E^{bot}_{d,comp}$ (%)	$E_{d,comb}$ (%)	$E^{top}_{d,turb}$ (%)	E^{bot}_{dturb} (%)	$E_{d,reg}$ (%)	$E^{top}_{d,ex}$ (%)	$E^{bot}_{d,ex}$ (%)
40	900	5	394.98	12.71	9.77	4.78	30.50	11.45	5.52	2.09	17.66	5.52
		10	370.94	7.96	10.50	5.13	30.20	12.25	5.91	2.08	20.08	5.89
		15	353.81	4.34	11.06	5.40	29.97	12.85	6.20	2.07	21.94	6.17
		20	336.70	0.34	11.67	5.69	29.72	13.50	6.52	2.07	24.01	6.48
		25	319.61		12.35	6.01	29.46	14.22	6.87	2.08	26.30	6.81
		30	302.55		13.08	6.36	29.19	15.02	7.26	2.10	28.84	7.18
		35	285.50		13.90	6.74	28.88	15.89	7.68	2.12	31.70	7.59
	1000	5	529.77	23.24	7.30	3.57	29.51	8.65	4.15	2.01	14.87	6.69
		10	504.66	20.33	7.71	3.77	29.24	9.09	4.37	1.97	16.51	7.02
		15	487.42	18.13	8.02	3.91	29.05	9.42	4.53	1.94	17.74	7.27
		20	470.20	15.75	8.35	4.07	28.85	9.76	4.70	1.92	19.07	7.53
		25	453.00	13.21	8.70	4.23	28.64	10.13	4.88	1.90	20.50	7.81
		30	435.83	10.47	9.07	4.41	28.42	10.53	5.07	1.88	22.05	8.10
		35	418.66	7.50	9.47	4.60	28.19	10.95	5.27	1.87	23.73	8.42
	1100	5	667.30	29.53	5.78	2.83	28.51	6.93	3.31	2.01	13.33	7.76
		10	642.03	27.47	6.05	2.96	28.27	7.21	3.45	1.95	14.56	8.06
		15	624.67	25.97	6.25	3.05	28.10	7.42	3.55	1.91	15.47	8.28
		20	607.33	24.39	6.45	3.14	27.92	7.63	3.65	1.88	16.44	8.51
		25	590.02	22.68	6.67	3.24	27.73	7.85	3.76	1.84	17.46	8.75
		30	572.73	20.88	6.89	3.35	27.54	8.09	3.88	1.81	18.55	9.01
		35	555.45	18.96	7.13	3.46	27.35	8.33	4.00	1.79	19.71	9.27
	1200	5	807.59	33.62	4.76	2.33	27.56	5.78	2.75	2.05	12.43	8.72
		10	783.09	32.09	4.95	2.42	27.34	5.97	2.84	1.98	13.42	9.00
		15	765.62	30.96	5.09	2.48	27.17	6.11	2.91	1.93	14.13	9.21
		20	748.16	29.80	5.23	2.55	27.01	6.25	2.98	1.89	14.89	9.42
		25	730.73	28.56	5.37	2.61	26.84	6.40	3.05	1.85	15.68	9.63
		30	713.30	27.26	5.52	2.68	26.67	6.56	3.13	1.81	16.52	9.86
		35	695.91	25.88	5.68	2.75	26.50	6.72	3.20	1.78	17.40	10.09
	1300	5	953.53	36.42	4.03	1.97	26.67	4.95	2.34	2.10	11.91	9.60
		10	927.92	35.21	4.17	2.04	26.45	5.09	2.41	2.03	12.73	9.86
		15	910.31	34.36	4.27	2.08	26.30	5.19	2.46	1.98	13.33	10.05
		20	892.73	33.43	4.37	2.13	26.15	5.29	2.51	1.93	13.95	10.24
		25	875.17	32.47	4.47	2.18	25.99	5.40	2.56	1.89	14.59	10.44
		30	857.62	31.50	4.58	2.23	25.84	5.51	2.61	1.85	15.26	10.64
		35	840.10	30.44	4.69	2.28	25.68	5.62	2.67	1.80	15.97	10.85
	1400	5	1101.41	38.43	3.48	1.70	25.83	4.33	2.03	2.17	11.64	10.40
		10	1076.57	39.45	3.58	1.75	25.63	4.43	2.09	2.09	12.34	10.64
		15	1058.83	36.75	3.66	1.79	25.48	4.51	2.12	2.04	12.85	10.82
		20	1041.41	36.01	3.74	1.82	25.34	4.58	2.16	1.99	13.37	10.99
		25	1023.41	35.24	3.82	1.86	25.20	4.66	2.20	1.94	13.92	11.18
		30	1005.73	34.45	3.90	1.89	25.05	4.74	2.24	1.90	14.48	11.36
		35	988.07	33.62	3.98	1.93	24.90	4.83	2.28	1.85	15.07	11.56

B.3 Simple Gas Turbine Cycle with Fogging

Table C.13: Simple gas turbine cycle with fogging (R_P = 10)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
10	900	5	718.76	28.39	3.77	36.30	5.20	26.35
		10	708.34	28.08	3.84	36.01	5.28	26.78
		15	698.48	27.75	3.91	35.73	5.37	27.23
		20	688.87	27.43	3.99	35.43	5.45	27.70
		25	679.88	27.08	4.06	35.13	5.53	28.20
		30	671.57	26.70	4.13	34.81	5.62	28.74
		35	664.14	26.31	4.20	34.47	5.69	29.32
	1000	5	853.81	29.48	3.17	34.67	4.42	28.26
		10	843.54	29.24	3.22	34.40	4.48	28.65
		15	833.89	28.99	3.27	34.14	4.54	29.06
		20	824.57	28.73	3.32	33.86	4.60	29.49
		25	815.97	28.45	3.37	33.58	4.66	29.94
		30	808.17	28.15	3.43	33.28	4.71	30.42
		35	801.44	27.84	3.47	32.97	4.77	30.94
	1100	5	992.61	30.21	2.72	33.20	3.84	30.02
		10	982.48	30.02	2.76	32.95	3.89	30.39
		15	973.06	29.80	2.79	32.70	3.93	30.76
		20	964.03	29.60	2.83	32.44	3.98	31.15
		25	955.82	29.37	2.87	32.18	4.02	31.56
		30	948.57	29.12	2.91	31.90	4.06	32.00
		35	942.57	28.86	2.95	31.61	4.09	32.48
	1200	5	1135.18	30.70	2.37	31.86	3.40	31.66
		10	1125.21	30.55	2.40	31.63	3.43	31.99
		15	1116.03	30.36	2.43	31.39	3.47	32.34
		20	1107.31	30.18	2.46	31.15	3.50	32.70
		25	1099.52	29.98	2.49	30.90	3.53	33.08
		30	1092.83	29.79	2.52	30.65	3.56	33.49
		35	1087.59	29.56	2.55	30.37	3.59	33.93
	1300	5	1281.59	31.03	2.09	30.64	3.04	33.18
		10	1271.79	30.90	2.12	30.42	3.07	33.49
		15	1262.84	30.74	2.14	30.20	3.10	33.81
		20	1254.45	30.58	2.17	29.97	3.12	34.15
		25	1247.09	30.42	2.19	29.74	3.15	34.51
		30	124099	30.24	2.21	29.50	3.17	34.89
		35	1236.56	30.04	2.23	29.24	3.19	35.30
	1400	5	1431.91	31.24	1.87	29.52	2.76	34.60
		10	1422.27	31.13	1.89	29.31	2.78	34.89
		15	1413.57	31.00	1.91	29.10	2.80	35.20
		20	1405.53	30.86	1.93	28.89	2.82	35.51
		25	1398.62	30.70	1.95	28.67	2.84	35.85
		30	1393.13	30.54	1.96	28.44	2.86	36.20
		35	1389.52	30.36	1.98	28.19	2.87	36.59

Table C.14: Simple gas turbine cycle with fogging (R_P = 15)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
15	900	5	635.22	29.97	4.83	34.61	7.22	23.41
		10	623.29	29.46	4.95	34.32	7.37	23.89
		15	611.89	28.98	5.07	34.04	7.52	24.39
		20	60074	28.46	5.19	33.74	7.68	24.93
		25	590.18	27.92	5.31	33.44	7.83	25.50
		30	580.26	27.36	5.43	33.12	7.98	26.11
		35	571.17	26.77	5.55	32.78	8.13	26.7
	1000	5	769.90	31.73	3.98	33.13	6.01	25.15
		10	758.10	31.38	4.06	32.86	6.11	25.58
		15	746.84	31.02	4.14	32.59	6.22	26.03
		20	736.04	30.63	4.22	32.32	6.32	26.50
		25	725.85	30.23	4.31	32.04	6.42	27.00
		30	716.45	29.81	4.39	31.75	6.52	27.54
		35	708.06	29.36	4.47	31.44	6.61	28.12
	1100	5	908.29	32.93	3.36	31.78	5.14	26.78
		10	896.64	32.65	3.42	31.53	5.21	27.17
		15	885.67	32.36	3.48	31.29	5.29	27.58
		20	875.08	32.06	3.54	31.03	5.36	28.00
		25	865.29	31.74	3.60	30.77	5.43	28.45
		30	856.42	31.40	3.66	30.50	5.50	28.93
		35	848.76	31.05	3.72	30.21	5.56	29.46

	5	1050.44	33.74	2.90	30.55	4.49	28.31	
	10	1038.94	33.52	2.95	30.32	4.54	28.67	
	15	1028.19	33.28	2.99	30.09	4.60	29.04	
1200	20	1017.92	33.04	3.04	29.85	4.65	29.43	
	25	1008.53	32.77	3.08	29.61	4.70	29.84	
	30	1000.22	32.49	3.13	29.35	4.75	30.28	
	35	993.32	32.19	3.17	29.08	4.80	30.76	
	5	1196.41	34.31	2.54	29.43	3.98	29.74	
	10	1185.06	34.12	2.58	29.21	4.02	30.07	
	15	1174.55	33.92	2.61	28.99	4.06	30.42	
1300	20	1164.59	33.70	2.65	28.76	4.10	30.78	
	25	1155.63	33.48	2.68	28.54	4.14	31.16	
	30	1147.91	33.25	2.72	28.30	4.18	31.56	
	35	1141.80	32.99	2.75	28.04	4.21	32.00	
	5	1346.26	34.69	2.25	28.39	3.57	31.09	
	10	1335.06	34.54	2.28	28.18	3.60	31.40	
	15	1324.81	34.36	2.31	27.98	3.64	31.72	
1400	20	1315.17	34.17	2.34	27.76	3.67	32.05	
	25	1307.04	33.97	2.36	27.57	3.70	32.40	
	30	1299.54	33.77	2.39	27.32	3.73	32.79	
	35	1294.26	33.55	2.42	27.08	3.75	33.20	

Table C.15: Simple gas turbine cycle with fogging (R_P = 25)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
25		5	515.59	28.79	6.79	32.58	11.14	20.69
		10	501.38	27.93	7.02	32.29	11.47	21.29
		15	487.83	27.01	7.26	32.00	11.82	21.93
	900	20	474.49	26.04	7.50	31.68	12.17	22.61
		25	461.73	24.99	7.76	31.37	12.53	23.34
		30	449.55	23.90	8.02	31.04	12.90	24.13
		35	438.16	22.76	8.28	30.68	13.27	25.01
		5	649.60	32.29	5.38	31.30	8.90	22.12
		10	635.65	31.70	5.52	31.03	9.11	22.63
		15	622.28	31.06	5.68	30.77	9.32	23.17
	1000	20	609.22	30.38	5.83	30.48	9.54	23.74
		25	596.82	29.71	5.99	30.20	9.76	24.34
		30	585.16	28.98	6.14	29.90	9.98	24.99
		35	574.45	28.22	6.30	29.58	10.19	25.71
		5	787.41	34.54	4.43	30.11	7.40	23.52
		10	773.59	34.10	4.53	29.86	7.54	23.97
		15	760.45	33.62	4.63	29.62	7.68	24.44
	1100	20	747.66	33.14	4.74	29.36	7.83	24.93
		25	735.65	32.63	4.84	29.10	7.97	25.46
		30	724.51	32.09	4.95	28.83	8.11	26.02
		35	714.51	31.53	5.05	28.53	8.24	26.64
		5	928.95	36.06	3.74	29.01	6.32	24.87
		10	915.27	35.71	3.82	28.78	6.42	25.27
		15	902.34	35.43	3.89	28.55	6.52	25.69
	1200	20	889.85	34.96	3.97	28.31	6.62	26.13
		25	878.24	34.55	4.05	28.07	6.72	26.60
		30	867.65	34.14	4.12	27.82	6.82	27.10
		35	858.42	33.70	4.19	27.55	6.91	27.65
		5	1074.28	37.12	3.23	27.99	5.50	26.16
		10	1060.79	36.83	3.29	27.77	5.58	26.53
		15	1048.04	36.53	3.34	27.56	5.66	26.90
	1300	20	1035.86	36.22	3.40	27.34	5.73	27.31
		25	1024.66	35.89	3.46	27.11	5.81	27.73
		30	1014.64	35.55	3.51	26.88	5.88	28.19
		35	1006.19	35.18	3.57	26.63	5.94	28.68
		5	1223.45	37.87	2.83	27.05	4.87	27.38
		10	1210.07	37.63	2.87	26.85	4.93	27.72
		`15	1197.65	37.37	2.92	26.65	4.99	28.07
	1400	20	1185.74	37.11	2.96	26.44	5.05	28.44
		25	1174.97	36.83	3.01	26.23	5.10	28.83
		30	1165.56	36.55	3.05	26.00	5.15	29.25
		35	1157.92	36.23	3.09	25.77	5.20	29.70

Table C.16: Simple gas turbine cycle with fogging (R_P = 30)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
30	900	5	468.42	27.11	7.79	31.87	13.19	20.04
		10	453.51	25.99	8.09	31.56	13.65	20.71
		15	439.11	24.78	8.41	31.27	14.13	21.42
		20	424.94	23.49	8.74	30.95	14.63	22.19
		25	411.32	22.12	9.09	30.63	15.15	23.03
		30	398.28	20.65	9.45	30.28	15.68	23.94
		35	385.99	19.12	9.82	29.90	16.21	24.96
	1000	5	602.34	31.66	6.05	30.67	10.33	21.30
		10	587.56	30.92	6.23	30.39	10.60	21.85
		15	573.40	30.13	6.43	30.13	10.89	22.43
		20	559.44	29.31	6.63	29.84	11.18	23.06
		25	546.19	28.41	6.83	29.56	11.47	23.73
		30	533.65	27.50	7.03	29.25	11.77	24.45
		35	522.04	26.54	7.24	28.92	12.06	25.24
	1100	5	739.93	34.51	4.91	29.53	8.46	22.59
		10	725.27	33.97	5.04	29.28	8.65	23.07
		15	711.28	33.41	5.17	29.04	8.83	23.57
		20	697.64	32.80	5.30	28.78	9.02	24.10
		25	684.77	32.19	5.43	28.52	9.21	24.66
		30	672.75	31.53	5.56	28.24	9.39	25.27
		35	661.87	30.85	5.69	27.95	9.57	25.94
	1200	5	881.23	36.40	4.12	28.48	7.15	23.85
		10	866.74	35.98	4.21	28.25	7.28	24.27
		15	852.93	35.55	4.30	28.02	7.41	24.72
		20	839.59	35.10	4.39	27.78	7.54	25.19
		25	827.11	34.63	4.48	27.54	7.67	25.69
		30	836.82	34.13	4.58	27.29	7.79	26.22
		35	805.50	33.61	4.67	27.02	7.91	26.80
	1300	5	1026.30	37.71	3.52	27.51	6.19	25.07
		10	1011.92	37.39	3.59	27.29	6.28	25.46
		15	998.36	37.04	3.66	27.08	6.38	25.86
		20	985.32	36.66	3.73	26.85	6.47	26.28
		25	973.26	36.28	3.80	26.63	6.56	26.72
		30	962.36	35.89	3.87	26.39	6.65	27.20
		35	953.01	35.47	3.93	26.14	6.73	27.72
	1400	5	1175.22	38.64	3.07	26.60	5.44	26.25
		10	1160.97	38.37	3.12	26.40	5.52	26.60
		15	1147.65	38.09	3.18	26.20	5.59	26.96
		20	1134.92	37.78	3.23	25.99	5.66	27.35
		25	1123.29	37.46	3.28	25.78	5.73	27.76
		30	1112.99	37.13	3.33	25.55	5.79	28.19
		35	1104.44	36.78	3.38	25.32	5.85	28.67

Table C.17: Simple gas turbine cycle with fogging (R_P = 35)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
35	900	5	426.76	24.87	8.84	31.26	15.37	19.65
		10	411.12	23.45	9.24	30.94	15.99	20.41
		15	395.98	21.86	9.65	30.64	16.63	21.21
		20	381.07	20.19	10.09	30.31	17.32	22.09
		25	366.70	18.39	10.55	29.97	18.04	23.05
		30	352.89	16.45	11.04	29.61	18.79	24.11
		35	339.82	14.40	11.54	29.21	19.55	25.29
	1000	5	560.49	30.64	6.72	30.13	11.78	20.73
		10	544.97	29.73	6.95	29.86	12.13	21.33
		15	530.03	28.62	7.19	29.59	12.50	21.97
		20	515.38	27.72	7.44	29.30	12.88	22.65
		25	501.37	26.64	7.70	29.01	13.26	23.39
		30	488.06	25.50	7.96	28.70	13.66	24.19
		35	475.67	24.31	8.23	28.36	14.04	25.06
	1100	5	697.88	34.14	5.39	29.05	9.52	21.90
		10	682.48	33.50	5.54	28.80	9.75	22.41
		15	667.75	32.82	5.70	28.56	9.98	22.94
		20	653.36	32.12	5.86	28.30	10.22	23.52
		25	639.73	31.38	6.02	28.03	10.45	24.13
		30	626.95	30.59	6.18	27.75	10.69	24.78
		35	615.27	29.79	6.34	27.45	10.92	25.50
	1200	5	838.96	36.44	4.47	28.04	7.97	23.08
		10	823.70	35.96	4.58	27.81	8.12	23.53
		15	809.17	35.45	4.69	27.58	8.28	23.99
		20	795.08	34.20	4.80	27.34	8.44	24.49
		25	781.84	34.37	4.91	27.10	8.60	25.02
		30	769.61	33.79	5.02	26.85	8.76	25.59

		35	758.68	33.20	5.13	26.57	8.91	26.20
	1300	5	983.81	38.02	3.80	27.10	6.84	24.24
		10	968.68	37.64	3.88	26.88	6.95	24.64
		15	954.38	37.29	3.96	26.67	7.07	25.06
		20	940.58	36.82	4.05	26.45	7.18	25.50
		25	927.75	36.38	4.13	26.22	7.30	25.97
		30	916.08	35.93	4.21	25.99	7.40	26.47
		35	905.94	35.46	4.28	25.73	7.50	27.02
	1400	5	1132.48	39.15	3.30	26.22	5.98	25.36
		10	1117.50	38.83	3.36	26.02	6.07	25.72
		15	1103.42	38.49	3.42	25.82	6.15	26.10
		20	1089.93	38.17	3.48	25.61	6.24	26.51
		25	107754	37.80	3.54	25.40	6.32	26.93
		30	1066.46	37.43	3.60	25.18	6.40	27.39
		35	1057.12	37.04	3.66	24.94	6.47	27.88

Table C.18: Simple gas turbine cycle with fogging (R_P = 40)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}$ (%)	$E_{d,comb}$(%)	$E_{d,turb}$(%)	$E_{d,ex}$(%)
40	900	5	389.22	22.11	9.97	30.72	17.72	19.48
		10	372.92	20.28	10.47	30.39	18.53	20.32
		15	357.13	18.28	11.01	30.08	19.40	21.24
		20	341.54	16.11	11.59	29.73	20.33	22.26
		25	326.50	13.75	12.20	29.37	21.31	23.37
		30	312.02	11.19	12.85	28.99	22.35	24.61
		35	298.24	8.47	13.54	28.56	23.43	26.01
	1000	5	522.77	29.25	7.41	29.67	13.27	20.33
		10	506.60	28.21	7.70	29.39	13.72	20.99
		15	490.99	27.03	7.99	29.12	14.18	21.69
		20	475.67	25.77	8.30	28.82	14.67	22.44
		25	460.99	24.43	8.62	28.52	15.17	23.26
		30	447.00	23.00	8.95	28.20	15.68	24.14
		35	433.91	21.58	9.28	27.85	16.18	25.12
	1100	5	659.98	34.10	5.86	28.64	10.57	21.38
		10	643.92	32.78	6.04	28.39	10.85	21.93
		15	628.52	31.99	6.23	28.14	11.14	22.50
		20	613.47	31.15	6.42	27.88	11.43	23.12
		25	599.16	30.27	6.61	27.61	11.73	23.77
		30	585.69	29.35	6.81	27.33	12.02	24.48
		35	573.31	28.40	7.01	27.02	12.31	25.26
	1200	5	800.87	36.27	4.82	27.67	8.76	22.48
		10	784.94	35.72	4.94	27.44	8.96	22.95
		15	769.75	35.12	5.07	27.21	9.15	23.44
		20	754.98	33.92	5.20	26.97	9.34	23.97
		25	741.06	33.88	5.33	26.72	9.53	24.53
		30	728.14	33.21	5.46	26.47	9.72	25.13
		35	716.50	32.52	5.59	26.19	9.90	25.79
	1300	5	945.52	38.14	4.07	26.76	7.47	23.57
		10	929.72	37.72	4.16	26.54	7.61	23.99
		15	914.74	37.24	4.26	26.33	7.74	24.43
		20	900.27	36.77	4.35	26.10	7.88	24.90
		25	886.76	36.27	4.44	25.88	8.01	25.39
		30	874.40	35.76	4.54	25.64	8.14	25.92
		35	863.54	35.23	4.63	25.39	8.27	26.49
	1400	5	1093.98	39.44	3.51	25.90	6.50	24.65
		10	1078.32	39.10	3.58	25.70	6.60	25.03
		15	1063.57	38.72	3.65	25.50	6.70	25.42
		20	1049.40	38.34	3.72	25.29	6.80	25.84
		25	1036.32	37.94	`3.79	25.08	6.90	26.28
		30	1024.54	37.53	3.86	24.86	6.99	26.76
		35	1014.49	37.10	3.93	24.62	7.08	27.27

B.4 ABC with Fogging

Table C.19: Simple gas turbine cycle with fogging (R_P = 10 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
10	900	5	718.76	30.41	3.76	2.01	36.25	5.14	2.34	1.56	14.75	3.76
		10	708.34	29.73	3.84	2.12	35.97	5.22	2.46	1.47	15.24	3.96
		15	698.48	29.09	3.91	2.19	35.69	5.31	2.54	1.41	15.76	4.09
		20	688.87	28.44	3.98	2.29	35.40	5.39	2.64	1.36	16.22	4.27
		25	679.89	27.73	4.06	2.36	35.10	5.47	2.72	1.32	16.84	4.40
		30	671.57	26.98	4.13	2.45	34.78	5.55	2.81	1.27	17.46	4.56
		35	664.14	26.20	4.20	2.55	34.43	5.63	2.92	1.23	18.09	4.75
	1000	5	853.81	33.00	3.16	1.69	34.63	4.37	1.98	1.73	14.71	4.73
		10	843.54	32.50	3.21	1.78	34.37	4.43	2.08	1.63	15.02	4.96
		15	833.89	32.05	3.27	1.83	34.11	4.49	2.14	1.58	15.42	5.11
		20	824.57	31.61	3.32	1.91	33.83	4.55	2.22	1.52	15.73	5.32
		25	815.97	31.08	3.37	1.96	33.	55.4.61	2.28	1.47	16.21	5.47
		30	808.17	30.53	3.42	2.03	33.26	4.66	2.35	1.42	16.67	5.65
		35	801.44	30.00	3.47	2.10	32.94	4.71	2.43	1.37	17.12	5.87
	1100	5	992.61	34.80	2.71	1.45	33.16	3.80	1.71	1.89	14.84	5.62
		10	982.48	34.47	2.75	1.52	32.92	3.85	1.79	1.79	15.02	5.89
		15	973.06	34.21	2.79	1.57	32.68	3.89	1.84	1.73	15.33	6.05
		20	964.03	33.80	2.83	1.63	32.42	3.93	1.91	1.67	15.52	6.28
		25	955.82	33.41	2.87	1.67	32.16	3.97	1.95	1.61	15.90	6.44
		30	948.57	33.00	2.91	1.72	31.88	4.01	2.01	1.56	16.25	6.65
		35	942.57	32.59	2.94	1.78	31.59	4.05	2.08	1.50	16.57	6.89
	1200	5	1135.18	36.11	2.37	1.27	31.83	3.36	1.50	2.04	15.09	6.44
		10	1125.21	35.87	2.40	1.33	31.60	3.40	1.57	1.94	15.16	6.73
		15	1116.03	35.60	2.43	1.36	31.37	3.43	1.61	1.87	15.40	6.91
		20	1107.31	35.39	2.46	1.41	31.13	3.46	1.67	1.81	15.50	7.16
		25	1099.52	35.07	2.49	1.45	30.89	3.49	1.71	1.75	15.81	7.34
		30	1092.83	34.77	2.52	1.49	30.63	3.52	1.75	1.69	16.07	7.55
		35	1087.59	34.47	2.54	1.54	30.35	3.55	1.81	1.64	16.28	7.81
	1300	5	1281.59	37.04	2.09	1.12	30.62	3.01	1.34	2.16	15.43	7.19
		10	1271.79	36.89	2.12	1.17	30.40	3.04	1.40	2.06	15.41	7.51
		15	1262.85	36.56	2.14	1.20	30.18	3.06	1.43	2.00	15.60	7.69
		20	1254.46	36.52	2.16	1.24	29.96	3.09	1.48	1.94	15.62	7.96
		25	1247.09	36.29	2.19	1.27	29.72	3.11	1.51	1.88	15.87	8.15
		30	1240.99	36.06	2.21	1.31	29.48	3.14	1.55	1.82	16.06	8.38
		35	1236.56	35.83	2.23	1.35	29.22	3.16	1.60	1.76	16.19	8.66
	1400	5	1400.62	37.74	1.87	1.00	29.50	2.73	1.20	2.27	15.83	7.87
		10	1422.27	37.64	1.89	1.04	29.30	2.75	1.26	2.18	15.74	8.21
		15	1413.57	37.48	1.91	1.07	29.09	2.77	1.28	2.12	15.88	8.40
		20	1405.55	37.39	1.93	1.11	28.87	2.79	1.33	2.05	15.85	8.69
		25	1398.62	37.19	1.95	1.13	28.66	2.81	1.35	2.00	16.04	8.88
		30	1393.13	37.01	1.96	1.16	28.43	2.83	1.39	1.94	16.17	9.12
		35	1389.52	36.84	1.98	1.20	28.18	2.84	1.43	1.87	16.24	9.42

Table C.20: Simple gas turbine cycle with fogging (R_P = 15 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
15	900	5	635.22	30.14	4.82	2.28	34.55	7.14	2.63	1.33	14.39	2.71
		10	623.29	29.11	4.94	2.42	34.28	7.29	2.78	1.25	15.05	2.87
		15	611.89	28.20	5.06	2.51	34.00	7.45	2.88	1.21	15.71	2.98
		20	600.74	27.22	5.18	2.63	33.70	7.60	3.02	1.18	16.34	3.12
		25	590.18	26.19	5.30	2.73	33.40	7.75	3.12	1.14	17.13	3.23
		30	575.19	25.30	5.47	2.86	32.54	7.97	3.27	1.12	18.07	3.40
		35	571.18	23.93	5.55	2.96	32.73	8.04	3.38	1.08	18.78	3.53
	1000	5	769.90	33.76	3.97	1.88	33.08	5.95	2.18	1.48	14.08	3.61
		10	758.10	33.04	4.05	1.98	32.83	6.05	2.30	1.40	14.54	3.80
		15	746.91	32.41	4.14	2.05	32.57	6.15	2.37	1.35	15.04	3.93
		20	736.04	31.73	4.22	2.14	32.30	6.26	2.47	1.30	15.47	4.10
		25	725.85	31.00	4.30	2.21	32.02	6.36	2.55	1.26	16.07	4.23
		30	716.45	30.23	4.38	2.29	31.72	6.45	2.64	1.22	16.66	4.39
		35	708.06	29.43	4.46	2.39	31.41	6.55	2.74	1.18	17.26	4.59
	1100	5	908.30	36.25	3.36	1.59	31.75	5.09	1.86	1.63	14.03	4.45
		10	896.64	35.75	3.42	1.67	31.51	5.16	1.95	1.57	14.33	4.67
		15	885.67	35.26	3.48	1.72	31.27	5.24	2.01	1.49	14.72	4.82
		20	875.08	34.78	3.54	1.80	31.01	5.31	2.09	1.44	15.01	5.02
		25	865.29	34.24	3.60	1.85	30.75	5.38	2.15	1.39	15.48	5.16
		30	856.42	33.67	3.66	1.91	30.48	5.45	2.22	1.34	15.93	5.34
		35	848.76	33.09	3.71	1.99	30.18	5.51	2.30	1.30	16.37	5.55

		5	1050.43	38.01	2.90	1.37	30.52	4.44	1.62	1.77	14.14	5.23
		10	1038.94	37.64	2.94	1.44	30.30	4.50	1.69	1.68	14.32	5.48
		15	1028.19	37.27	2.99	1.48	30.07	4.55	1.74	1.62	14.63	5.63
	1200	20	1017.92	36.95	3.04	1.54	29.83	4.61	1.80	1.57	14.82	5.86
		25	1009.01	36.50	3.08	1.58	29.62	4.66	1.85	1.52	15.19	6.01
		30	1000.22	36.09	3.12	1.63	29.33	4.71	1.90	1.47	15.53	6.21
		35	993.32	35.66	3.16	1.69	29.06	4.75	1.97	1.42	15.85	6.44
		5	1196.41	39.29	2.54	12.0	29.40	3.94	1.42	1.90	14.36	5.95
		10	1185.06	38.93	2.57	1.26	29.19	3.98	1.49	1.81	14.45	6.22
		15	1174.55	38.74	2.61	1.29	28.97	4.02	1.53	1.75	14.68	6.39
	1300	20	1164.59	38.49	2.65	1.34	28.75	4.07	1.58	1.69	14.79	6.63
		25	1155.63	38.16	2.68	1.38	28.52	4.10	1.62	1.64	15.10	6.79
		30	1147.91	37.84	2.71	1.42	28.28	4.14	1.67	1.58	15.36	7.00
		35	1141.80	37.51	2.75	1.47	28.02	4.17	1.72	1.53	15.58	7.25
		5	1346.26	40.22	2.25	1.06	38.37	3.54	1.27	2.01	14.67	6.61
		10	1335.00	40.03	2.28	1.11	28.17	3.57	1.32	1.92	14.73`	6.87
		15	1324.81	39.83	2.31	1.14	27.96	3.60	1.36	1.86	14.86	7.08
	1400	20	1315.17	39.64	2.34	1.19	27.75	3.64	1.41	1.81	14.90	7.33
		25	1306.66	39.38	2.36	1.21	27.54	3.67	1.44	1.75	15.14	7.51
		30	1299.54	39.11	2.39	1.25	27.31	3.69	1.47	1.70	15.34	7.73
		35	1294.26	38.87	2.41	1.29	27.07	3.72	1.52	1.64	15.48	7.99

Table C.21: Simple gas turbine cycle with fogging (R_P = 25 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
		5	515.50	23.72	6.77	2.81	32.64	8.81	3.25	1.61	17.09	3.28
		10	501.38	22.00	7.01	3.01	32.37	9.08	3.46	1.53	18.05	3.50
		15	487.82	20.37	7.25	3.15	32.09	9.36	3.62	1.49	19.02	3.66
	900	20	474.49	18.61	7.46	3.34	31.79	9.64	3.83	1.47	19.97	3.87
		25	461.73	16.73	7.75	3.49	31.48	9.93	4.00	1.43	21.12	4.05
		30	449.55	14.76	8.01	3.67	31.15	10.22	4.19	1.41	22.33	4.27
		35	438.16	12.63	8.27	3.87	30.78	10.51	4.41	1.39	23.61	4.52
		5	649.60	29.38	5.37	2.23	31.35	7.06	2.59	1.73	16.09	4.21
		10	635.65	28.23	5.52	2.37	31.10	7.23	2.74	1.64	16.72	4.46
		15	622.29	27.12	5.67	2.47	30.84	7.40	2.85	1.59	17.41	4.64
	1000	20	609.22	25.99	5.82	2.59	30.57	7.57	2.99	1.55	18.03	4.88
		25	596.82	24.75	5.98	2.70	30.29	7.75	3.11	1.51	18.85	5.07
		30	585.16	2347	6.14	2.81	29.99	7.92	3.23	1.47	19.67	5.30
		35	574.45	22.12	6.29	2.95	29.66	8.09	3.38	1.43	20.51	5.56
		5	787.41	33.02	4.42	1.84	30.15	5.88	2.15	1.85	15.60	5.07
		10	773.60	32.24	4.52	1.94	29.92	6.00	2.27	1.76	16.02	5.34
		15	760.45	31.45	4.63	.201	29.68	6.11	2.34	1.71	16.53	5.53
	1100	20	747.66	30.66	4.73	2.11	29.42	6.23	2.45	1.66	16.94	5.79
		25	735.65	29.78	4.84	2.18	29.17	6.34	2.53	1.61	17.56	5.99
		30	724.51	28.88	4.95	2.27	28.90	6.45	2.62	1.56	18.15	6.23
25		35	714.52	27.95	5.05	2.36	28.60	6.56	2.73	1.51	18.73	6.51
		5	928.95	35.55	3.74	1.55	29.05	5.03	1.83	1.98	15.43	5.84
		10	915.27	34.96	3.81	1.64	28.83	5.12	1.92	1.88	15.68	6.15
		15	902.34	34.40	3.89	1.69	28.60	5.20	1.98	1.82	16.07	6.35
	1200	20	889.85	33.81	3.97	1.77	28.37	5.28	2.07	1.77	16.34	6.62
		25	878.24	33.15	4.04	1.82	28.13	5.36	2.13	1.71	16.82	6.83
		30	867.65	32.49	4.12	1.89	27.88	5.44	2.20	1.66	17.26	7.07
		35	858.42	31.81	4.19	1.96	27.60	5.51	2.28	1.61	17.67	7.37
		5	1074.27	37.35	3.23	1.34	28.03	4.40	1.59	2.09	15.44	6.55
		10	1060.74	36.91	3.28	1.41	27.82	4.46	1.67	1.99	15.58	6.88
		15	1048.04	36.47	3.34	1.45	27.61	4.52	1.72	1.93	15.88	7.08
	1300	20	1035.86	36.04	3.40	1.51	27.39	4.58	1.78	1.87	16.04	7.37
		25	1024.66	35.53	3.46	1.56	27.17	4.64	1.83	1.82	16.42	7.58
		30	1014.64	35.02	3.51	1.61	26.93	4.69	1.89	1.76	16.75	7.84
		35	1006.19	34.51	3.57	1.67	26.67	4.75	1.96	1.71	17.03	8.14
		5	1223.46	38.64	2.82	1.17	27.09	3.90	1.40	2.18	15.59	7.20
		10	1210.07	38.33	2.87	1.23	26.89	3.95	1.47	2.09	15.63	7.54
		15	1197.60	37.97	2.92	1.27	26.69	3.99	1.51	2.03	15.86	7.76
	1400	20	1185.74	37.66	2.96	1.32	26.48	4.04	1.57	1.97	15.94	8.06
		25	1174.97	37.26	3.01	1.35	26.27	4.09	1.60	1.92	16.24	8.27
		30	1165.56	36.86	3.05	1.40	26.05	4.13	1.65	1.86	16.49	8.53
		35	1157.93	36.46	3.09	1.45	25.81	4.17	1.71	1.80	16.68	8.85

Table C.22: Simple gas turbine cycle with fogging (R_P = 30 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
30	900	5	468.42	19.98	7.77	3.10	31.98	9.69	3.57	1.76	18.56	3.59
		10	453.51	17.82	8.08	3.33	31.69	10.03	3.83	1.68	19.69	3.85
		15	439.12	14.07	8.40	3.50	31.41	10.39	4.02	1.65	20.86	4.05
		20	424.41	13.45	8.73	3.73	31.10	10.76	4.28	1.63	22.01	4.31
		25	411.22	11.04	9.08	3.92	30.79	11.14	4.49	1.60	23.41	4.53
		30	398.28	8.44	9.43	4.15	30.45	11.53	4.73	1.58	24.89	4.80
		35	385.99	5.69	9.80	4.40	30.06	11.92	5.01	1.57	26.45	5.10
	1000	5	602.34	26.89	6.04	2.41	30.75	7.61	2.80	1.86	17.12	4.53
		10	587.56	25.50	6.23	2.56	30.49	7.82	2.97	1.77	17.85	4.81
		15	573.36	24.16	6.42	2.68	30.24	8.03	3.10	1.72	18.64	5.02
		20	559.45	22.73	6.62	2.83	29.96	8.24	3.26	1.68	19.37	5.30
		25	546.19	21.20	6.82	2.95	29.68	8.46	3.40	1.64	20.32	5.52
		30	533.65	19.61	7.03	3.09	29.38	8.68	3.55	1.60	21.28	5.79
		35	522.05	17.92	7.23	3.25	29.05	8.89	3.73	1.57	22.27	6.10
	1100	5	739.93	31.27	4.91	1.95	29.60	6.26	2.29	1.96	16.39	5.38
		10	725.27	30.30	5.03	2.07	29.37	6.39	2.42	1.87	16.86	5.68
		15	711.28	29.37	5.16	2.15	29.13	6.53	2.51	1.82	17.44	5.90
		20	697.64	28.39	5.29	2.26	28.88	6.67	2.63	1.77	17.91	6.19
		25	684.77	27.33	5.43	2.35	28.62	6.81	2.72	1.72	18.61	6.42
		30	672.76	26.23	5.56	2.44	28.34	6.95	2.83	1.67	19.28	6.69
		35	661.87	25.10	5.69	2.55	28.05	7.08	2.95	1.62	19.95	7.01
	1200	5	881.23	34.20	4.11	1.64	28.54	5.30	1.93	2.07	16.05	6.15
		10	866.71	33.51	4.20	1.73	28.32	5.40	2.03	1.97	16.34	6.48
		15	852.93	32.82	4.29	1.79	28.10	5.50	2.10	1.92	16.78	6.70
		20	839.59	32.14	4.39	1.87	27.86	5.60	2.19	1.86	17.09	7.00
		25	827.11	31.36	4.48	1.94	27.63	5.69	2.26	1.81	17.62	7.23
		30	815.64	30.55	4.57	2.01	27.37	5.78	2.34	1.76	18.11	7.51
		35	805.51	29.74	4.66	2.09	27.10	5.87	2.44	1.70	18.57	7.83
	1300	5	1026.30	36.28	3.52	1.40	27.56	4.60	1.66	2.17	15.96	6.85
		10	1011.92	35.78	3.59	1.48	27.35	4.67	1.75	2.07	16.12	7.19
		15	998.36	35.24	3.66	1.53	27.14	4.74	1.80	2.02	16.45	7.42
		20	985.33	34.73	3.73	15.9	26.92	4.81	1.88	1.96	16.64	7.73
		25	973.26	34.12	3.80	1.64	26.70	4.88	1.93	1.90	17.05	7.97
		30	962.37	33.53	3.87	1.70	26.46	4.95	1.99	1.85	17.42	8.25
		35	953.01	32.92	3.93	1.76	26.21	5.01	2.07	1.79	17.73	8.58
	1400	5	1175.22	37.76	3.07	1.22	26.65	4.06	1.46	2.26	16.03	7.48
		10	1160.98	37.40	3.12	1.29	26.45	4.11	1.53	2.17	16.08	7.85
		15	1147.65	36.99	3.17	1.32	26.26	4.17	1.57	2.11	16.34	8.08
		20	1134.92	36.61	3.23	1.38	26.05	4.22	1.64	2.05	16.43	8.40
		25	1123.29	36.12	3.28	1.42	25.84	4.27	1.68	1.99	16.76	8.63
		30	1112.99	35.64	3.33	1.46	25.61	4.32	1.73	1.94	17.03	8.92
		35	1104.44	35.17	3.38	1.52	25.38	4.36	1.79	1.88	17.24	9.26

Table C.23: Simple gas turbine cycle with fogging (R_P = 35 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
35	900	5	426.76	17.57	8.82	3.40	31.41	10.63	3.92	1.92	20.13	3.93
		10	411.12	13.14	9.22	3.67	31.12	11.06	4.23	1.85	21.48	4.23
		15	395.99	10.51	9.63	3.89	30.83	11.51	4.46	1.83	22.87	4.47
		20	381.31	7.66	10.07	4.05	30.55	11.98	4.64	1.80	24.59	4.66
		25	366.70	4.52	10.54	4.40	30.19	12.49	5.04	1.79	25.97	5.06
		30	352.90	1.18	11.02	4.68	29.83	13.00	5.35	1.78	27.77	5.39
		35	339.83	-ve	11.52	5.00	29.43	13.53	5.70	1.78	29.71	5.77
	1000	5	560.49	24.26	6.71	2.59	30.25	8.17	3.01	1.99	18.18	4.85
		10	544.97	22.59	6.94	2.77	29.99	8.42	3.20	1.90	19.02	5.17
		15	530.03	20.95	7.18	2.90	29.73	8.68	3.35	1.85	19.94	5.41
		20	515.38	19.21	7.43	3.07	29.45	8.95	3.55	1.81	20.78	5.73
		25	501.37	17.35	7.69	3.21	29.17	9.21	3.70	1.78	21.88	6.00
		30	488.06	15.39	7.95	3.38	28.86	9.49	3.88	1.74	23.00	6.31
		35	475.67	13.33	8.21	3.57	28.52	9.75	4.09	1.71	24.15	6.67
	1100	5	697.88	29.43	5.38	2.07	29.15	6.63	2.43	2.07	17.17	5.68
		10	682.48	28.29	5.53	2.20	28.91	6.79	2.57	1.98	17.70	6.02
		15	667.75	27.15	5.69	2.30	28.67	6.95	2.67	1.93	18.36	6.27
		20	653.37	26.01	5.85	2.42	28.42	7.12	2.81	1.88	18.90	6.59
		25	639.73	24.76	6.01	2.51	28.16	7.29	2.91	1.83	19.68	6.85
		30	626.95	23.44	6.18	2.62	27.88	7.45	3.04	1.78	20.45	7.16
		35	615.28	22.10	6.34	2.75	27.58	7.61	3.18	1.74	21.20	7.52
	1200	5	838.96	32.82	4.47	1.72	28.12	5.57	2.03	2.17	16.66	6.44
		10	823.70	32.03	4.57	1.82	27.90	5.68	2.14	2.07	16.99	6.80
		15	809.17	31.20	4.68	1.89	27.68	5.79	2.22	2.01	17.48	7.04
		20	795.08	30.39	4.80	1.98	27.44	5.91	2.32	1.96	17.83	7.83
		25	781.84	29.48	4.91	2.05	27.21	6.02	2.40	1.90	18.41	7.63
		30	769.61	28.54	5.02	2.13	26.95	6.13	2.48	1.85	18.96	7.94

		35	758.68	27.60	5.13	2.22	26.67	6.23	2.59	1.80	19.47	8.29
		5	983.81	35.19	3.80	1.46	27.17	4.80	1.74	2.26	16.46	7.13
		10	968.68	34.62	3.88	1.55	26.96	4.88	1.83	2.16	16.64	7.50
		15	954.38	33.98	3.96	1.60	26.76	4.96	1.89	2.10	17.01	7.75
	1300	20	940.58	33.40	4.04	1.67	26.53	5.04	1.97	2.04	17.22	8.09
		25	927.75	32.70	4.12	1.72	16.31	5.12	1.03	1.99	17.67	8.34
		30	916.08	31.99	4.20	1.79	26.07	5.20	2.10	1.93	18.07	8.65
		35	905.94	31.30	4.28	1.86	25.82	5.27	2.18	1.87	18.42	9.01
		5	1132.48	36.91	3.29	1.27	26.28	4.21	1.52	2.34	16.45	7.75
		10	1117.50	36.47	3.35	1.34	26.09	4.27	1.59	2.24	16.52	8.14
		15	1103.42	35.96	3.42	1.38	25.89	4.33	1.64	2.18	16.80	8.39
	1400	20	1089.93	35.53	3.48	1.44	25.69	4.39	1.71	2.12	16.91	8.73
		25	1077.54	34.98	3.54	1.48	25.48	4.45	1.75	2.07	17.27	8.98
		30	1066.46	34.44	3.60	1.53	25.25	4.51	1.81	2.01	17.56	9.29
		35	1057.12	33.91	3.66	1.59	25.02	4.56	1.87	1.95	17.79	9.66

Table C.24: Simple gas turbine cycle with fogging (R_P = 40 & r_p = 6)

R_P	TIT(°C)	T_{amb} (°C)	EX_{CH} (kJ/kg)	W(%)	$E_{d,comp}^{top}$ (%)	$E_{d,comp}^{bot}$ (%)	$E_{d,comb}$ (%)	$E_{d,turb}^{top}$ (%)	E_{dturb}^{bot} (%)	$E_{d,reg}$ (%)	$E_{d,ex}^{top}$ (%)	$E_{d,ex}^{bot}$ (%)
		5	389.22	11.24	9.94	3.73	30.91	11.64	4.30	2.10	21.85	4.29
		10	372.92	7.94	10.45	4.05	30.61	12.18	4.66	2.03	23.44	4.64
		15	357.13	4.61	10.99	4.31	30.32	12.75	4.95	2.02	25.11	4.94
	900	20	341.55	0.96	11.56	4.65	29.99	13.37	5.33	2.01	26.81	5.32
		25	326.51	-ve	12.18	4.95	29.65	14.02	5.66	2.01	28.88	5.67
		30	312.02	-ve	12.83	5.30	29.27	14.70	6.05	2.01	31.10	6.07
		35	298.25	-ve	13.51	5.70	28.84	15.40	6.50	2.02	33.50	6.55
		5	522.78	21.43	7.40	2.77	29.81	8.76	3.22	2.12	19.29	5.18
		10	506.60	19.47	7.68	2.98	29.55	9.06	3.45	2.03	20.25	5.55
		15	490.99	17.50	7.98	3.13	29.29	9.36	3.62	1.99	21.30	5.83
	1000	20	475.67	15.40	8.29	3.33	29.01	9.69	3.84	1.96	22.29	6.19
		25	460.99	13.14	8.61	3.50	28.72	10.02	4.03	1.93	23.55	6.50
		30	446.99	10.76	8.94	3.69	28.40	10.35	4.24	1.90	24.85	6.87
		35	433.91	8.54	9.27	3.91	28.05	10.69	4.49	1.87	26.19	7.29
		5	659.98	27.49	5.85	2.19	28.76	7.01	2.57	2.19	17.97	6.00
		10	643.92	26.16	6.03	2.34	28.52	7.19	2.73	2.09	18.57	6.37
		15	628.52	24.83	6.22	2.44	28.28	7.38	2.84	2.04	19.30	6.64
	1100	20	613.47	23.49	6.41	2.58	28.02	7.58	2.99	1.99	19.92	7.00
		25	599.16	22.02	6.61	2.68	27.76	7.78	3.11	1.95	20.79	7.30
		30	585.69	20.47	6.80	2.81	27.48	7.97	3.25	1.90	21.65	7.64
40		35	573.31	18.89	7.00	2.95	27.17	8.16	3.41	1.86	22.50	8.05
		5	800.87	31.40	4.81	1.80	27.76	5.83	2.13	2.26	17.27	6.73
		10	784.95	30.48	4.94	1.91	27.54	5.96	2.25	2.16	17.65	7.12
		15	769.75	29.52	5.07	1.99	27.32	6.09	2.33	2.11	18.18	7.39
	1200	20	754.98	28.59	5.20	2.09	27.08	6.22	2.44	2.05	18.58	7.75
		25	741.06	27.53	5.33	2.16	26.84	6.35	2.53	2.00	19.22	8.03
		30	728.14	26.45	5.46	2.25	26.59	6.47	2.63	1.95	19.82	8.37
		35	716.51	25.36	5.59	2.36	26.31	6.59	2.74	1.90	20.39	8.76
		5	945.52	34.10	4.07	1.52	26.84	4.99	1.81	2.34	16.95	7.40
		10	929.72	33.41	4.16	1.61	26.63	5.08	1.91	2.24	17.16	7.80
		15	914.74	32.71	4.25	1.67	26.42	5.17	1.97	2.18	17.56	8.07
	1300	20	900.27	32.02	4.35	1.75	26.20	5.26	2.06	2.12	17.80	8.43
		25	886.76	31.22	4.44	1.80	25.98	5.35	2.12	2.07	18.29	8.71
		30	874.41	30.42	4.53	1.87	25.74	5.44	2.20	2.01	18.73	9.04
		35	863.55	29.64	4.62	1.95	25.49	5.52	2.29	1.96	19.11	9.43
		5	1093.98	36.00	3.51	1.31	25.97	4.35	1.57	2.42	16.85	8.01
		10	1078.32	35.52	3.58	1.39	25.78	4.42	1.65	2.31	16.94	8.42
		15	1063.57	34.96	3.65	1.43	25.58	4.49	1.70	2.26	17.25	8.69
	1400	20	1049.40	34.44	3.72	1.49	25.38	4.56	1.77	2.20	17.38	9.06
		25	1036.32	33.82	3.79	1.54	25.17	4.63	1.82	2.14	17.76	9.33
		30	1024.54	33.21	3.86	1.59	24.95	4.69	1.88	2.08	18.08	9.65
		35	1014.50	32.61	3.92	1.66	24.71	4.75	1.95	2.02	18.34	10.04

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