MOVEMENT OF THE WETTING FRONT DURING WATER JET IMPINGEMENT QUENCHING ON HOT SOLID SURFACE

Md. Monjur Rahman

Department Of Mechanical Engineering
Bangladesh University Of Engineering & Technology
Dhaka, Bangladesh

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Movement of the Wetting Front during Water Jet Impingement Quenching on Hot Solid Surface

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by

Md. Monjur Rahman

Student No: 0409102078

Under the supervision of

Dr. Aloke Kumar Mozumder

In partial fulfillment of the

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of

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RECOMMENDATION OF THE BOARD OF EXAMINERS

The board of examiners hereby recommends to the Department of Mechanical Engineering, BUET, Dhaka, the acceptance of this thesis, **"Movement of the Wetting Front during Water Jet Impingement Quenching on Hot Solid Surface,"** submitted by Md. Monjur Rahman, in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

Chairman (Supervisor) : ______________________________

Dr. Aloke Kumar Mozumder
Assosiate Professor
Department of Mechanical Engineering
BUET, Dhaka, Bangladesh.

Member (Ex-officio) : ______________________________

Dr. Muhammad Mahbubul Alam
Professor & Head
Department of Mechanical Engineering
BUET, Dhaka, Bangladesh.

Member : ______________________________

Dr. Md. Ashraful Islam
Professor
Department of Mechanical Engineering
BUET, Dhaka, Bangladesh.

Member(External) : ______________________________

Dr. Hasan Mohammad Mostofa Afroz
Associate Professor
Department of Mechanical Engineering
DUET, Gazipur, Bangladesh.

DECLARATION

This to certify that the presented paper is the outcome of the accomplishment of the project and thesis on **"Movement of the Wetting Front during Water Jet Impingement Quenching on Hot Solid Surface."** carried out by a student of Mechanical Engineering Department, BUET, Dhaka under the supervision of Dr. Aloke Kumar Mozumder, Associate Professor, Mechanical Engineering Department, BUET, Dhaka and it has not been submitted anywhere for any award of degree or diploma, nor it has been published in any technical journal.

Name	Student Number	Signature
1. Md. Monjur Rahman	0409102078	

SUPERVISOR

Dr. Aloke Kumar Mozumder

Associate Professor

Dept. of Mechanical Engineering

BUET, Dhaka-1000.

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ABSTRACT

The criterion for the movement of the wetting front (visible leading edge of a moving wetting area) on a hot solid surface due to impingement of liquid jet is important for clear understanding of quenching / cooling phenomenon by jet impingement quenching. No complete understanding of this important criterion has yet cited in literature. A comprehensive study on this phenomenon is essential at the moment for obtaining a model of jet quenching. The present study represents the wetting front movement criterion during free jet impinging quenching on a heated surface by impinging circular water jet. The water jet struck with jet force on the heated surface and wanted to move towards the circumference of the heated plate but during the movement, some other forces produced against the driving jet force and resisted the movement of the wetting front. These resisted forces are; shear force, bubble detaching force and the bubble explosion pressure force. When the fluid flows over the stationary surface, the velocity of the fluid adjacent to the stationary surface becomes zero and this layer effects the velocity of the adjacent layer and so on. This phenomenon occurs due to the viscosity of the fluid. This force varies with the viscosity of the fluid and traveled distance. When the water comes into contact with super heated surface, boiling occurs. The continuous bubbles form on the surface which resists the water flow due to surface tension. The temperature of the heated surface during quenching at various position and time is estimated by many researchers. The bubbles burst continuously and create a stream of vapor, this stream of vapor resist the water flow. If the driving jet force is greater than the summation of these three resistance forces, the wetting front will move, if equal the wetting front will stagnant and if less, then the wetting front will not reached there. The occurring of maximum heat flux is the most desirable event during quenching process which always occurs after the movement of the wetting front. Therefore, the criterion for the movement of the wetting front can be regarded as a criterion for the maximum heat flux and ultimately maximum cooling.

NOMENCLATURE

CHF	critical heat flux [w/m^2]
MHF	maximum heat flux [w/m^2]
T_{liq}	liquid temperature [°C]
d_d	departure diameter
T_w	surface temperature [°C]
T_w^*	surface temperature at resident time (at r = r*) [°C]
ΔT_{sat}	wall superheat temperature [°C]
*t**	resident time [s]
W	boiling width [mm]
r_n	position in the radial direction of the block at nth point [mm]
t_n	flowing fluid thickness over the hot surface at nth [mm]
*r**	radial position of wetting front during resident time [mm]
k	thermal conductivity [kW/m K]
T_b	block initial temperature [°C]
ΔT_{sub}	liquid subcooling [$=T_{sat} - T_{liq}$] [K]
V	jet velocity [m/s]
F_j	jet force [N]
F_s	shear force [N]
F_{de}	bubble detaching force [N]
F_{exp}	bubble explosive pressure force [N]
V_n	jet velocity at nth position distance [m/s]
A_b	boiling area [m^2]
N	nucleation site density per unit area [number/m^2]
T_i	solid–liquid interfacial temperature [°C]
$T_{i, Estm}$	Estimated temperature from Eqn. (3.21) [°C]
T_q	quench temperature [°C]
T_{rw}	Rewet temperature [°C]
P_{exp}	bubble explosive pressure [N/m^2]
P_{atm}	atmospheric pressure [N/m^2]
d	jet diameter [mm]

C_{pl}	specific heat of liquid [kJ/kg K]
C_{pw}	specific heat of solid surface [kJ/kg K]
Bo	Bond number [-]
Pr	prandalt number [-]
J_a	Jakob numbers [-]
Pa	Pascal [N/m^2]
t	time (counted from the impingement of jet) [s]
Ra	surface roughness [μm]

Subscripts

l	liquid
s	solid

Greek symbols

θ_d	departing angle
ρ	density [kg/m^3]
σ	surface tension force [N/m]

CHAPTER -1

INTRODUCTION

Quenching and boiling are the important branches in thermal engineering. Quenching is the process of rapid cooling of high temperature solid surface by suitable cooling media. At the initial stage, quenching was done by immersing solid metal into a bath of water. Now quenching is widely used in many manufacturing industries in different way. Free impinging jet of liquid on heated solid surface is one of them. In this section, various applications of quenching and its definition of different terms of quenching will be discussed. Finally, the objectives of the present study will be included.

1.1 Application of Quenching

In many manufacturing industries for cooling and controlling of mechanical properties of materials, quenching is very important. The physical dimensions, metallurgical and mechanical properties are important for quality products. Cooling rate plays a vital role for controlling of these properties. In the manufacturing world, quenching is widely used in different processes such as extrusion, casting, forging, annealing and so on.

In water-cooled nuclear reactors, it is essential to control the heat removal rate from the fuel element during a loss of coolant accident (LOCA). At that time the fuel element will overheat even though the reactor is immediately shutdown. In the event of such an emergency it is necessary to provide an alternative cooling system known as emergency core cooling (ECC). For the purpose of emergency core cooling, water jets are impinged on the hot fuel element. Several other applications of this phenomenon are where heat produces during cutting or machining, cooling of a rocket nozzle, electrical and electronic component etc.

1.2 Quenching and Boiling Phenomena

Due to increasing demand for utility of quenching in industry, researchers and scientists have carried out analytical and experimental investigations for clear understanding of quenching phenomena. Most of the researchers can be divided into two groups according to the main interest, the first group includes those who are interested in the mechanical properties of metals such as hardness, toughness, strength and the second group includes those who are interested in the mechanism of heat transfer during the cooling process. In this study, a brief history for the literatures of the second group will be discussed. The quenching process is very complicated; it involves many sub-processes which are also complicated themselves. Definitions of some phenomena associated with quenching are also discussed here.

1.2.1 Definition of Quenching

Quenching can be defined as a heat transfer process in which extremely rapid cooling results from bringing high temperature solid into sudden contact with lower temperature fluid. Generally, the keyF_{exp}ure responsible for the rapid cooling is a rewetting process which is believed to occur when the temperature of the hot surface is below a certain value referred as the rewetting temperature. However, the rewetting temperature does not appear to be a simple function of the liquid properties. Surface rewetting refers to the establishing of liquid contact with a solid surface whose initial temperature is higher than the sputtering temperature, the temperature up to which a surface may wet. Rewetting as the onset of transition or unstable boiling in going from stable film boiling to nucleate boiling, and found that it corresponded to the minimum film boiling heat flux on the standard boiling curve.

1.2.2 Jet Impingement Quenching

One of the most efficient ways of cooling is jet impingement quenching. When liquid jet is first impinged on the hot solid surface, the liquid becomes stagnant near the small impinged region for a certain period of time (which is defined as resident time) and splashes out form that region before moves forward. Mozumder et al. [1] found that during the water jet cooling, before the movement of the wetting front (the leading front edge of the wetting zone), the temperature near the liquid impingement center is steadily decreasing and the heat flux is steadily increasing. At instant when the wetting front starts moving forward, the temperature at the edge of wetted region (defined as wetting front) is close to interface temperature of the liquid and solid. The maximum heat flux always occurred just after the movement of the wetting front, generally 40-50 times higher heat flux than the heat flux of stagnation period / resident time period. Both of these wetting front movement and maximum heat flux occurs at definite temperature range which depend on the solid initial temperature, jet velocity, liquid sub-cooling temperature and thermo-fluid properties of liquid and solid.

The heat transfer coefficients for this cooling system typically exceed the ones for pool boiling enormously, starting at values of about 10, 000 W/m^2 K reported by D. H. Wolf et al. [2]. This characteristic makes this cooling system preferable for many practical applications. Figure 1.1 shows a pictorial definition of wet zone, wetting front, dry zone and wetting front velocity during quenching of a high temperature solid surface by using liquid jet impingement.

When the liquid jet is impinged on the hot solid surface, the entire hot surface does not wet immediately. The liquid splashed out from the local impinged region. The solid temperature drops to a certain value and then the liquid is allowed to move over the hot surface. After starting the wetting of the hot surface, the moving front of the wet region is

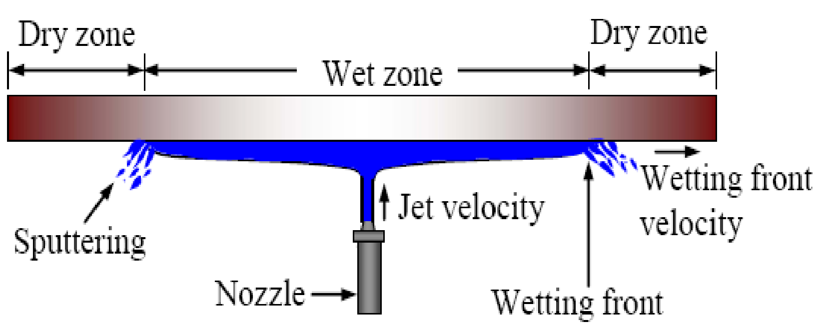


Fig.1.1: Jet impingement quenching

described as wetting front in this study. The local wall temperature at the wetting front is important for theoretical modeling of the quenching problem.

1.2.3 Boiling Phenomena

The interaction between liquid and hot solid objects occurs in a wide variety of industrial, domestic and environmental applications. When a liquid contacts on a hot solid surface, heat is transferred from the solid to the liquid phase by the processes of conduction, convection and radiation. This energy can be used to increase the temperature of the liquid, or alternatively to vaporize liquid from the base of the liquid. A typical pool boiling curve is shown in Fig. 1.2. Different regimes of pool boiling were first identified by Nukiyama [3]. An appreciation for the underlying physical mechanisms may be obtained by examining the various modes or regimes of pool boiling as shown in Fig. 1.2. Different boiling regimes may be delineated according to the value of wall superheat, ΔT_{sat}.

Natural convection: Natural convection boiling exists when the wall superheat, $\Delta T_{sat} \leq 5$ ^{0}C. In this regime there is an insufficient vapor in contact with the liquid phase to cause boiling at the saturation temperature. As the wall superheat is increased, bubble inception will eventually occur, but below the point of Onset of Nucleate Boiling, ONB, fluid motion is determined principally by natural convection effects.

Nucleate boiling: Nucleate boiling exists when the wall super heat, ΔT_{sat} = 5~30 ^{o}C. In this range, two different flow regimes may be distinguished. Isolated bubbles form at nucleation sites and separate from the surface, as illustrated in Fig. 1.2. For the higher value of ΔT_{sat} in the nucleate boiling range, the vapor escapes as jets or columns, which subsequently merge into slugs of vapor. At the end of this regime, the heat flux reaches its maximum value which is usually termed as critical heat flux, CHF.

Transition boiling: The regime corresponding to ΔT_{sat} = 30~120 ^{o}C is termed as transition boiling, unstable film boiling, or partial film boiling. Bubble formation is now so rapid that a vapor film or blanket begins to form on the surface. At any point on the surface, conditions may oscillate between film and nucleate boiling, but the fraction of the total surface covered by the film increases with increasing ΔT_{sat}.

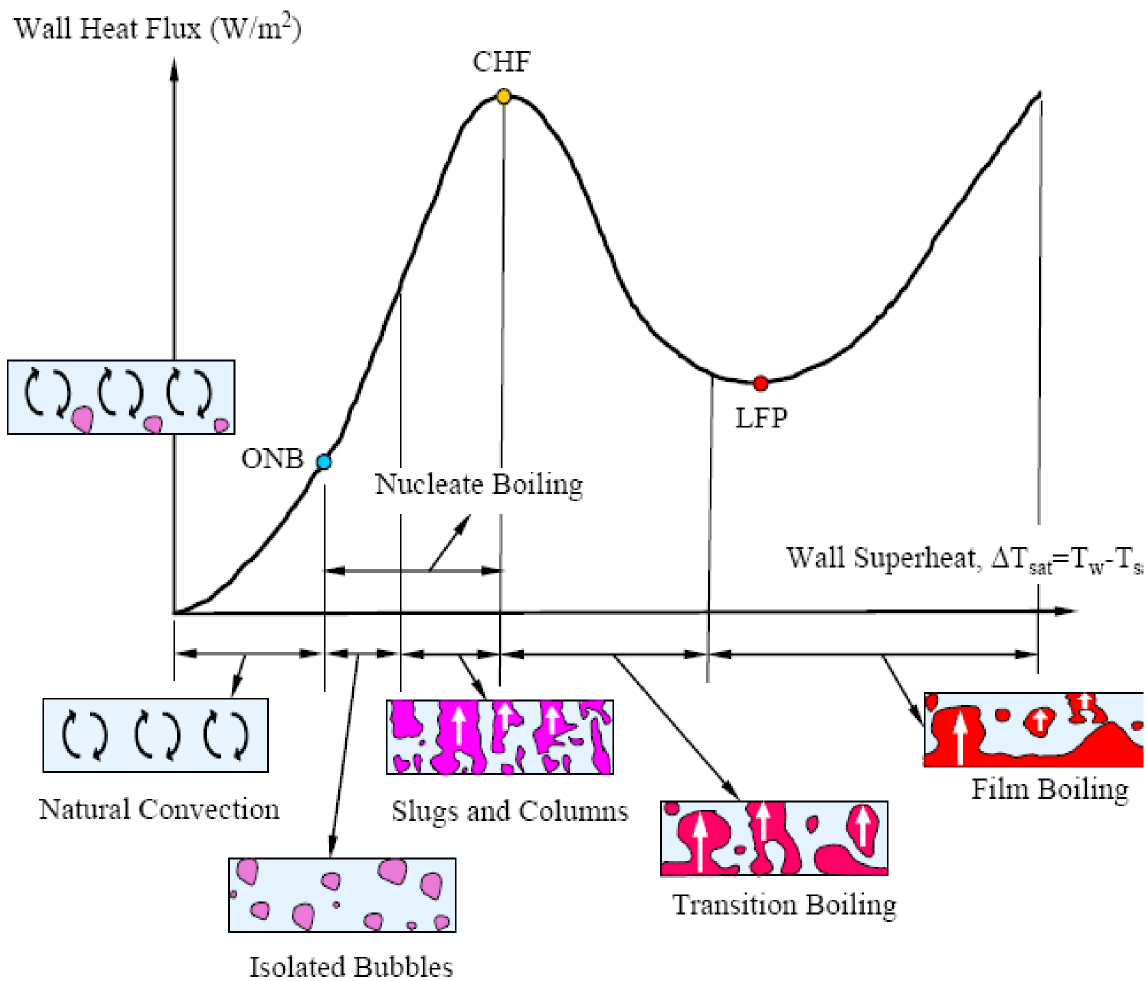


Fig.: 1.2 Typical pool boiling curve for water at one atmosphere.

Film boiling: This mode of heat transfer happens when the value of ΔT_{sat} exceeds 120 ^{o}C and at this stage the surface is completely covered by a vapor blanket. The minimum heat flux point in the film boiling regime is sometimes described as the Leidenfrost point, LFP.

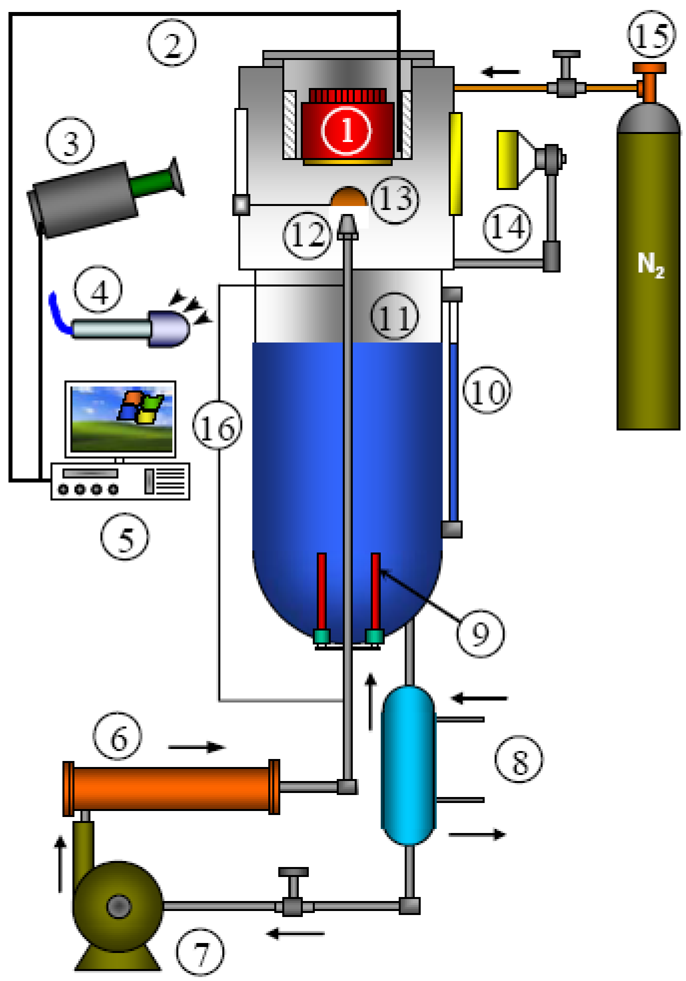
1.3 Literature Survey

Free impinging jet of liquid on heated solid surface is used in many manufacturing industries for cooling and controlling of mechanical properties of materials. It is the most effective cooling technique at the moment and it is popular for its simplicity [4]. Required temperature control is one of the important criteria to obtain a particular mechanical property of a steel strip employed in the metal processing industry. Accelerated cooling is employed in steel mills to reduce the duration of cooling process, in order to obtain the desired grain structure [5]. During the loss of coolant accident (LOCA) in Nuclear Power plant, jet impingement cooling is the most appropriate technique. In order to control the effective cooling process on required level, it is important to accurately evaluate the heat flux distribution as well their history on the hot solid surface.

Many experimental and theoretical researches have carried out on jet impingement quenching for clear understanding of this important process. Filipovic et al. [6,7] developed mathematical models for planar and circular impinging jets on a moving carbon steel plate and found that the increase of the sub cooling that represent the difference between the saturation and the jet temperatures, heat flux increases, considerably, at the stagnation point. The same trend was found experimentally by Robidou et al. [8] for film and transition boiling regimes and the critical heat flux, for an impinging jet with rectangular cross sectional area of $1 \times 9 mm^2$ on a stainless steel plate. They also found that the increase of the jet velocity from 0.7 to 0.8 m/s did not produced any significant effect on the heat flux for the entire boiling curve.

In experimentally investigation of the "Thermal and Hydrodynamic Characteristics of Jet Impingement Quenching for High Temperature Surface", by A. K Mozumder, et al.[1] is used the various components of the experimental setup and test procedure for collecting the thermal, audible and visible data during quenching of the hot cylindrical blocks are discussed detail in Mozumder et al. [1]. Brief description of the major components of the experimental apparatus is given below.

The experimental set-up shown in Fig. 1.3 contains five major components, a heated block, a fluid flow system, a data acquisition system, a high-speed video camera and a sound measuring unit. At the beginning of the experiment, the water container (11) is filled with distilled water up to a certain level which can be seen through the level gauge (10). The pump (7) produces a water jet through the nozzle (12) of diameter 2 mm, which is located centrally 44 mm from the test surface (1). A shutter (13) is mounted in front of the nozzle to prevent water from striking the block (1) prematurely and to maintain a constant water temperature by forcing it to run within a closed loop system. The desired temperature of the water is obtained by controlling the main heater (9), auxiliary heater (6) or by adding cooling water to the cooler (8). The desired initial temperature of the block (1) is achieved by heating it with an electrical heater mounted around the block. A dynamic strain meter (16) is attached at two points of the flow line before the nozzle for



1. Tested block, 2. Thermocouple wire, 3. High-speed video camera, 4. Microphone, 5. Data acquisition system, 6. Auxiliary heater, 7 Pump, 8. Cooler, 9. Main heater, 10. Level gauge, 11. Liquid tank, 12. Nozzle, 13. Rotary shutter, 14. Spot light, 15. Nitrogen cylinder 16. dynamic strain meter (for measuring jet velocity)

Fig. 1.3: Schematic diagram of the experimental set-up

measuring differential pressure from which jet velocity is calculated and this velocity is adjusted by a regulating valve. Nitrogen gas is fed around the heated surface by opening the cylinder valve (15) to create an inert atmosphere and consequently, prevent oxidization of the test surface. The whole experiment is conducted at one atmospheric pressure. When all the desired experimental conditions are fulfilled, then the shutter (12) is opened for the water jet to strike the center of the flat surface of the heated block. The high speed video camera (3) starts simultaneously at the signal of the shutter opening to record the flow pattern over the heated block surface and at the same time, the sixteen thermocouples measure the temperatures inside the heated block. Sound has been also recorded simultaneously with the microphone (4) for some conditions.

1.3.1 Wetting Front

Hammad et al. [9] conducted experiments for investigating the heat transfer characteristics and wetting front during quenching of a high temperature cylindrical block by water jet at atmospheric pressure. Ochi et al. [10] also experimentally investigated transient heat transfer using circular water jet impingement. Their test piece was a flat plate. They observed that heat flux at the stagnation point (in the central region) was higher the values at further radial positions. In the stagnation region the heat flux increases with water subcooling and with jet velocity divided by the nozzle diameter. Their observation revealed that the velocity of the rewetting front increases with nozzle diameter, jet velocity and water subcooling.

In quenching experiments on large test pieces a phenomenon termed ‘wetting front’ [9], ‘quench front’ [11] or ‘wet-front’ [12] has been observed. It is a little difficult to definitely define what the ‘wetting front’ is. The wetting front phenomenon should not be thought of as a single point or line but the entire transition boiling region should be understood to be a part of the wetting front. However, for convenience of discussion, in the present study, the wetting front is defined as follows:

In all of the experiments conducted by Mozumder et al. [1] and Hammad et al. [9], a black region at the outer zone of the moving liquid was observed on the basis of the video images. The wetting front is defined as the visible outer edge of this black region in the present study. Most of the time, an inner edge of this black region is also visible. A complete thermal and hydrodynamic criterion for this moving wetting front has not yet been clarified.

1.3.2 Wetting Delay / Resident Time in Quenching

When the liquid was first impinged on the hot surface it remained stagnant in a small impingement region for a certain period of time before covering the entire surface. This time period varied from fraction of second to a few minutes which depend on the experimental conditions. This wetting delay period is described as the resident time, t^* in the present study. The radius of the stagnation area during the resident period is described as the stagnation radius, r^*. The local wall temperature at the stagnation radius at the resident time is represented by T_w^* in this study. Figure 1.3 describes the above mentioned definition of quenching phenomena by using a cooling curve. Just after the resident time the wetting front starts moving and

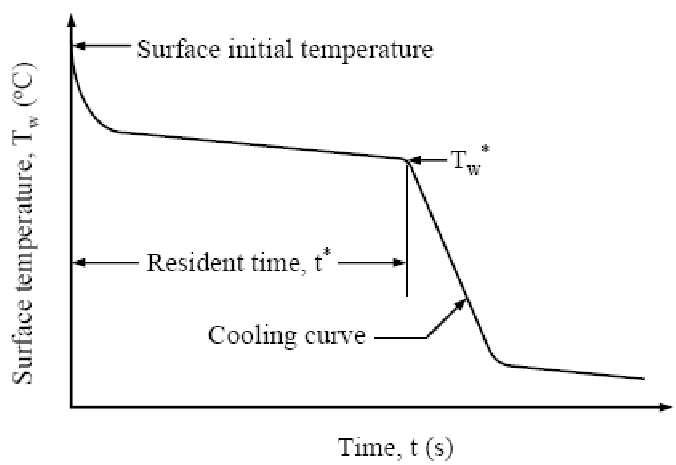


Fig.: 1.3 Cooling Curve during Quenching

consequently the surface temperature drops at a faster rate. Before the resident time, the surface temperature drops slowly and almost at a constant rate though there is a sudden drop of temperature at the very beginning of the jet impingement.

1.3.3 Rewetting Temperature

Chan and Banerjee [13] is defined the rewetting as the re-establishment of continuous liquid contact with a hot dry surface. Carbajo [14] reported that rewetting or quenching of a hot surface occurred when the coolant re-established contact with the dry surface. Furthermore, this phenomenon took place when the temperature of the surface cooled down enough to allow a change in heat transfer region from film boiling to transition or nucleate boiling.

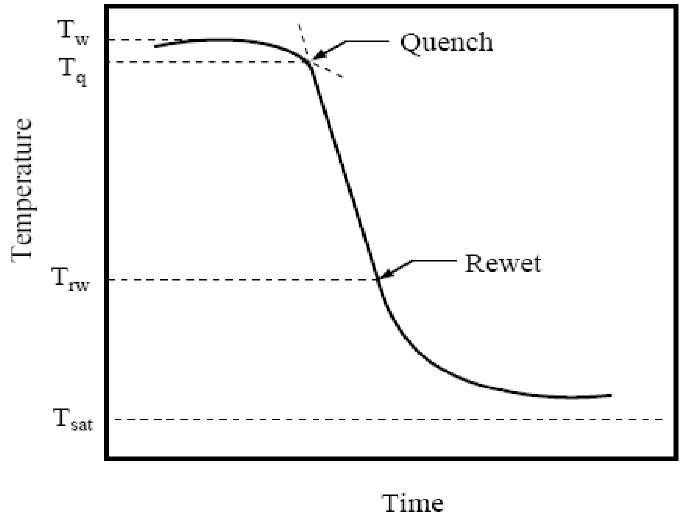


Fig.: 1.4 Illustration of quench and rewet temperatures

1.3.4 Rewetting Velocity

Rewetting velocity is described as the rate of movement of the wetting front position over the heated surface or in short, the speed of the rewetting point. It gives an indication of how quickly the coolant contributes to effective heat removal from the hot surface. Locating the position of the wet front is very difficult either because of the very fast wet-front velocities or due to the large generation of vapor which prevents clear visibility of the wet front. Dua and Tien [15] defined wetting velocity as wet-front velocity which was calculated by measuring the time taken for the wet front to pass between two marked locations on the tube surface. The time taken by the wet front to traverse this distance was measured directly by a stop watch and also by the chart recorder with the aid of an electronic marker which is pressed to mark, on the Temperature-time plot, both of the times when the wet front passes through two specified locations on the tube.

1.3.5 Surface Temperature and Boiling Width

Mozumder at al. [1] reported that the width of the visible black region is designated as the 'boiling width'. The outer edge of this 'boiling width' is defined as the 'wetting front' and the inner edge is by 'stop boiling'. It is assumed here that the boiling is stopped (or not vigorous) and the forced convection mode of heat transfer becomes dominating in the radial position located at the further inside of the 'stop boiling'. The temperature at the stop boiling is significantly higher than 100 ^{o}C. Therefore, there is a chance of boiling but the stop boiling region's corresponding color is not dark. The dark region is described as the vigorous boiling region in this study. So, this might be explained in this way that boiling at a lower intensity (not vigorous nucleate) might happen in that position and somehow the visual observation can not detect that.

The main objective of this sub-section is to introduce a possible interrelation between the surface temperature and boiling width. The surface temperature at maximum heat flux position is always within a certain range for any experimental condition. This range is considered as the temperature range from 120-200 ^{o}C for the nucleate boiling. The maximum heat flux, q_{max} position is always in between the position of wetting front and stop boiling and the surface temperature for q_{max} is also always in between the temperature of the wetting front and the stop boiling as expected. The surface radial temperature gradient in the boiling zone decreases with radial position. The nucleate boiling temperature range covers more area if the radial temperature gradient is smaller. Therefore, it is easy to expand the boiling temperature range in the wider region where the temperature gradient is smaller and thus the boiling width, W increases with radial position.

1.3.6 Solid Material Properties and Boiling Width

Material thermo-physical properties affect the width of the boiling region. Mozumder et al. [1] reported that, when all the experimental parameters remain the same, for a particular position of wetting front, the boiling width is observed to be wider for copper than brass. The low density spacing of isotherms or lower temperature gradient with space [1] indicates that the boiling width is wider. The boiling width for steel is not as wide as copper and brass because of the higher density of isotherms of steel and brass compared to copper.

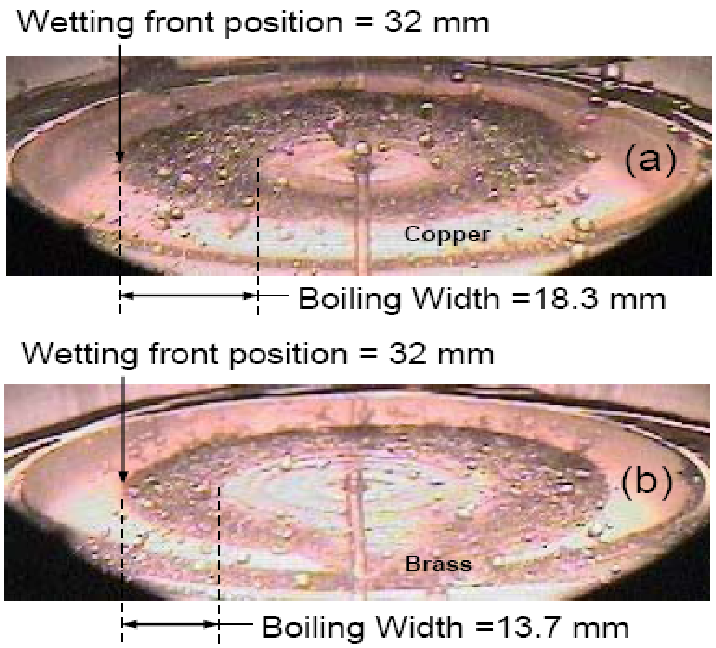


Fig. 1.5 : Variation of boiling width with materials for the same wetting front position [1]

(a) Cu, $T_b = 300\ ^oC$, $\Delta T_{sub} = 20$ K, u = 3 m/s, long resident time.

(b) Bs, $T_b = 300\ ^oC$, $\Delta T_{sub} = 20$ K, u = 3 m/s, short resident time.

Figures 1.5 (a) and (b) reveal that for the same wetting front position (32 mm) the boiling width for copper is 18.3 mm and that of brass is 13.7 mm.

1.4 Objectives

The present study is conducted mainly in analytically (and using empirical correlations) and the analytical solution is verified with the experimental data collected by Mozumder et al. [1]. The primary aim of this study is to obtain the criteria for the movement of the wetting front.

Specific objectives of this study are as follows:

i. To investigate the wetting front movement mechanism and search for the dominating parameters responsible for this movement.

ii. To establish a relationship among dominating parameters of wetting front movement.

iii. To propose a governing equation for the balancing of the generated forces (jet impingement force on solid surface (driving force); shear force between moving liquid and solid surface; surface tension force by the bubbles to the solid surface; and bubbles' bursting pressure force).

iv. To establish a criteria for the movement of the wetting front from the proposed force balancing equation.

v. To verify the proposed criteria for the wetting front movement with the experimental data collected by Mozumder et al. [1].

The results of this analysis will improve the understanding for the heat transfer mechanism of water jet cooling and hence improve the controlled cooling process.

CHAPTER-2

ANALYTICA MODEL

2.1. Introduction

After impinging a water jet on a hot solid surface, different forces come into play against the driving jet force due to hydrodynamic and thermal reasons. These forces are driving Jet force, F_j; Resisting shear force between the moving liquid and the solid surface, F_s; Bubble detaching force created due to the viscosity of liquid, F_{de} and Bubble explosive or bubble bursting pressure force, F_{exp}.

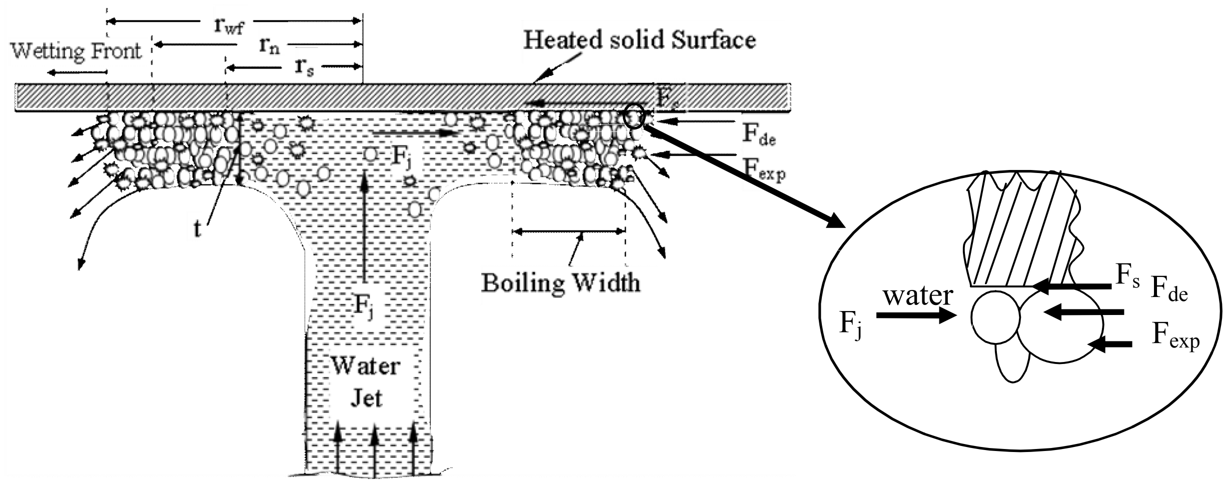


Fig. 2.1 : Simplified geometry for various forces and wetting front movement during jet impingement quenching

2.2. Driving Force

Driving force is simply the force needed for the wetting front to go towards the outer circumference of the hot surface. The jet force is the only driving force here which drives the fluid to a forward movement.

2.2.1. Jet Force

In steady flow conditions, the force on a fluid flow in a set direction is equal to its mass flow rate times by the change in velocity in the set direction. The Jet force, F_j on a stationary flat plate is-

F_j = mass x change of velocity

$= Q\rho V_j = \rho A V_j^{\,2}$……………………………………….(2.1)

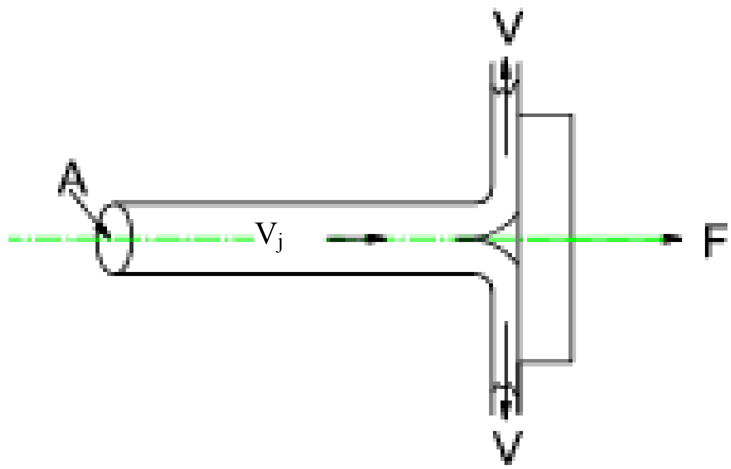


Fig. 2.2 : Water jet impinging on a hot solid surface

Considering forces only in the horizontal direction $u_1 = V$ and $u_2 = 0$ [u_1 = horizont component and u_2 = vertical component]

Jet force F_j is the driving force of water which is resisted by different type of resistan forces generated during movement of the wetting front.

2.3. Resistance Forces

The resistance forces act against the driving force, F_j. The resistance force are summation of Shear force, F_s; Bubble detaching force, F_{de} and Bubble explosive pressure force, F_{exp}. When all the forces are balanced, the driving force is equal to the summation of all the resistance forces. The balancing criteria and their mechanism will be described in this chapter.

2.3.1. Shear Resistance Force

Shear resistance force is created due to the viscosity of the fluid and the surface roughness of the solid surface. Shear resistance force is directly proportional to the viscosity of the fluid and the surface roughness of the solid surface. Viscosity is the property of the liquid which resist the flow between two successive layers. When the fluid flows over the solid surface, the fluid layer adjacent to the surface come to the velocity of the stationary surface, i.e. zero velocity. This fluid layer effects the adjacent layer. This viscous effect comes to play up to the boundary layer and consequently the overall flow velocity retards.

The resisting shear force is equal to the product of the shear stress and the area of the surface over which the fluid flows. This force calculated by this equation,

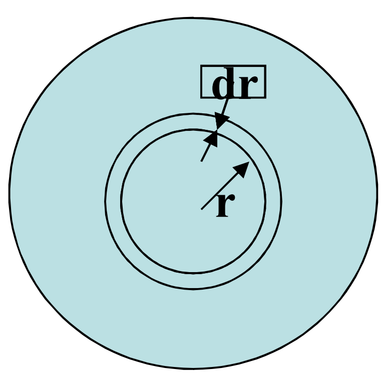
$$F_s = \tau \int dA \qquad \text{.................................(2.2)}$$

The shear stress can be estimated from Newton's law of viscosity, which states that-The shear stress acting on a fluid is proportional to the rate of shear strain.

Mathematically, $\tau \alpha \frac{du}{dy}$

$$\tau = \mu \frac{du}{dy} \qquad \text{.......................................(2.3)}$$

Area of the surface dA over which the fluid flow is obtained by integrating the radius dr from 0 to r.



$$\mathbf{A=} \int dA = \int_0^r 2\pi r dr \qquad \text{...............(2.4)}$$

Putting the value of (2.3) and(2.4) in (2.2)

$$F_s=\int_0^r \mu\frac{V}{t}2\pi r dr \text{ ....(2.5)}$$

du is the velocity difference between the layer adjacent to the stationary surface and the free surface of the liquid, i.e. du = u-0 = u= V. V is the local liquid velocity on the surface. The thickness t of the flowing fluid over the hot solid surface is obtained by applying the continuity equation between the jet flow rate and flow rate over the surface at a point.

The flow rate due to the jet with velocity V_j: $Q = AV_j$

$$= \frac{\pi d^2 V_j}{4} \text{ ....(2.6)}$$

And flow rate over the surface is-

$$Q=2\pi r t V \text{ ....(2.7)}$$

Equating the Eqns. (2.6) and (2.7) obtained the thickness t as-

$$t = \frac{d^2 V_j}{8rV} \text{ ....(2.8)}$$

Now, for a particular position n, Eqn. (2.5) becomes-

$$F_s = \frac{16\pi\mu V_n^2 r_n^3}{3d^2 V_j} \text{ ....(2.9)}$$

Remaining net jet force after overcoming the shear force is equal to the force of fluid at point n is-

$$F_r= \rho A_n V_n^2. \text{ ....(2.10)}$$

Where A_n is the area of the cross section through which the fluid flows.

$$A_n= 2\pi r_n t$$

$$= \frac{\pi d^2 V_j}{4V_n} \qquad \text{[Putting, } t = \frac{d^2 V_j}{8 r_n V_n} \text{]}$$

The value of A_n putting in the equation(2.10)

$$F_r = \frac{\rho \pi d^2 V_j V_n^2}{4V_n}$$

$$= \frac{\rho \pi d^2 V_j V_n}{4} \quad \text{.......................................(2.11)}$$

Now by force balancing among the Eqns.(2.1), (2.9) and (2.11)

$$F_S + F_r = F_j$$

$$\frac{16\pi\mu V_n^2 r_n^3}{3d^2 V_j} + \frac{\rho \pi d^2 V_j V_n}{4} = \rho \frac{\pi d^2 V_j}{4} \quad \text{.................................(2.12)}$$

From this equation can be obtained the velocity V_n of the fluid at point n. Putting the value of V_n in Eqns. (2.9) and (2.11), the values of F_s and F_r can be estimated.

2.3.2. Bubble detaching force

Throughout the bubble growth process, interfacial tension acts along the contact line where the interface meets the solid surface and tends to hold the bubble in place on the surface. The wetting front go to forward need to over come this bubble detaching force. This force is calculated by the following equation:

$$F_{de} = 2\pi R\sigma \quad \text{Newton / Bubble.........................(2.13)}$$

Where R is the bubble departure diameter and it is calculated by Van P. Carey [17] and σ is the surface tension of the fluid with unit N/m.

The diameter at release is primarily determined by the net effect of force acting on the bubble as it grows on the surface. Interfacial tension action along the contact line in variably acts to hold the bubble in place n. The surface buoyancy is often a major player in the force balance although its effect depends on the orientation of the surface with respect to the accelerating gravitational body force vector. For an upward facing horizontal surface, buoyancy directly acts to detach the bubble, whereas for similar downward facing surface buoyancy acts to keep the bubble pressed against the wall which is actually the situation in the present study.

If bubble grows very rapidly, the inertia associated with the induced liquid flow field around the bubble may also tend to pull the bubble away from the surface. When the liquid adjacent to the surface has a bulk motion associated with it, drag and lift forces on the growing bubble may also act to detach the bubble from the surface. The rate of bubble growth and the shape of the bubble (hemispherical or spherical) may effect the condition for bubble release, the departure diameter may be effected by wall superheat or heat flux, the contact angle, the thermo physical properties of the liquid and vapor phases. The departure diameter of bubbles during nucleate boiling has been the subject of numerous investigations over the past 60 years. In experimental studies, the departure diameter was typically determined from high speed movies of the boiling process. Based on the data obtained in this manner, a number of investigators have proposed correlation equations that can be used to predict the departure diameter of bubbles during nucleating boiling. In a subsequent study, Cole[18] proposed the equation.

$$B_o^{1/2}=0.04J_a \quad \text{……………………..…….(2.14)}$$

This correlations is written in terms of Bond number B_o defined as

$$B_o=\frac{g(\rho_l-\rho_v)d_d^2}{\sigma} \quad \text{……………….……..(2.15)}$$

and Jakob numbers J_a defined as

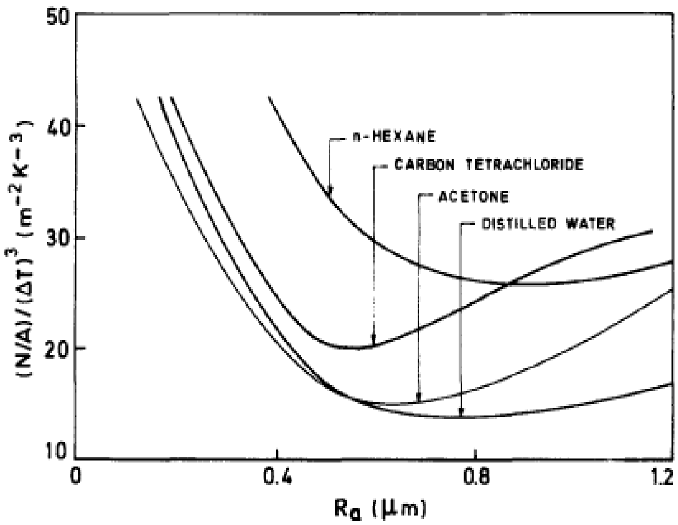
$$J_a=\frac{\rho_l c_{pl}[T_w-T_{sat}]}{\rho_v h_{vl}} \quad \text{…………...……………(2.16)}$$

If the total number of bubbles (NA_b) multiply with the equation (3.10), then the total bubble detaching force is

$$F_{de}=2\pi r_n \sigma \; NA_b \;\; \text{Newton ..…………………………..…..(2.17)}$$

Where N is the nucleation site density per unit area and A_b is the boiling area.

Nucleation site density as a function of the heat flux for various surface finishes. It can be seen from Fig. 2.3 that, as the micro roughness increases, the nucleation site density decreases and then increases after a certain heat flux.



Figu

Figure. 2.3: Dependence of *(N/A)/(Δ T)* ^{3} on Ra [18].

This nucleation site density not only depend on the surface roughness but also on the surface micro roughness, the surface tension of the liquid, the thermo physical properties of the heating surface and the liquid and the wall superheat. With the consideration of all the parameters (i.e., at different wall superheats, liquids, and surface materials), a correlation proposed by the R. J. Benjamin et al. [19] for the nucleation site density was obtained as-

$$\frac{N}{A_b} = Number\ of\ Bubbles\ per\ Area = 218.8(\mathrm{Pr})^{1.63}(\frac{1}{\gamma})\theta^{-0.4}(\Delta T)^3 \ldots\ldots\ldots\ldots\ldots\ldots(2.18)$$

Where Pr is the Prandlt number and is defined as-

$$\mathrm{Pr} = \frac{C_p \mu}{k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.19)$$

Counting for the physical properties of the liquid being boiled, the surface-liquid interaction parameter, γ, is defined by

$$\gamma = \left(\frac{k_s \rho_s C_{ps}}{k_l \rho_l C_{pl}} \right)^{1/2} \quad \text{……………………..………(2.20)}$$

and θ is given by

$$\theta = 14.5 - 4.5\left(\frac{RaP}{\sigma} \right) + 0.4\left(\frac{RaP}{\sigma} \right)^2 \quad \text{…………(2.21)}$$

The wall superheat, ΔT here is defined as T_i - T_{sat}. Where T_i is the interfacial temperature obtained by the following Equation [with the aid of the average temperature ($T_{s.avg}$), which is the average temperature at stop boiling (r_s) and front boiling (r_{wf}) positions]:

$$T_i = \frac{T_{s.avg} - T_l}{1 + \sqrt{(\rho c_p k)_l / (\rho c_p k)_s}} + T_l \quad \text{…………………..(2.22)}$$

T_l is here liquid initial temperature (same as the beginning of the jet impingement). But actually the liquid temperature increases as it travels over the hot solid surface. For the simplicity in the present study, the liquid temperature and its thermo physical properties are considered at corresponding initial temperature. A_b is the boiling area obtained by integrating the radius from stop boiling to front boiling. The radiuses of the stop boiling and front boiling are obtained from the video images of Mozumder et al. [1].

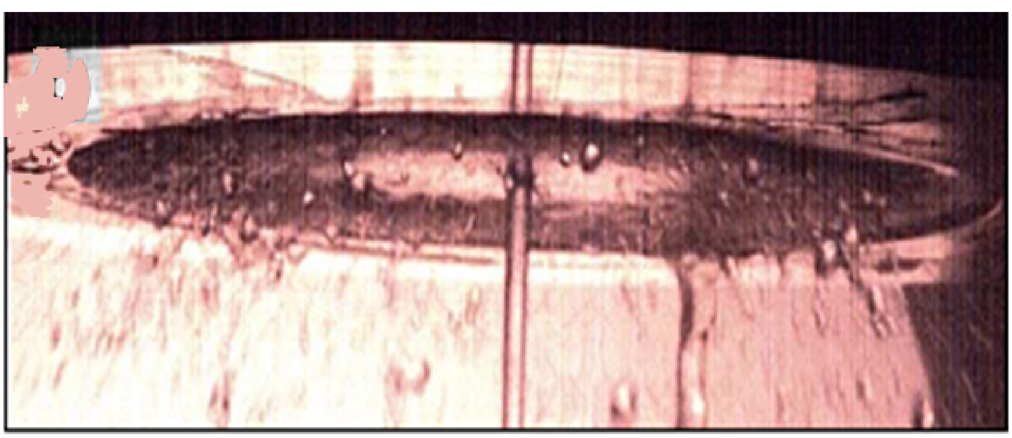


Fig. : 2.4 Boiling width during jet quenching.

$$A_b = \int_{s.b}^{w.f} 2\pi r dr \quad \text{………………………..(2.23)}$$

The boiling area varies with the conductivity of the materials. If the conductivity of the material is high, boiling width is wider due low temperature gradient like cupper and if the conductivity of material is low, the boiling width is narrower due to high temperature gradient like brass and steel. This happens, because, during quenching, low conductive material dissipates less heat to the liquid and consequently its temperature gradient remains high [1].

2.3.3. Bubble explosive force

When water come into contact with superheated solid, water takes heat from the hot solid surface at very high rate which depend on the temperature gradient and produce huge amount of vapor which goes away. This high stream of vapor creates high resistance to flow the water over the hot surface. This high resistance of vapor pressure plays a role for the water to change its direction of the flowing fluid at some angle. This bubble explosive pressure force, F_{exp} can be estimated by the following Equation:

$$F_{exp}=(2\pi r_n t_n)(P_{exp}-P_{atm}) \qquad (2.24)$$

Bubbler explosive pressure, (P_{exp}) of water is taken at surface temperature of n^{th} position. If the vapor explosive pressure, P_{exp} becomes weaken for the low temperature of the solid surface, the liquid over comes this pressure and goes forward. On the other hand, far from the center, temperature of the solid surface becomes low, but also fluid energy become very low. Hence the velocity of the flowing fluid becomes very small which cannot overcome this bubble explosive force.

Now, the driving force is only the jet force which plays against all the resistance forces and helps the wetting front to move forward on the hot surface. The total resisting force is the summation of Shear force, F_s; Bubble detaching force, F_{de} and Bubble explosive pressure force, F_{exp}.

If the driving force is smaller than the total resistance forces at a particular position; the wetting front will not reach there.

This condition can be written mathematically by the following Equation:

$$F_j < (F_s + F_{de} + F_{exp}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.25)$$

If the driving force is equal to the total resistance force at a particular position on the hot solid surface the wetting front will be stagnant at that point.

This condition can be written by the following Equation:

$$F_j = (F_s + F_{de} + F_{exp}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.26)$$

If the driving force is greater than the total resistance force at a position on the solid surface, the wetting front will be moving forward till the condition prevails.

This condition can be written by the following Equation:

$$F_j > (F_s + F_{de} + F_{exp}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.27)$$

CHAPTER -3

RESULT AND DISCUSSION

3.1. Experimental Validation

The data for the validation of the above criteria discussed in previous chapter of wetting front movement [Eqns. (2.25-2.27)] are incorporated from Mozumder, et al. [1] with various solid surface initial temperature, water sub cooled temperature, jet velocity and different solid surface material.

3.1.1. Experimental Data

Temperatures were measured [1] beneath the hot surface inside the block on which the jet was impinged. These temperatures were then used to estimate the surface temperature because it was impossible to measure the surface temperature directly during quenching with the present apparatus. A two-dimensional inverse solution [9] for heat conduction was applied for estimating the surface parameters based on the measured temperatures. Temperature was measured at eight different locations for each particular depth inside the block. To improve the space resolution of the calculation procedure additional points were interpolated between the measured points taking into account time and space trends in the data. The Eqn. (2.22) is used for calculating the appropriate interfacial surface temperatur at the every time [1, 9].

When the jet first struck the center of the hot surface, liquid did not cover the entire heated area immediately. The liquid quickly spreads over a small central region about two to four times the jet diameter and then splashed out or deflected away from the surface. The size of this region of liquid/solid interaction remained relatively fixed for a considerable period of time. Finally the wetting front began to move across the surface and the departing angle increased with radial position. Reported by Mozumder et al. [1], the width of the visible black region is designated as the ‘boiling width’. The outer edge of this ‘boiling width’ is defined by them as the ‘wetting front’ and the inner edge is by ‘stop boiling’. The wetting front and the stop boiling position are detected from the video images. The corresponding surface temperatures at these key positions are estimated from the inverse solution. The surface radial temperature gradient in the boiling zone decreases with radial position. The nucleate boiling temperature range covers more area for the smaller radial temperature gradient. Therefore, it is easy to expand the boiling temperature range in the wider region where the temperature gradient is smaller and thus the boiling width increases with radial position.

Radial temperature distribution and time at different positions are presented in Table 3.1 during the movement of the wetting front.

Table 3.1: Experimental data for the position and surface temperature during wetting front movement (Cu, $T_b = 400\ ^oC$, $\Delta T_{sub} = 80$ K, u = 15 m/s.) [1]

Time (sec.)	Stop boiling position, r_{sb} (mm)	Wetting Front position, r_{wf} (mm)	Avg. radial distance r_n(mm) $=(r_{sb}+r_{wf})/2$	Stop boiling temp., T_{sb} (^oC)	Wetting Front temp., T_{wf} (^oC)	Avg. temp. $T_{s.avg.}$(^oC) $=(T_{sb}+T_{wf})$	Avg. interfacial temp. $T_{i,Expt.}$ (^oC), [Eqn.(2.22)]
1.1	4	8	6	180	240	210	202
2.4	8	13	10.5	150	220	185	178
4.9	14	20	17	140	220	180	173.2
8.3	18	26	22	125	200	162.5	156.45
11.2	24	32	26	120	170	145	139.6
16.5	37	47	42	125	140	132.5	127.64

The data from Table 3.1 are putted into the Eqns. (2.9-2.24) to calculate different forces. These forces are presented in Table 3.2 and compared with the actual phenomenon which occurred during the experiment (conducted by [1]). Estimated

3.1.2. RESULTS

Calculated forces are presented in Table 3.2.

Table 3.2 : Forces, time and position during movement of wetting front

(Cu, $T_b = 400\ ^oC$, $\Delta T_{sub} = 80$ K, u = 15 m/s)

Tim (sec)	r_n (mm)	Jet force F_j (N)	Shear force, F_s (N)	Bubble detaching force, F_{de} (N)	Remaining net driving force = (F_j- F_s- F_{de}) (N)	Bubble Explosive force F_{exp} (N)	$T_{i, Estm}$ (^oC) Eqn.(2.24& 2.26)	% of Error
1.1	6	0.705	0.013	0.1202	0.5717	5.040	130.21	35.6
2.4	10.5	0.705	0.061	0.1998	0.4443	2.980	121.00	32.1
4.9	17	0.705	0.175	0.353	0.1768	3.210	108.15	37.6
8.3	22	0.705	0.263	0.3356	0.1051	2.592	104.20	33.4
11.2	26	0.705	0.350	0.236	0.1185	1.729	103.82	25.6
16.5	42	0.705	0.479	0.203	0.023	1.412	100.75	21.1

(All the calculations are shown in Appendix-B)

The water jet starts to move with the jet force F_j=705 mN. For the uniform steady flow the jet force is constant for every time at the beginning of jet impingement. After passing the average radial distance 6 mm by the liquid in time 1.1 sec, the surface temperature reduced and hence reduced the resistance force. When the jet force becomes higher than the resistance force, the wetting front moves to start. At the average radial distance 6 mm, the shear force, F_s becomes 13 mN calculated by the Eqn. (2.9) which resists the jet force F_j. This shear force is smaller then the jet force, thus the wetting front overcomes this force and with the remaining jet force the wetting front wants to move forward, on the other hand, the higher surface temperature produces huge amount of bubbles at a continuous stream. These bubbles produce resistance to flow for the liquid over the hot solid surface. The bubbles resistance / detaching force acts all over the boiling width where the boiling take place. This bubbles resistance or detaching force at the radial distance 6 mm is 120.2 mN calculated by the equation (2.17). The remaining force (R.F.) after overcoming the shear and bubbles' resistance/detaching forces is 571 mN. The remaining force drive the wetting front to move forward, but the explosive force produced resistance by the high steam flow which steam is produced from the contacted liquid by the super heated solid. This explosive force is 5040 mN calculated by the equation (2.24).Where the remaining force is smaller than the explosive. At this condition the wetting front is stagnant at radial distance 6 mm. When the jet force or the remaining force is greater than the explosive force then the wetting front will be move forward. For the constant jet force it only possible when the surface temperature will be less then 130.33 ^{0}C. The temperature 130.33 ^{0}C is obtained from the saturated table corresponding to the saturated pressure (P_{exp}=281689 Pa) of water. Saturated pressure of water is obtained by equating the remaining force with the bubble explosive force Eqn. (3.24).

With increasing the traveled distance by the jet of liquid, shear force increases and jet force is weaken gradually. The bubble detaching force is increased due to the increase of the boiling width caused by the falling of the surface temperature. The bubble explosive force is gradually decrease by the decrease of the surface temperature. But summation of all the resistance forces gradually increases which decreases the net driving jet force. Hence, after traveling a definite distance, the net driving jet force becomes very small which cannot overcome the resistance forces. The calculation at time 16.5 sec with the radial distance 42 mm [Table 3.2], the remaining force after overcome the shear force and bubble detaching force is 23.0 mN. At this force the wetting front cannot move forward at temperature 100.75 ^{0}C. [Actually the net driving force is 23.0 mN, which is much less than the bubble explosive force 1412 mN. Therefore, there is no way for the wetting front to move].

3.1.3. Calculated Parameters

Figure 3.1 represents the comparison between the experimental interfacial surface temperature, T_{exp} (^{o}C) and the estimated interfacial surface temperature, T_{Estm} (^{o}C). An average error of around 30 % is observed here. Many physical parameters are involved during the process of estimating the temperatures which contributes a part of this error.

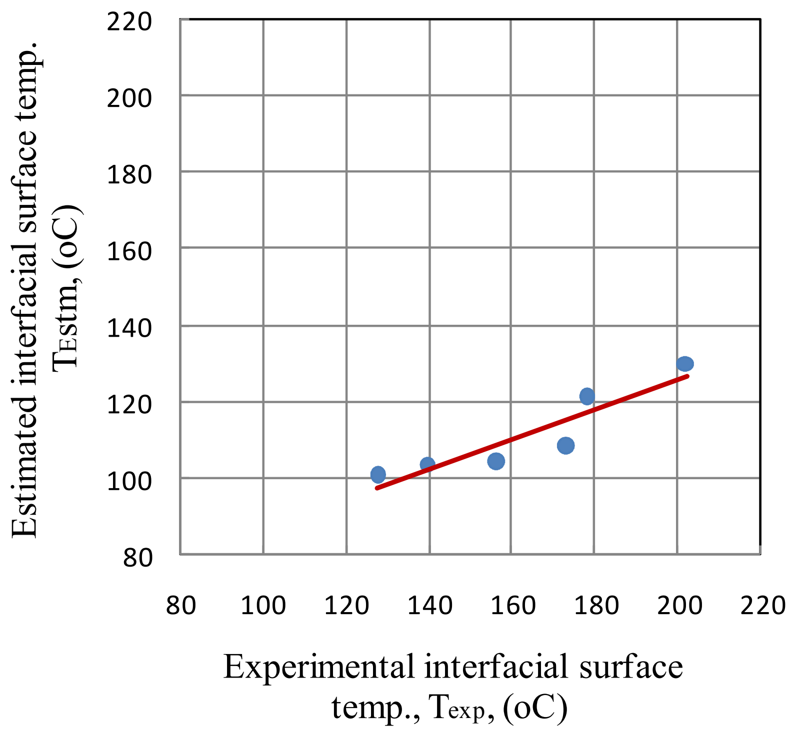


Fig.3.1: Agreement between experimental interfacial surface temperature, T_{exp} (^oC) and estimated interfacial surface temperature, T_{Estm} (^oC)

Figure 3.2 shows the variation of shear force with radial distance. Share force is mainly a hydrodynamic property, due to which, as the moving front of the liquid covers more distance, the share force increases monotonously. Figure 3.2 also represents the bubble detaching force as a function of radial position on hot solid surface. With the increase of radial distance up to about 20 mm, the solid surface temperature is such that it favors the bubble nucleation which consequences the formation of many vapor bubbles on the hot surface. On the other hand, the total bubble detaching force from a surface directly depends on the number of bubbles generated on that surface. For this reason, the bubble detaching force is higher near about 20 mm radial position. After that, the solid surface temperature is not suitable for generating much number of bubbles, which results in decrease of bubble detaching force.

The variation of bubble explosive force with radial distance is shown in Fig. 3.3. The bubble explosive force directly depends on the vapor pressure generated inside the tiny bubbles and this vapor pressure depends on the saturated temperature of the liquid. Therefore, somehow the explosive force is a function of solid surface temperature. With the increase of radial distance, the solid surface temperature decreases which consequences of exponential falling of explosive force as reveals in the Fig. 3.3.

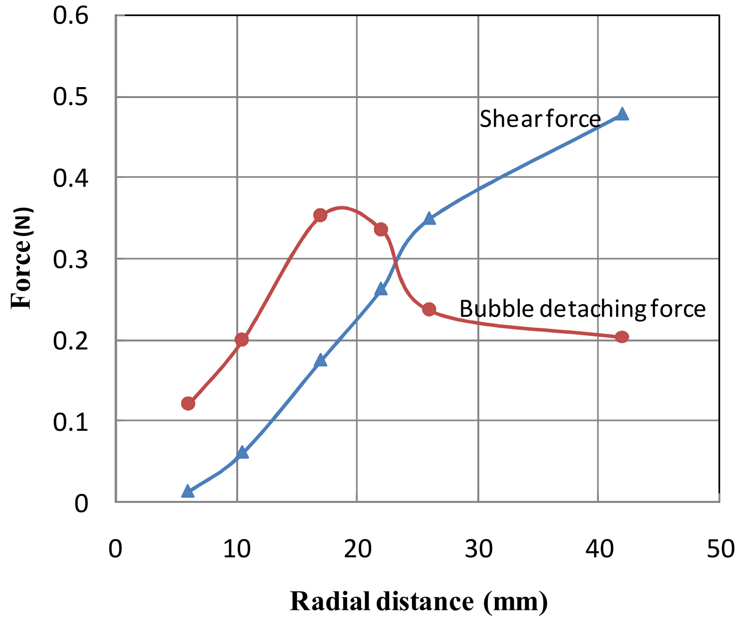


Fig. 3.2: Shear force and bubble detaching force with radial distance

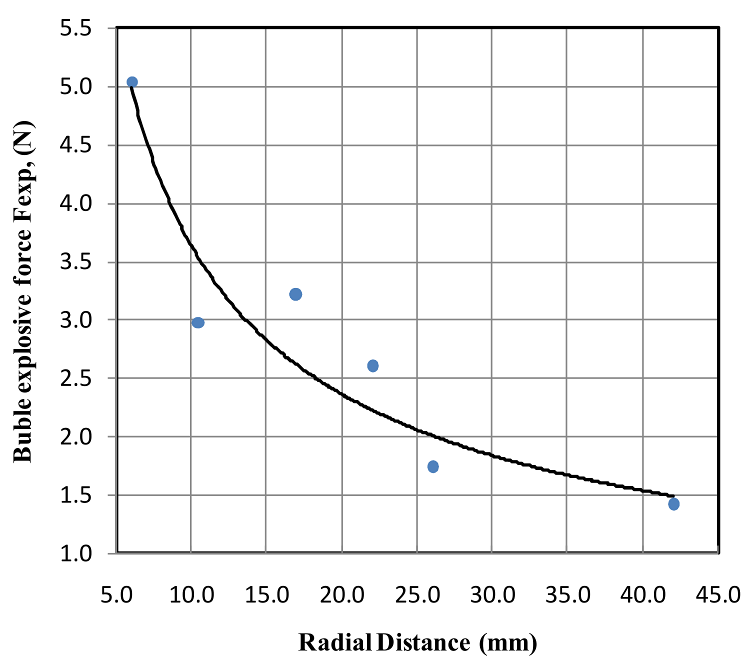


Fig. 3.3: Variation of Bubble explosive force with radial distance

3.2. Discussions

A lot of variables are involved in different force balancing processes and sub-processes in jet quenching. Starting from the thermo-physical properties of the solid and liquid, all of the experimental parameters considered are associated with this complicated quenching phenomenon. Some of the important variables other than experimental parameters that have been considered in the present investigation could be mentioned including the boiling width, the boiling pressure, the wetting front temperature, the stop boiling temperature and so on which were also judged by other researchers as they appeared in the literature. In this study a new term "wetting front movement criteria" has been introduced which may be for the first time in literature.

The thermo-physical properties of the solid and liquid are very difficult to determined with the change of temperature during the jet quenching process at different point. The jet force F_j is calculated at the initial water temperature, one the other hand to find out the wetting front velocity V_n the density of water is used at the initial water temperature. But in actual case, the water density decreases with increasing the water temperature. The same difficulty arises for the calculation of shear force. For the calculation of shear force, the water absolute viscosity is taken at the initial water temperature. But the absolute viscosity of water varies with temperature change at every point. The thickness of water (flows over the hot surface) is obtained by the use of continuity equation. In this case, the assumption is- there is no loss of water. But actually, when water flows over the super heated surface, a negligible portion of liquid turns into vapor and splashes away. This amount of vapor is not counted in the calculation. In calculating the bubble detaching force, equal bubble density allover the boiling width is considered. The temperature at the inner radius is always less than the outer. The bubble density at the inner portion of the boiling width is less than the outer portion of the boiling width. The boiling area is obtained by integrating the radius from stop boiling to front boiling radius. The stop boiling and front boiling radius is obtained visually Mozumder et al. [1]. The explosive force is calculated from the explosive pressure and considering the area generated due to the fluid thickness on the hot plate. During the force balance calculation, every individual bubble is considered two times. One is for the estimation of bubble detaching (viscous force) resistance and another is for the bubble explosive force calculation. If the bubble diameter is subtracted from the following fluid thickness for calculating the bubble explosive force, some error may be reduced. When the jet struck the surface, an explosive flow pattern was observed where the jet broke into thousands of tiny droplets with some departing angle [1]. The estimated surface temperature is obtained by equating the net remaining driving force with the bubble explosive force [with the aid of Eqn. (2.24) and (2.26)]. To find the net remaining force, all the thermo-physical properties of the solid and liquid are taken at the experimental surface temperature. This experimental temperature [1] contains some error naturally. If this error can be reduced, more accurate verification of the experimental data for the wetting front movement with the proposed criteria could be obtained.

CHAPTER-4
CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion

A relation for the wetting front movement in terms of the thermo-physical properties of the heating surface and the liquid and the metrological properties of the surface has been developed. This has been explained in terms of the viscosity, surface tension, shear stress, bubble radius, the wall superheat, bubble density, vapor pressure, and various dimension less number. There are very few publications in the literature that give the wetting front movement criteria during jet impingement quenching. The present investigation will make essential contributions in this field. Further comprehensive study is requisite for understanding these complicated phenomena. Overall intrinsic achievements at present from this investigation are summarized as:

1. There the bubble detaching force (creates due to surface tension) has estimated which acts against the jet force when the jet of liquid flows over the generated bubbles. This force is associated with the number of bubbles, bubbles diameter and surface tension of the liquid. The number of bubbles depends on the surface temperature which also associated with the thermal properties of the materials.
2. The bubble explosive force has been calculated which produced due to the bubbles explosion and which acts against the jet force when the jet of liquid flows towards the circumference. The bubble explosive force depends on the velocity of steam produced by the bursting of bubbles.
3. A relationship has been established among the driving force and the resistance forces which determines the criteria weather the wetting front will move or stagnant.
4. The criteria can also estimate the position of the wetting front i.e. the wetting front has reached or not reached at a specific point where the surface temperature is known.

5. An equation is established to estimate the theoretical velocity of the hydrodynamic wetting front of the liquid at different radial position. The wetting front velocity increases with the jet velocity for a specific distance and surface temperature.

4.2 Recommendation

In this science era, faster growing technology promotes mankind to augment their standard of living. The prerequisite for this technological development is the research and development in the sector of science and technology. Human beings are eagerly awaiting for the latest invention which leads to the consequence that research and development are an endless job. In this context, the research work delineated in this dissertation may serve as a primary foundation for some of the phenomena which will lead to future study.

The following study may be performed to get a more developed criterion for the wetting front movement:

i. A numerical code can be developed for a wide range of verification of the wetting front movement criteria as there is an enormous involvement of calculation for the verification of the criteria with experimental data.
ii. More precise experimental data is required for getting better verification.
iii. Direct measured data for the surface temperature, in spite of getting it from inverse solution [9], will be better to establish and verify the proposed criteria.

In future study, the criteria proposed in the present study for the movement of the wetting front, might be used for estimating the resident time during jet impingement quenching.

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Appendix-A

(Thermo-Physical properties of Materials)

Thermo-physical properties of working fluid and solid are tabulated in this section.

Table A.1: Thermo-physical properties of test section materials *

Material	Temp. (^{o}C)	Density, ρ (kg/m^3)	Sp. heat, c (kJ/kg.K)	Conductivity, λ (W/mK)	Diffusivity, a (m^2/s) $x10^{-5}$	√ρcλ ($kJ/m^2K\sqrt{s}$)
Copper	100	8862	0.393	379	10.00	36.33
	200	8831	0.406	374	10.41	36.62
	300	8794	0.416	369	10.08	36.74
	400	8752	0.425	363	9.759	36.75
Brass (70% Cu, 30% Zn)	100	8530	0.389	128	3.857	20.61
	200	8530	0.414	144	4.077	22.55
	300	8530	0.444	147	3.881	23.60
	400	8530	0.477	147	3.612	24.46
Steel (0.45% C)	100	7833	0.485	52	1.368	14.06
	200	7806	0.509	48	1.208	13.81
	300	7775	0.545	45	1.061	13.81
	400	7741	0.589	42	9.211	13.84

TableA.2 : Thermo-physical properties of water (up to saturation temperature)**

T_{liq} (^oC)	Density (kg/m^3)	Specific heat (J/kg.K)	Conductivity (W/mK)	Diffusivity (m^2/s) $x10^{-7}$	Viscosity (m^2/s) $x10^{-7}$	Prandtl number
20	997.755	4183.65	0.59909	1.44	10.3	7.2077
50	987.830	4178.50	0.64000	1.55	5.44	3.5086
80	971.635	4199.35	0.64684	1.64	3.62	2.2054
95	961.123	4214.00	0.67848	1.67	3.05	1.8253

Table A.3 : Thermo-physical properties of water (for superheated water) ***

Chemical formula: H_2o Molecular weight: 18.0156				Critical temperature: 647.3 K Critical pressure: 22,129 kPa Critical density: 351 kg/m^3			
T_{sat} (K) P_{sat} (kPa)	373.15 101.3	400 247	430 571	460 1172	490 2185	520 3773	550 6124
ρ_l (kg/m^3)	958.3	937.5	910.3	879.4	844.3	803.8	756.1
ρ_v (kg/m^3)	0.597	1.370	3.020	5.975	10.95	18.90	31.52
h_{lv} (kj/kg)	2256.7	2183.0	2092.8	1990.4	1871.5	1731.0	1562.6
c_{pl} (kj/kgK)	4.22	4.24	4.28	4.45	4.60	4.48	5.07
k_l (mW/mK)	679	685	683	671	646	618	581
Pr	1.72	1.35	1.10	0.98	0.90	0.87	0.87
σ (mN/m)	58.91	53.50	47.16	40.66	33.90	26.96	19.66

*Based on JSME Heat Transfer Hand Book, 1993, The Japan Society of Mechanical Engineers ed.

**Based on standard text book

***Based on Van P. Carey [17]

Appendix-B

(Calculations for the Experimental Verification)

Observation: 1 (time, t = 1.1sec)

Jet force or driving force with which the jet struck the surface [Eqn. (2.1)]

$$F_j = \rho A V_j^{\ 2} \qquad (A.1)$$

$$=998*(3.14*0.001^2)*15^2$$

$$=0.7051 \text{ N}$$

The value of water density ρ has been taken at jet water temperature from appendix B

Shear resistance up to the radial distance r_n is [Eqn. (2.9)]

$$F_s = \frac{16\pi\mu V_n^2 r_n^{\ 3}}{3d^2 V_j} \qquad (A.2)$$

And the remaining jet force after over coming the shear resistance force is [Eqn. (2.11)]

$$F_r = \rho A_n V_n^{\ 2}$$

$$= \frac{\rho\pi d^2 V_j V_n}{4} \qquad (A.3)$$

It can be obtained the velocity, V_n of jet after traversing a distance and at r_n radial position by the following force balance:

$$F_j - F_s = F_r$$

$$\text{or, } F_s + F_r - F_s = 0$$

$$\text{or, } \frac{16\pi\mu V_n^2 r_n^{\ 3}}{3d^2 V_j} + \frac{\rho\pi d^2 V_j V_n}{4} - \rho A V_j^{\ 2} = 0 \qquad (A.4)$$

From the Table 3.1, the stop boiling radius is 4 mm and front boiling radius is 8 mm and respectively the temperatures are 180 ^oC and 240 ^0C. Water properties are taken at jet issuing temperature from Appendix-A then,

$$\frac{16*\pi*1.005*10^{-3}*V_n^2*\left(6*10^{-3}\right)^3}{3*2*10^{-3}*15} + \frac{998*\pi*2*10^{-3}*15*V_n}{4} - 0.7051 = 0$$

$$V_n = 14.72 \text{ m/s}$$

Now putting this value in equation (A.2) and (A.3) to obtain the shear resistance force as

$$F_s = 0.0131 \text{ N}$$

And the remaining jet force at r_n radius after over coming the shear force is-

$$F_r = 0.692 \text{ N}$$

Now the total bubble detaching force is calculated by the equation

$$F_{de.total} = 2\pi R^* \sigma * NA_b$$

$$= \left[\pi * \sigma * \left\{ \frac{\sigma * Bo}{g*(\rho_l - \rho_v)} \right\}^{1/2} \right] *$$

$$\left[218.8*(P_r)^{1.63} * \left(\frac{1}{\gamma}\right) * \theta^{-0.4} * (\Delta T)^3 * 2\pi \int_{s.b}^{f.b} rdr \right] \qquad (A.4)$$

Where the bubble radius and the nucleation site density are measured by all the solid and liquid properties taken at the interfacial temperature from Appendix-A. This interfacial temperature [Eqn. (2.22)] is-

$$T_i = \frac{T_{s.avg} - T_l}{1 + \sqrt{(\rho c_p k)_l / (\rho c_p k)_s}} + T_l \qquad [T_{s.avg} = (T_{sb} + T_{fb})/2] \qquad (A.5)$$

$$= \frac{(210 - 20)}{1 + \sqrt{(862 * 4460 * 0.66)/(8831 * 407 * 374)}} + 20$$

$$= 202\ ^0C$$

$$\text{Bond Number, } B_o = \left\{ 0.04* \frac{\rho_l c_{pl} [T_{wi} - T_{sat}]}{\rho_u h_{ul}} \right\}^{1/2} \qquad (A.5)$$

$$= \left\{ 0.04 * \frac{862 * 4460 * [202 - 100]}{8.46 * 1678500} \right\}^2$$

$$= 0.924$$

Pranlt Number, $Pr = 0.94$

The surface-liquid interaction parameter, γ, is

$$\gamma = \sqrt{\frac{k_s \rho_s c_{ps}}{k_l \rho_l c_{pl}}} \qquad (A.6)$$

$$\gamma = \sqrt{\frac{862 * 4460 * .66}{374 * 8831 * 407}}$$

$$\gamma = 23.016$$

And, $\Delta T = T_i - T_{sat}$ (A.7)

$=(202-100)$

$=102$ K

Now putting this value in equation (A.4),

$$F_{de.total} = \left[\pi * 0.0372 * \left\{ \frac{0.0372 * 0.924}{9.81 * (862 - 8.46)} \right\}^{1/2} \right] *$$

$$\left[218.8 * (0.94)^{1.63} * \left(\frac{1}{23.02} \right) * (12.13)^{-0.4} * (102)^3 * 2\pi \int_{0.004}^{0.008} 0.006 \right]$$

$=0.1202$ N

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

$$F_j - F_s - F_{de.} = 0.7051 - 0.0131 - 0.120 = 0.5717 \text{ N}$$

The bubble explosive force

$$F_{exp} = (2\pi r_n * t_n) * (P_{exp} - P_{atm})$$

$$= \frac{\pi * d_j^2 * V_j}{4 * V_n} * (P_{exp} - P_{atm}) \qquad (A.8)$$

$$= \frac{\pi * 2 * 10^{-3} * 15}{4 * 14.72} * (1678500 - 103000)$$

$=5.04$ N

If the bubble explosive force is 5.04 N then on the behalf of the remaining jet force is not possible to over come, it only possible if the bubble explosive force is less then 0.5717 N. The bubble explosive force will be 0.5717 N if the explosive pressure is

$$0.5717 = \frac{\pi * 2 * 10^{-3} * 15}{4 * 14.72} * (P_{exp} - 103000)$$

$$P_{exp} = 281689 \text{ Pa}$$

And the saturated Estimated Temperature, $T_{i,Estm}$ corresponding to the superheated pressure, P_{exp}=281689 Pa of water is-

$$T_{i,\,Estm} = 130.33\ ^0C$$

Percentage of error of the estimated saturated temperature of the superheated liquid with respect to the estimated experimental interfacial surface temperature is

$$E=\frac{[Exp.value, T_i - Estm.value, T_{i,\,Estm}]}{Exp.value, T_i} \qquad (A.9)$$

$$=\frac{(202-130.21)}{202}$$

$$=35.6\ \%$$

Observation: 2 (time, t = 2.4 sec)

If the stop boiling radius 8 mm and front boiling radius is 13 mm and the temperature are 150 and 200 ^{0}C. the water properties taken at jet issuing temperature then the jet velocity is

V_n =13.70 m/s using the equation (A.3)

and the shear force is, F_s= 0.061 N

Bubble detaching force is F_{de} =0.1998 N using the equation (A.4)

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

$$F_j\text{-}F_s\text{-}F_{de.}=0.4443\ N$$

The bubble explosive force is,

F_{exp}=2.983 N using the equation (A.8)

If the bubble explosive force is 2.983 N then the jet is not possible to over come, it only possible if the bubble explosive force is less then 0.4443N. The bubble explosive force will be 0.4443 N if the explosive pressure is

$$P_{exp}=232270\ Pa$$

And the surface temperature with respect to the saturation pressure P_{exp}=232270 Pa is

$$T_i=121\ ^0C$$

Percentage of error of the calculated interfacial surface temperature with respect to the measured interfacial surface temperature is

$$E=32.10\ \%$$

Observation: 3 (time, t = 4.9 sec)

If the stop boiling radius 14 mm and front boiling radius is 20 mm and the temperature is 140 and 250 ^{0}C. The water properties taken at jet issuing temperature then the jet velocity is

V_n =11.27 m/s using the equation (A.3)

and the shear force is, F_s= 0.1752 N

Bubble detaching force is F_{de} =0.3531 N using the equation (A.4)

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

F_j-F_s-$F_{de.}$ =0.1768 N

The bubble explosive force is,

F_{exp}=3.210 N using the equation (A.8)

If the bubble explosive force is 3.210 N then the jet is not possible to over come. It only possible if the bubble explosive force is less then 0.1768 N. The bubble explosive force will be 0.1768 N if the explosive pressure is

P_{exp}=145315.66 Pa

And the surface temperature with respect to the saturation pressure P_{exp}=145315.66 Pa is

T_i=108.15 ^{0}C

Percentage of error with respect to the measured surface temperature is

E=37.6 %

Observation: 4 (time, t = 8.3 sec)

If the stop boiling radius 18 mm and front boiling radius is 26 mm and the temperature is 140 and 230 ^{0}C. the water properties taken at jet issuing temperature then the jet velocity is

V_n =9.39 m/s using the equation (A.3)

and the shear force is, F_s= 0.2635 N

Bubble detaching force is $F_{de.}$ =0.3365 N using the equation (A.4)

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

F_j-F_s-F_{de} = 0.1051 N

The bubble explosive force is,

F_{exp}=2.592 N using the equation (A.8)

If the bubble explosive force is 2.592 N then the jet is not possible to over come. It only possible if the bubble explosive force is less then 0.1051 N. The bubble explosive force will be 0.1051 N if the explosive pressure is

P_{exp}=123950.9 Pa

And the surface temperature with respect to the saturation pressure P_{exp}=123950.9 Pa is

T_i=104.2 ^{0}C

Percentage of error with respect to the measured surface temperature is

E=33.4 %

Observation: 5 (time, t = 11.2 sec)

If the stop boiling radius 24 mm and front boiling radius is 32 mm and the temperature is 135 and 225 ^{0}C. The water properties taken at jet issuing temperature then the jet velocity is

V_n =7.54 m/s using the equation (A.3)

and the shear force is, F_s= 0.3505 N

Bubble detaching force is F_{de} =0.2361 N using the equation (A.4)

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

F_j-F_s-$F_{de.}$ =0 .1185 N

The bubble explosive force is,

F_{exp}=1.729 N using the equation (A.8)

If the bubble explosive force is 1.729 N then the jet is not possible to over come. It only possible if the bubble explosive force is equal or less then 0..1185 N. The bubble explosive force will be 0.1185 N if the explosive pressure is

P_{exp}=121978.11 Pa

And the surface temperature with respect to the saturation pressure P_{exp}=121978.11 Pa is

T_i=103.8 ^{0}C

Percentage of error with respect to the measured surface temperature is

E=25.6 %

Observation: 6 (time, t = 16.5 sec)

If the stop boiling radius 37mm and front boiling radius is 47 mm and the temperature is 125 and 140 ^{0}C. The water properties taken at jet issuing temperature then the jet velocity is

V_n =4.80 m/s using the equation (A.3)

And the shear force is, F_s= 0.4793 N

Bubble detaching force is F_{de} =0.203 N using the equation (A.4)

And the remaining jet force at r_n radius after over coming the shear force and bubble detaching force is

F_j-F_s-$F_{de.}$= 0.0228 N

The bubble explosive force is,

F_{exp}=1.412 N using the equation (A.8)

If the bubble explosive force is 1.412 N then the jet is not possible to over come. It only possible if the bubble explosive force is equal or less than 0.0228 N. The bubble explosive force will be 0.0228 N if the explosive pressure is

P_{exp}=105321.29Pa

And the surface temperature with respect to the saturation pressure P_{exp}=105321.29 Pa is

T_i=100.74 ^{0}C

Percentage of error with respect to the measured surface temperature is

E=21.1 %