INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING
WWW.IJRAME.COM
ISSN (ONLINE): 2321-3051

Vol.11 Issue 4,
April 2023
Pg:- 17- 30

A Comparative Analysis of Evaporative Heat Transfer Effect in Nucleate Pool Boiling Process on Copper Substrate

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Abstract

Nuclear pool boiling has been the primary focus for research in heat transfer arena and has drawn the attention of many research scholars. Invoking the recent theories of bubble and vapour mass growth on heating surface in nucleate pool boiling postulated the formation of thin liquid layers between the solid surface and the growing vapour. The high rates of heat transfer in boiling occurs owing to the transient heat conduction through the thin layer in presence of high temperature differential across it. In this paper, the mechanism of formation of these layers and their effect on heat transfer by nucleate boiling process is analysed. In order to understand this phenomenon, existing studies on nucleate boiling heat transfer, as well as characteristics of boiling phenomena such as bubble departure diameter, microlayer as well as macrolayer formation, bubble departure frequency, and their impact on pool boiling heat transfer is analysed and result are validated by invoking the previous research works. The comparison of results of former exploration done till date with the experimental results shows that this model can be considered capable of fairly accurate predictions regarding heat transfer during the nuclear boiling process.

Keywords: Bubble formation, heat flux, macrolayer, microlayer, nucleate boiling process, regimes of boiling.

1. Introduction

Boiling represents the phenomenon of largely ferocious phase change, significant for various artificial operations because of its truly large heat transfer rates that can be achieved but truly complex and challenging for modeling. There is nearly no field of sedulity where this heat transfer mode could not be applied, chemical engineering, biochemistry, petrochemical, nuclear power, thermal power shops, food sedulity, microelectronic device, computer data centers, electric vehicle, etc. Due to the large heat transfer during the changing phase from liquid to vapor, the boiling heat transfer has a advanced heat transfer measure regarding conduction and convection. Also, working life prophecy delicacy of hot water boilers, thermal and nuclear power shops, refrigeration, and air exertion units, largely depends on heat transfer measure modeling. still, the boiling extremity, which is characterized by temperature increase, potentially leading to heater damage or melting, constitutes a limit to this effective heat transfer phenomenon. The physical nature of nucleate pool boiling is still far from being well understood despite the extensive exploration sweats by multitudinous scientists worldwide.

Among the four stages of pool boiling heat transfer, the most effective heat transfer region is the nucleate pool boiling which is the region from the point of nucleation to the point of critical heat flux value. It consists of two corridor the insulated bubble region, where bubbles bear singly; and the slugs and columns region, where bubbles start to combine and to depart from the heated face using spurts which also form large bubbles, or slugs, above the face.

Once a bubble nucleates, it grows through evaporation of liquid at the liquid/ vapor interface. A snappily growing, hemispherical shaped bubble can trap a thin subcaste of liquid between the growing bubble and the superheated wall (the micro subcaste), and evaporation of this liquid contributes to bubble growth. Because of the heat removed from the micro subcaste hard the three- phase contact line, the temperature in the vicinity of the nucleate point will drop significantly. Although it could be inferred from the previous studies that the contribution of the evaporation of these entrapped liquid films to heat transfer may be quite important but the complexity of the mechanism of the formation and difficulties in the direct experimental measurement of the transient thickness of these layers has impeded the development of a composite hypothesis to explain the heat transfer mechanism on this basis. However, investigations have been quite extensive and conclusive in the discrete bubble regime flow heat flux, $(0 \le q/q_c \le 0.60)$ and the macrolayer regime (high flux near critical, $(0.6 \le q/q_c \le 1.0)$. These regions for boiling water have been shown in figure.

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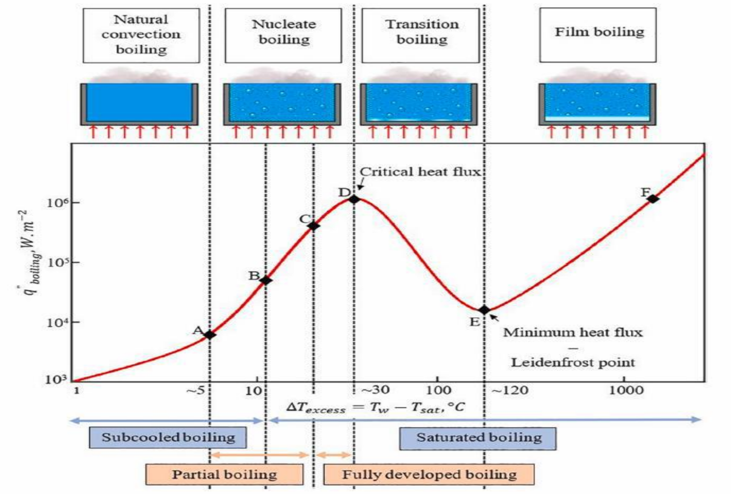

Figure 1. Pool boiling curve

When the bubble grows big enough, forces acted upon it, mainly the buoyancy in a gravitational field will make its departure from toast face. Also, the nucleate point will go through a recovering or staying process until its superheat reaches the critical value and a new posterior bubble form again. therefore, conformation, growth, and detachment of the vapor bubble and the rate of heat transfer there of bear the knowledge of bubble dynamics parameters.

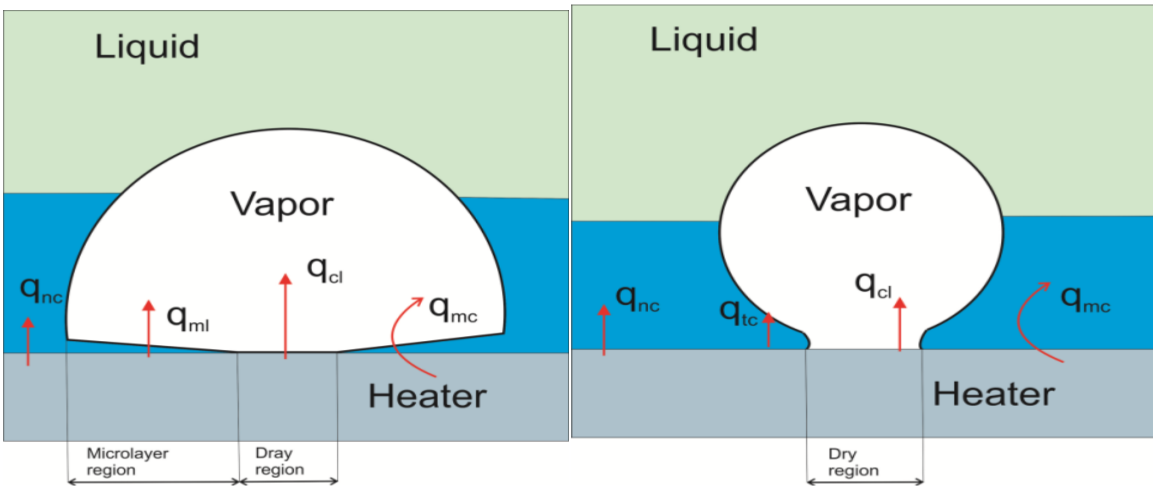

Figure 2. Physical mechanism of heat transfer during single-bubble nucleate boiling; (a) bubble growth period; (b) bubble departure period [11]

These bubble dynamics parameters are nucleation point density, bubble departure fringe, bubble staying period, bubble growth period, and bubble departure frequency. The determination of the boiling heat transfer measure can be done by using either empirical or semi-empirical correlations developed using bubble dynamics parameters.

2. Literature Review

A comprehensive review of nucleate pool boiling models with future prospectus is given in Ilic *et al.* [1]. Each model/correlation has its disadvantages because of the limitations of experimental conditions. As a result, no well-established theory exists for predicting the rate of heat transfer during boiling. Nevertheless, because of the practical importance of boiling heat transfer, thermal engineers have proposed various phenomenological models based on the insight gained from the experimental observations. In general, these models contain one or more empirical constants and have different levels of accuracies for different data sets. Until the complex physics of boiling is understood, the scope for improving such mechanistic models remains. Heat transfer rates could be improved by surface modification techniques that provide larger surface area, a higher density of nucleation sites, and smaller superheat for the phase change heat transfer. The accurate prediction of the critical heat flux, which can lead to heating surface destruction, is essential for the design and safe operation of high-power density thermal systems such as boilers, heat exchangers, and nuclear reactors. In recent years, new boiling applications to the systems such as micro-mini scales, highly transient, or reduced-gravity conditions have come to light, so a full understanding of the boiling phenomenon is urgently required. This paper summarizes recent developments in the investigation Heat transfer mechanism in pool boiling is highly complex owing to its dependence on large number of parameters such as thermal properties of liquid, thermo-physical properties, orientation, configuration and surface conditions of heater, input heat flux and mode of heating. Furthermore, the mechanism differs considerably in different regimes of boiling. At low heat flux, a thin liquid layer is formed between a bubble and heated surface. This very thin liquid layer is known as 'microlayer' and has been hypothesized to be responsible for major portion of heat transfer between the heating surface and the bubble. But under high heat flux conditions, the individual bubbles due to very high site density Coalesce and form vapour masses entrapping a relatively thicker film of liquid between the growing vapour mass and the heating surface The evaporation of layer known as 'macrolayer' and is the main parameter governing heat transfer. The first study on nucleate pool boiling was performed by Nukiyama [2]. He distinguished different modes of pool boiling such as partial nucleate boiling, fully developed nucleate boiling, transition boiling, and film boiling. He has shown his results on the curve of the heat flux against the temperature difference which is called the boiling curve. Modelling pool boiling process requires many hypotheses whose validity cannot always be assessed. This results in a large number of different models, often with corrective factors. The results predicted by these models are sometimes far from the experimental results. Experiments in boiling also receive their share of difficulties. Phenomena are fast, bubbles interact, scales are multiple, material properties are not always well defined, especially wall roughness, and physical parameters are hard to measure in fluids. Boiling needs to be simplified in order to identify the role of the different mechanisms involved. An analysis of these works shows that major parameters affecting the heat transfer coefficient (HTC) under nucleate pool boiling conditions are heat flux, saturation pressure and thermo physical properties of a working fluid. Many empirical and semi-empirical correlations for the determination of heat transfer values have been proposed which may supersede costlier experiments. Research efforts are directed towards the improvement of the boiling mechanism by lowering the surface tension between the boiling water and the solid surface [4,5]. A significant influential parameter on boiling HTC is the liquid thermal conductivity and characteristics of the heated surface. Experimental conditions, such as gravitational force value [6], surface orientation [7], external fields [8], and boiling pressure [9] are some other parameters that affect boiling HTC. A comprehensive literature survey on parameters affecting nucleate boiling heat transfer performed by Pioro et al. [10] showed that the surface effects consist of thermo physical properties of the surface material (thermal conductivity and thermal absorption), the interaction between the solid, liquid, and vapor interface, and surface micro geometry (dimensions and shape of cracks and efficiency). Although it could be inferred from the previous studies that the contribution of the evaporation of these entrapped liquid films to heat transfer may be quite important but the complexity of the mechanism of the formation and difficulties in the direct experimental measurement of the transient thickness of these layers has impeded the development of a composite hypothesis to explain the heat transfer mechanism on this basis. However, investigations have been quite extensive and conclusive in the discrete bubble regime flow heat flux, $(0 \leq q/q_c \leq 0.60)$ and the macrolayer regime (high flux near critical, $(0.6 \leq q/q_c \leq 1.0)$. Many of the early models were based on bubble agitation/micro convection being the primary heat transfer mechanism. These models did not include phase change but relied on an analogy with forced convection, *i.e.*, the role of the bubble was to change the length and velocity scales used to correlate data (e.g., Rosenhow 1952; Forster and Zuber, 1955; Forster and Greif 1959; Zuber 1963; Tien 1962). For example, the vapor-liquid exchange model proposed by Forster and Greif [12] assumed that bubbles act as micro pumps which remove a quantity of hot liquid from the wall equal to a hemisphere at the maximum bubble radius, replacing it with cold liquid from the bulk. The heat transferred from a single site was the energy required to heat this volume of liquid from the bulk temperature to the average of the wall and bulk temperatures. Katto and Yokoya [13] developed a heat transfer model based on macro layer evaporation. Haramura and Katto and Pan *et al.* [14, 15] developed their macro layer model termed as near field phenomena considering the instability at the macro layer interface as the main controlling parameter through the boiling process. Among the other efforts of near field model, Pasamehmetoglu [16] described the phenomena by dry out of microlayer (liquid layer of very small thickness below the growing bubble) and macro layer. He *et al.* [17], Stojanovic *et al.* and Pezo [18, 19], numerically predicted the total boiling curve. They considered three-dimensional transient heat conduction through the heated wall to investigate the spatial variation of wall temperature. Han and Griffith [22] consider that the heating surface consists of two regions, one that is influenced by the departing bubble - the area of bulk convection, and the other not influenced by the bubbles - the area of natural convection. In the area of bulk convection, Han and

Griffith assumed formation of a superheated thermal boundary layer by transient heat conduction which induces bubble formation.

3. Methodology and Experimental set up

A new heat transfer model has therefore been proposed which considers the effect of thinning down of the macrolayer as heat flow proceeds. The modified model assumes the following:

- Initial temperature profile in the solid is linear.
- A constant heat input, q at the bottom of the solid,
- The macrolayer liquid is at uniform temperature equal to T at the end of waiting period of the vapour mass,
- At the end of the waiting period the temperature of liquid-vapour interface falls to saturation temperature as the vapour mass formation is initiated.
- The rate of consumption of macrolayer is proportional to input heat flux q_w.
- Macrolayer is free of vapour stems.
- Heat transfer is one dimensional.
- Heat flux through macrolayer is calculated by using finite difference method

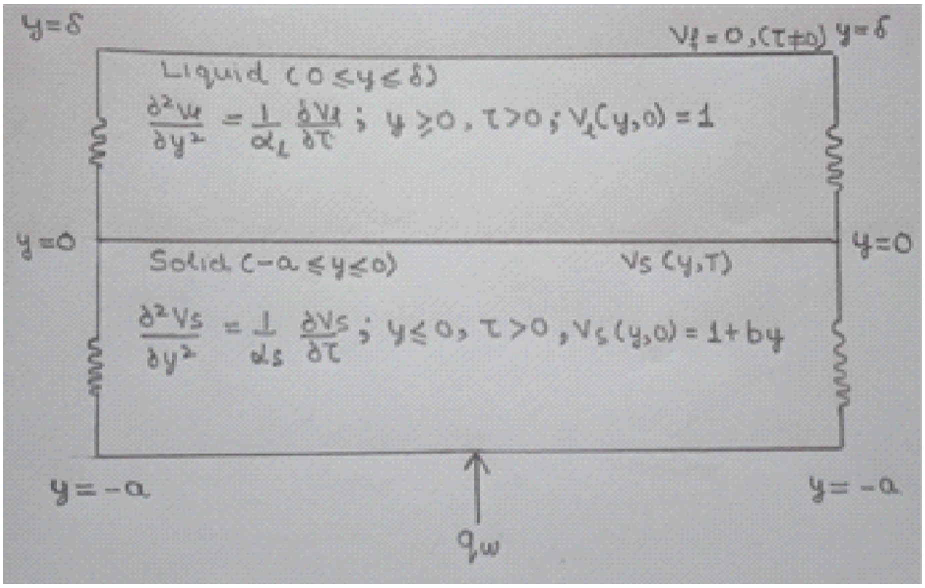

Figure 3. Modelling of macrolayer heat transfer system.

3. *Heat Transfer Mechanism*

A number of analytical heat transfer models based on microlayer evaporation have been proposed. Several investigators established that heat is transferred to the vapour in the form of latent heat transport by way of evaporation of an equivalent amount of liquid from the microlayer consequently decreasing the microlayer thickness. Transient heat transfer rate itself is a function of instantaneous thickness, physical properties and liquid and the initial and constraints of the system. The heat transfer is predicted by solution of transient one-dimensional heat conduction equation through the microlayer and heater as a composite solid. The results showed that a major portion of heat transfer from microlayer of heater boundary rate of solution heated surface to bubble take place through the microlayer as shown in table 2.

Table 2. Experimental frequency record at different occasions above the heated surface

Distance from heating surface (in mm)	Bubble Frequency (cycle/min)
0	70
0.4	70
0.8	69
1.2	68
1.6	66
2	64
2.4	58
2.8	54

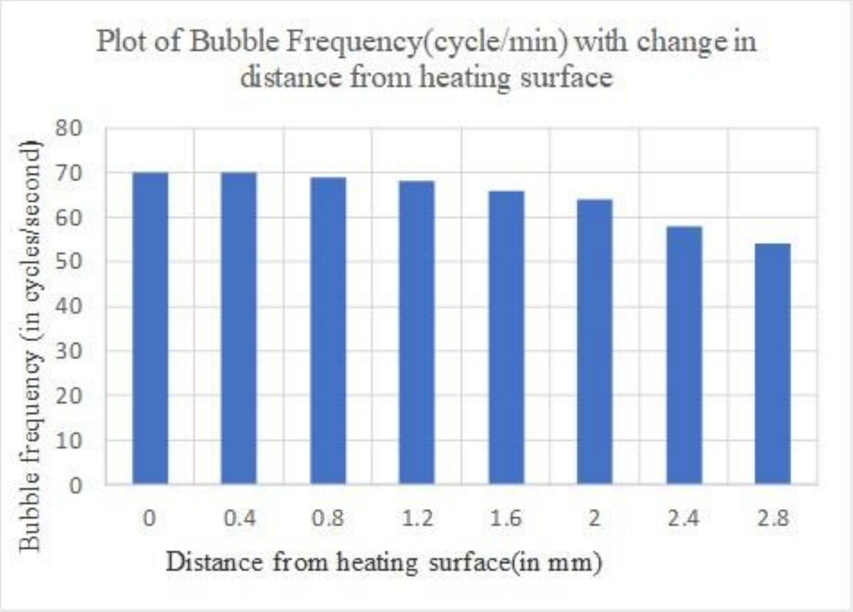

Figure 4. Plot of variation of bubble frequency (cycles/min) with distance from substrate heating surface

It is seen from the table there is a sharp fall in frequency from a very high value and this occurs at a height which is close to initial macrolayer thickness values predicted by investigations. This method was used to find the macrolayer thickness under different heat flux conditions.

3.1 Liquid microlayers under isolated bubbles

As the bubble grows on a heated surface, the liquid adjacent to the surface offers resistance to flow and advancing bubble wall entrap a thin liquid layer under it. Its small thickness can produce a large temperature gradient across the layer and hence can remove thermal energy at a very fast rate.

Moore and Mesler [25] measured temperature fluctuations during nucleate pool boiling to obtain indirect evidence of the existence of a thin layer (microlayer) on the heated surface. A number of investigators experimentally observed the existence of micro-layer. [26],[27] used interferometric technique to observe evaporation and dry out of these layers. Cooper and Lloyd [28] estimated the thickness of microlayer to be surface

$$\boldsymbol{\delta_0=C(\upsilon/t_g)^{0.5}} \qquad (1)$$

Where C is a constant, υ is bubble frequency and t_g represents the tine when the bubble wall reaches the saturation temperature.

3.2 Liquid macrolayers

In the high heat flux regime, individual the bubbles departing from surface cannot escape into the free liquid but coalesce to form a larger vapour mass because of the high active site density. The vapour mass so formed still remains connected to the heated surface through number of vapour columnar stems while a liquid layer is entrapped between the growing vapour mass and the heated surface. Figure shows the formation of these layers. Gaertner [29] gave the following relationship for initial macrolayer thickness (δ_o) in terms of bubble departure diameter D_d

$$\boldsymbol{\delta_o = 0.6\ D_d} \qquad (2)$$

Lida and Kobayashi [30] gave the following relationship in terms of wall heat flux

$$\boldsymbol{\delta_o=3.2296\ x10^5 q_w^{-1.5148}} \qquad (3)$$

The detailed investigations into the mechanism of formation of macrolayer by the lateral coalescence of vapour Stem led Bhat et al [31] to arrive at a relation

$$\boldsymbol{\delta_o = (D_d/2) + u\ (t_o - t_d)} \qquad (4)$$

where u is average bubble rise velocity, and $(t_o - t_d)$ is the tine interval during which bubble diameter increases from D_d to D_o

Based on the hypothesis that in the interference region nucleate boiling is subjected to Helmholtz's instability, Rajvanshi et al [32] gave a general expression of for macrolayer thickness (δ_o)

$$\boldsymbol{\delta_o=0.01\sigma\rho_v(\Delta h_v/q_w)^2(\rho_v/\rho_1)^{0.4}} \qquad (5)$$

A unique indirect measurement of initial thickness of the macrolayer was attempted by Bhat et al [33] by measuring the bubble frequency as a function of distance from the heated surface. Although it has been accepted to a reasonable extent that liquid layers are entrapped between the heated surface and vapour, there is still a good amount of controversy regarding quantitative mates of its initial thickness, its consumption rate and consequent heat transfer rates. It has been observed that the rate of increase of vapour mass is almost throughout the growth constant period and the consumption of macrolayer is proportional. to the input heat flux. The temperature fluctuations at the solid-liquid interface that have been extensively that indicate suitable heat studied flow model has to be developed that should be in consonance with the observed behavior. An attempt was made to model the initial distribution in superheat temperature the solid and liquid layers at the beginning of the vapour mass initiation-growth. Bhat et al [34] departure cycle while assumed initial constant superheat. Prasad et al [35] extensively investigated the effect of heater thickness with reference to a dimensionless parameter Z given by the relation:

$$\mathbf{Z = (K_1 \Delta T / \delta q_w)} \qquad (6)$$

where Δ T is wall being superheat and is expressed as

$$\mathbf{\Delta T = (T_w - T_{sat})} \qquad (7)$$

where ΔT is superheated temperature, T_w is uniform surface temperature and T_{sat} is saturation temperature.

Most of the models assumed a constant thickness of the liquid macrolayer. The latest of heat flow model assumes one dimensional transient conduction heat flow through a composite wall comprising two layers, one solid heater of thickness a ($a<y<0$) initially having a temperature gradient, energy input at a constant rate at the bottom and other of liquid macrolayer of thickness $\delta(0<y<\delta)$ initially at a uniform temperature (Tw), when the temperature at the top layer falls to saturation temperature, T_{sat} ($T_{sat}<T_w$).

Table 3: Variation of Heat Transfer Rate with increase in temperature difference for copper substrate

Temperature difference (in K)	**Heat Transfer Rate (in MW/m^2)**
5	0.000013
10	0.000052
15	0.0033
20	0.145
25	0.947
30	1.13
35	1.36
40	1.42
45	1.53
50	1.66

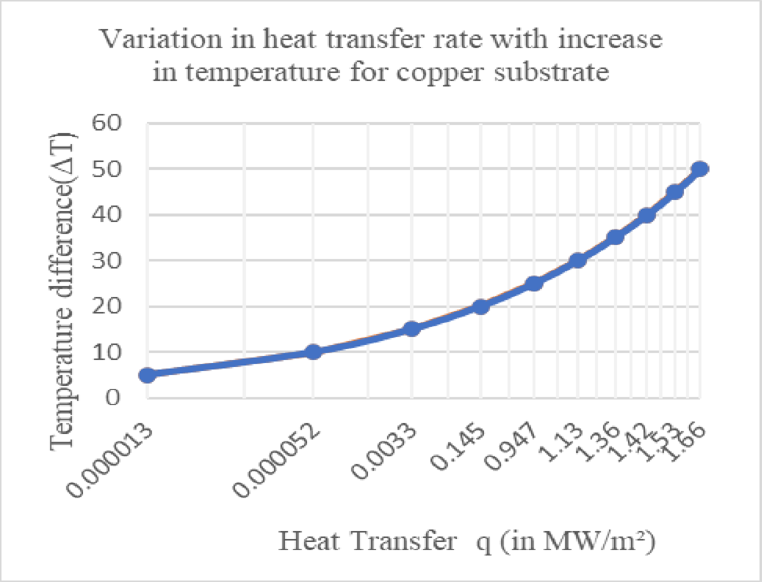

Figure 5: Logarithmic plot showing variation of heat transfer rate with increase in temperature difference for copper substrate

Table 4: Variation of heat transfer rate with increase in bubble macrolayer thickness for copper substrate

Macrolayer thickness (in mm)	**Heat transfer (in MW/m²)**
0.04	2.44
0.08	1.94
0.1	1.33
0.12	0.96
0.14	0.87
0.16	0.83
0.2	0.78

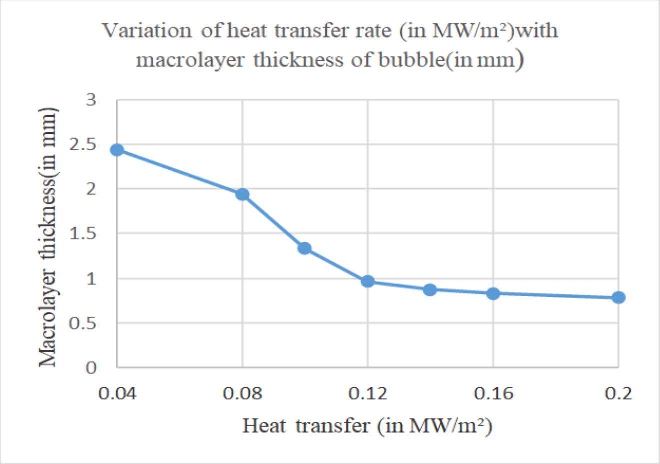

Figure 6: Plot showing variation of heat transfer rate with increase in bubble macrolayer thickness.

Table 5: Empirical estimation of bubble diameter with increase in bubble macrolayer thickness.

Macrolayer thickness(δ_o) (in mm)	**Bubble diameter (in mm)**
0.08	0.048
0.1	0.06
0.12	0.072
0.14	0.084
0.16	0.096
0.18	0.108
0.2	0.12

Table 6: Variation of substrate surface temperature with passage of time for copper substrate

Time (in seconds)	**Surface Temperature (in K)**
0	391
40	394
80	397
120	399
160	400
200	401
240	401

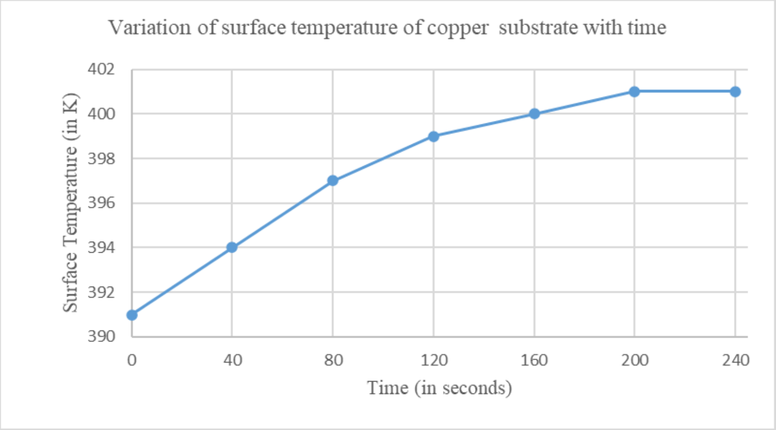

Figure 7: Plot showing variation of variation of substrate surface temperature with passage of time.

Table 7: Comparative analysis of experimental heat transfer rate values of macrolayer thickness with values of other research works for water on copper surface.

Macrolayer thickness (in mm)	Experimental Values of q_w (in MW/m^2)	Values of heat transfer q_w (in MW/m^2) predicted by earlier researchers		
		Rajwanshi et.al	Bhat et.al	Geatmer et.al
0.04	1.52	1.56	1.68	1.63
0.06	1.48	1.44	1.46	1.52
0.08	1.25	1.18	1.28	1.45
0.1	1.07	0.94	1.14	1.22
0.12	0.99	0.88	0.99	1.12
0.14	0.89	0.82	0.85	1.06
0.16	0.86	0.78	0.83	0.98
0.18	0.81	0.73	0.74	0.82
0.2	0.71	0.68	0.69	0.77

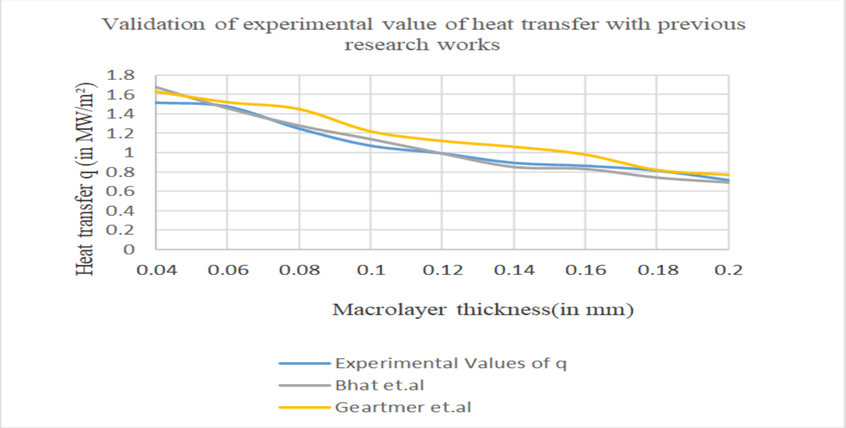

Figure 8: Plot showing Comparative analysis of experimental heat transfer rate values with macrolayer thickness with values of previous research works.

4. Conclusion

In this research work, the values of average heat flux at the liquid-vapour interface and the temperature at the solid-liquid interface were obtained from the solution of heat transfer equations was discussed. The experimental boiling conditions i.e., the input heat flux, wall superheat, initial macrolayer thickness and the vapour mass frequencies were used for prediction of heat transfer rates for water the existence of liquid layers flow heat flux and vapour masses under high heat flux conditions on copper substrate under atmospheric pressure have been fairly well established.

A fairly good agreement of the results of heat transfer model with experimental results indicates that the latent heat transport accounts for the major portion of heat transfer from heater surface in pool boiling at high heat flux. Finally comparative analysis of experimental heat transfer rate values with macrolayer thickness with values of previous research works was done in order to validate the experimental values of heat transfer for particular range of bubble macrolayer thickness values.

Acknowledgment:

I am very thankful to Head, Mechanical Engineering Department, Government College of Engineering and Technology, Jammu for providing guidance and necessary logistic support.

Disclosure Of Interest:

It is declared that there is no relevant or material financial interests of both authors pertaining to the research work. The data used in this research is proprietary in nature.

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