An experimental study and comparitive validation of macrolayer thickness in nucleate pool boiling for horizontal copper tube heater

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Abstract. Nucleate Pool boiling is characterised by the progression of several nucleation sites (bubble formation), which surge from distinct points on a surface, whose temperature is slightly above the liquids. To investigate and evaluate this, a pool boiling setup was fabricated with a horizontal copper tube heater of 28mm diameter by imposing cartridge heater. An analytical expression, suggested by literature helps to determine the thickness of macrolayer based on bubble diameter was used. The macrolayer thickness for water was found by measuring the bubble diameter by using Photographic and CAD method. Experiment was carried out in a stainless steel container insulated with Teflon cover to observe the bubble growth and bubble departure characteristics for the heat flux range of 1000-42,000 W/m^2. The bubble diameter were measured and the measured parameters were been used to determine the initial layer thickness, macro layer thickness and critical heat flux and validated through various models. The observed and calculated values are in good agreement as reported in various literature.

Keywords: nucleate boiling, macrolayer, critical heat flux, bubble diameter.

1. Introduction

Boiling one among the major process in industries is an intricate and insubstantial process. Several investigaters have done various researches to recognize the pool boiling process of water and other fluids. Several investigators [l-3] confirmed that phase change heat transfer plays a significant role in nucleate pool boiling which occurs at peak heat flux. But still the mechanism of boiling is not revealed fully. In an attempt to understand this Yu & Mesler [4] found the occurrence of a new liquid layer, between the bubbles and the heated surface, called the macrolayer. Also, the study found that the growth of bubbles takes place only at specific locations and proved its occurrence in nucleate boiling occurring at high heat flux. A vapour mass is developed by merging of these vapour columns, which produces a fluid film between the bubbles and the source of heat which is called macrolayer. Macro layer's role in transmitting heat energy from the heater to the boiling fluid is very important. When the bubble starts to grow, the thickness is reduced as the liquid in the macrolayer is diminished quickly. The maximum thickness at the time of origination is called the initial macrolayer thickness. when the

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bubble leaves the heater surface, the liquid makes contact with the heater surface because of that macro layer vanishes.

Gaertner [5] found the initial macrolayer thickness by the photos snapped during boiling of water over a copper tube at high heat flux. Later it was validated with other experimental data on bubble diameter and derived the following correlation:

$$\delta_o = 0.6\ d_b \qquad (1)$$

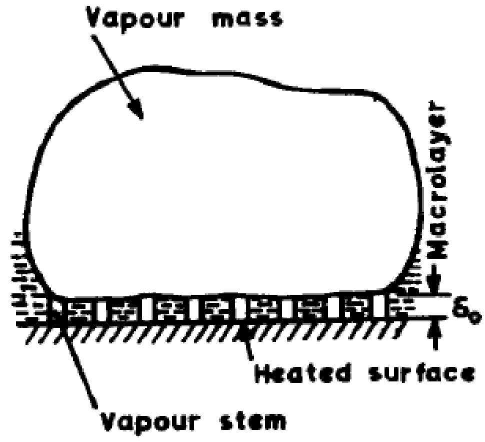

Figure 1. Generation of vapour mass in nucleate boiling.

This formula is to obtain the initial macrolayer thickness based on bubble diameter. Thus initial layer thickness of the macrolayer formed is found and using this decrease in macro layer thickness can be determined by eqn(2).

2. Literature Review

The following researches are reviewed to understand the pool boiling phenomenon:

To reveal the mechanism behind the boiling, photographic study of pool boiling in high heat flux was done by Gaertner[5]. This was done by several hundereds of photos taken by 12 high speed video camera to understand the phenomenon. The research revealed the existence of three to four heat transfer regimes depending on the vapour formation and concluded that the heat transfer emprical relations derived based on single mechanisms must be contradicting . Later Rajvanshi[7] investigated the macrolayer occurrence and derived an expression for Predicting the macrolayer thickness value.The expected values have been interrelated with those attained by experimentation and showed promising results. Saini [8] established a new analytical model for defining the heat conduction flow rate over macrolayer in elevated heat flux range using finite difference method.

The model is in tremendous settlement with investigational values of input heat flux. Heat transfer from heated surface at high heat flux is characterised by heat conduction thru the macrolayer. Ying He[9] developed a numerical model by simulation to scrutinize pool boiling heat transfer at high heat flux and found the macrolayer thickness by arithmetically expressing a boiling curve. The study discloses that the occurrence of evaporation caused by the development of bubble is mainly due to heat flux, and also approves the establishment of nucleation site density and the consequence of surface irregularity is also studied. Nadia Caney[10] developed a numerical model to recognise the influence of bubble diameter and the contact angle upon boiling process. The study leads to the development of an empirical relation between bubble diameter and contact angle.

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Table 1. Literature review

S. NO.	JOURNAL NAME/ TITLE OF THE PAPER	AUTHORS	WORK DONE	PARAMETERS STUDIED	METHODOLGY USED	OUTCOMES
1	Journal of heat transfer / Photographic study of nucleate pool boiling on a horizontal surface	Gaertner R. F.: (1965)	i) A photographic study is made of nucleate pool boiling ii) Two polished surfaces (platinum &copper) were studied.	i) Heat transfer ii) Burnout heat flux iii)Photographic results	Using high speed camera and still photographs	i) It was found that 3 to 4 heat-transfer regions were existing in pool boiling, based on the means of vapour production ii) It was settled that heat-transfer validations are based on bubble parameter changes. iii)The Validation will be wrong if it validated with lone mechanism
2	International journal of heat mass transfer / Investigation of Macrolayer Thickness in Pool Boiling at High heat flux nucleate	Rajvanshi **A.** K..et.al. (1992)	i) An analytical relation to forecast the data's of initial macrolayer thickness was derived warped on the thermal and physical properties of the liquid ii)The initial macrolayer thickness for different liquids was found experimentally	i) Macrolayer thickness	i)electrical resistance probe method	i) The graph drawn between the frequency and distance could be used to find the macrolayer thickness. ii) The formula obtained for macrolayer is predicting the value of macrolayer thickness with close approximate
3	International journal of heat mass transfer /A new model for heat flow through macrolayer in pool boiling at high heat flux	Jairajpuri A. M. and Saini J. S (1991)	i) analytical model for transitory 1-D heat flow along a reducing macrolayer thickness ii) The model calculates the conduction heat flow rates at the bubble interface for water and methanol	i) Wall temperature ii) Heat flux	Finite Difference Solution	i) model agrees well with experiment values of heat flux. ii)At peak heat flux the conduction of heat in the macrolayer constitutes the major mode of heat transfer.
4	International journal of heat mass transfer /Numerical investigation of high heat flux pool boiling heat	Ying He. et.al. (2001)	i) a model for pool boiling heat transfer established on macrolayer model ii)boiling curve is symbolized by defining the macrolayer thickness	i) Heat flux ii)Macrolayer thickness	To find heat flux based on Macrolayer model	i) evaporation owing to development of vapour stem is main contribution to heat flux ii) occurrence of nucleation site density iii)effect of surface roughness is inspected iv) developed model is consistent
5	International Communications in Heat and Mass Transfer /A model to predict the effect of contact angle on the bubble departure diameter during heterogeneous	Nadia Caney et.al. (2010)	i)a model is established to explain the influence of contact angle on the bubble departure from a horizontal surface	i) Contact Angle ii) Bubble departure diameter	Deriving an experimental relation numerically	i) an empirical relation between the bubble diameter and the contact angle ii) Agrees with existing experimental data confirming the predicting nature of the current model

3. Experimentation

3.1 Experimental Setup:

The details of the system:

The setup consists of a 75x75x180mm rectangular SS vessel and it was covered with thick insulating Teflon cover from outside. The vessel was attached two glasses which was used as observation windows. On the top, a glass reflux condenser was fixed for condensing the water vapour back to vessel. The condenser was retained at desired temperature by flowing water from a storage unit. A pressure gauge was attached at the top to observe the boiling pressure. To sustain the atmospheric pressure, a vent was provided in the top of the vessel. A cartridge heater of 18 mm diameter was used and it was inserted in a desired copper block of 28 mm diameter. The copper block, containing the cartridge heater was fixed in vessel with high temperature adhesive.

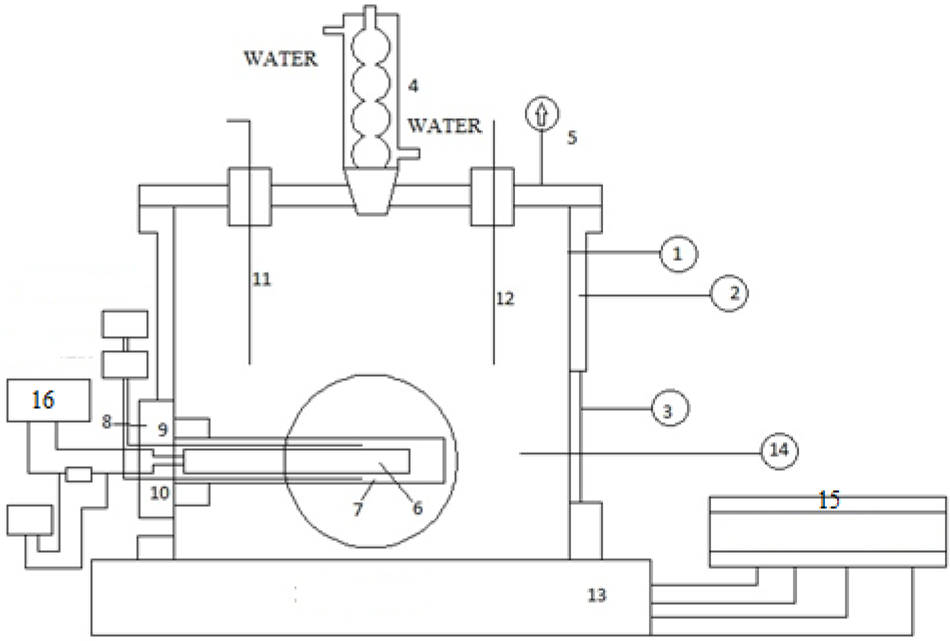


Figure 2.Layout of experimental setup.

1 - Vessel
2 – Teflon cover
3 – Glass slights
4 – Glass reflux Condenser
5 – Pressure gauge
6 – Cartridge type heater
7 – Copper heater
8 – Thermocouple scanner
9 to 12 – K type thermocouples
13 – Preheater
14 – Water
15- Controller for preheater
16 – AC power supply

In this experiment, K-type thermocouples were used to measure the heater temperature and the fluid temperature.The signal from the thermocouple was feed to the Thermocouple Scanner which displays the various temperatures. An AC regulated power was supplied using a Dimmer starter to the cartridge Heater. The power input was calculated from the current (*I*) and voltage (*V*) across the heater by using a Ammeter and Voltmeter respectively.

Figure 3. Experimental setup.

3.2 Experimental Procedure

Test fluid was filled in the stainless steel vessel until the copper heater is completely immersed (for this setup 500 ml water was used) .Then the fluid was heated to rise the base temperature to 30 ^{o} C by keeping the vessel in the preheater. After setting the base temperature preheater unit need to be cut-off, further increase in temperature for the test fluid is achieved by means of copper heater.

An AC regulated power was supplied by using a dimmer stater to the heater until the fluid reaches saturation. The entire boiling process was recorded using camera through sight glasses.The experiment was carried out for 5 different base temperatures ranging from 30^{o}C to 50^{o} C in the interval of 5^{o}C

3.3 Measured bubble

The sample photos of the original bubble taken from the videos and measured bubble using CAD for different base temperatures as shown below:

i) When base temp = 30ºC

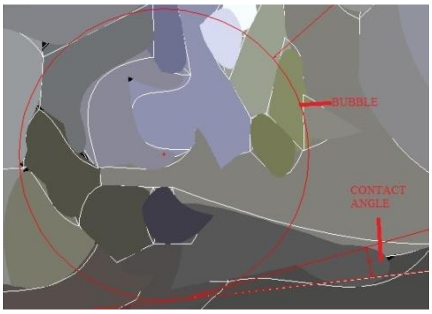
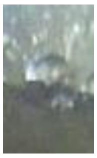


Figure 4. Photo for bubble formation. **Figure 5**. Measured bubble.

ii) When base temp = 40ºC



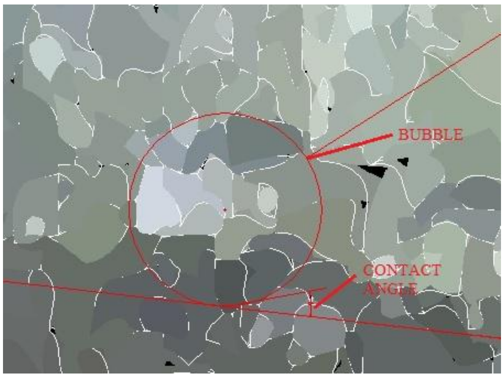


Figure 6. Photo for bubble formation. **Figure 7**. Measured bubble.

iii) When base temp = 50ºC

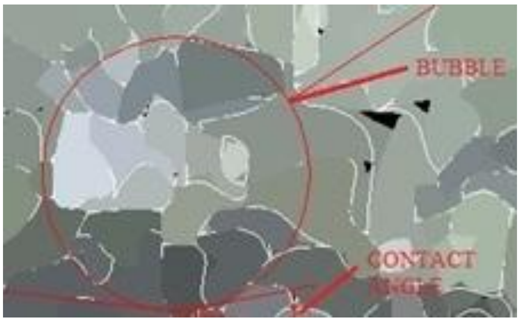


Figure 8. Photo for bubble formation. **Figure 9**. Measured bubble.

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4. Results and discussion

4.1 Results

The results are calculated based on the following formulae and tabulated:

Nadia Caney Model:

$$D_{th} = (6\sqrt{\frac{3}{2}})^{1/3} (\frac{\rho_l}{\rho_v})^{-1/2} (\frac{\rho_l}{\rho_v} - 1)^{1/3} \tan \Theta^{-1/6} L_c \qquad (2)$$

Thickness of macrolayer:

$$\delta(t) = \sqrt{\delta_o^2 - 2\,\frac{\lambda \Delta T}{\rho_l H_{fg}} t} \qquad (3)$$

CHF:

$$q_{CHF} = \frac{\Pi}{24} \rho_v H_{fg} [\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}]^{1/4} \qquad (4)$$

Table 2. Calculated values for different base temperature

BASE TEMP	CHF (W/m²)	INITIAL MACROLAYER THICKNESS (mm)	MACROLAYER THICKNESS (mm)	BUBBLE DIAMETER, (mm)
	Range	Range	Range	Range
30ºC	4.7515E6-1.5526E6	1.8840 - 0.5275	1.8737 - 0.5107	3.14 -0.8791
40ºC	9.2251E6 - 0.6644E6	2.6100 - 0.4440	2.6055 - 0.4304	4.35 - 0.74
50ºC	4.2873E6 - 0.5622E6	1.9260 - 0.9600	1.9198 -0.9519	3.21-1.43

The various plots obtained through experiments for different base temperatures are as follows:

i) When base temp=30ºC;

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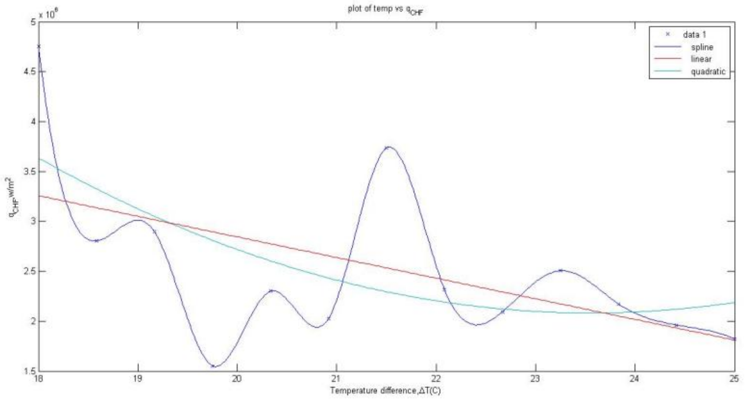

Figure 10. Plot between temperature difference and qCHF.

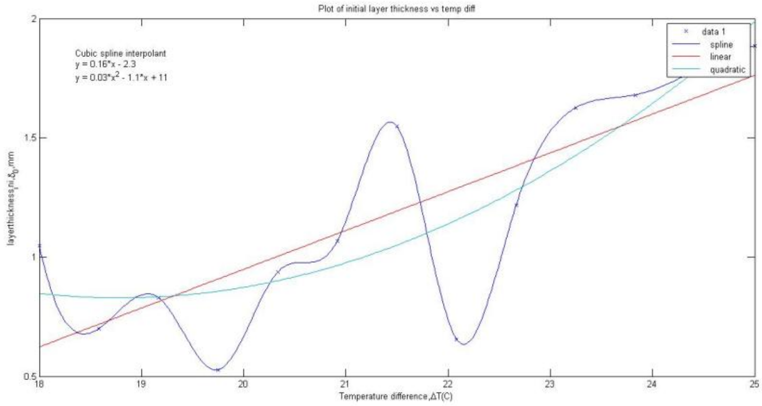

Figure 11. Plot between temperature difference and initial layer thickness.

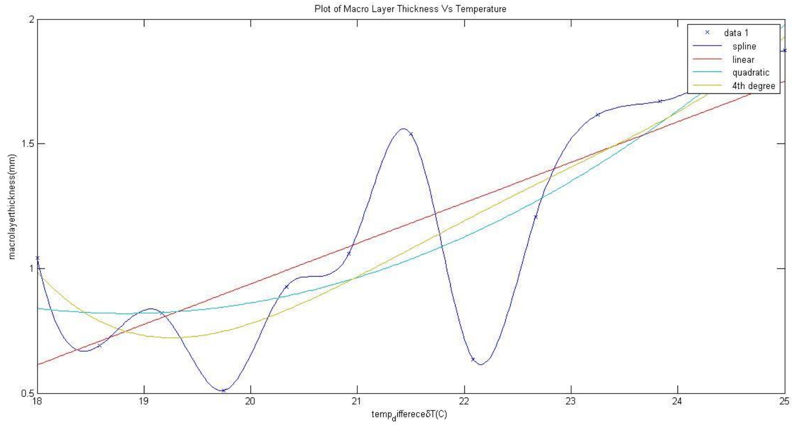

Figure 12. Plot between temperature difference and macro layer thickness.

ii) When base temp=40ºC;

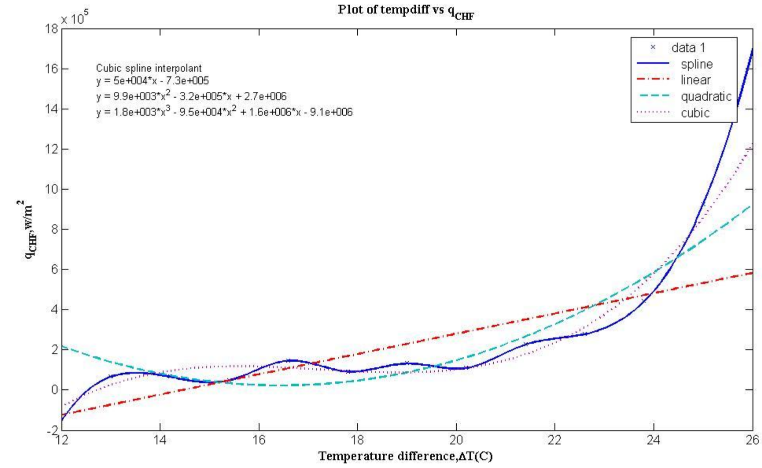

Figure 13. Plot between temperature difference and qCHF.

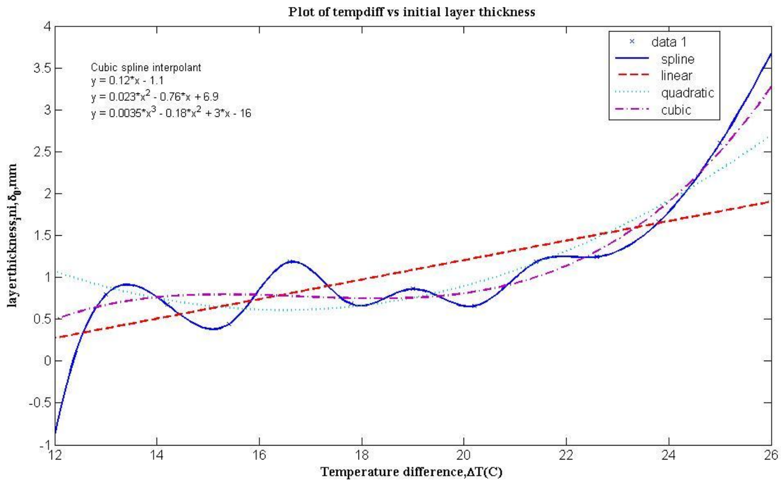

Figure 14. Plot between temperature difference and initial layer thickness.

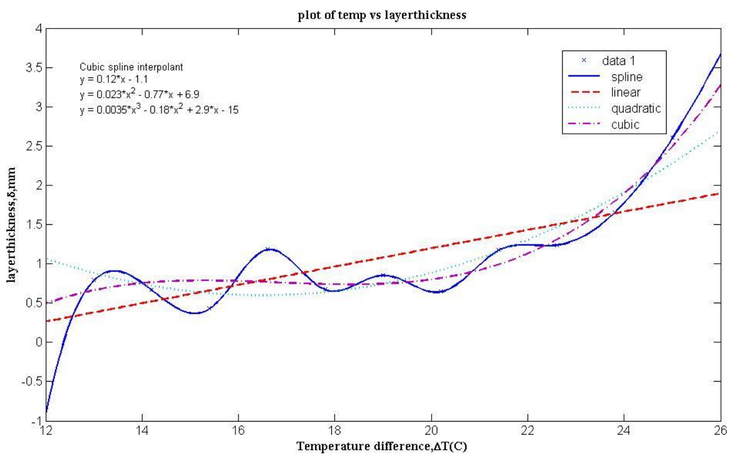

Figure 15. Plot between temperature difference and macro layer thickness.

iii) When base temp = 50ºC

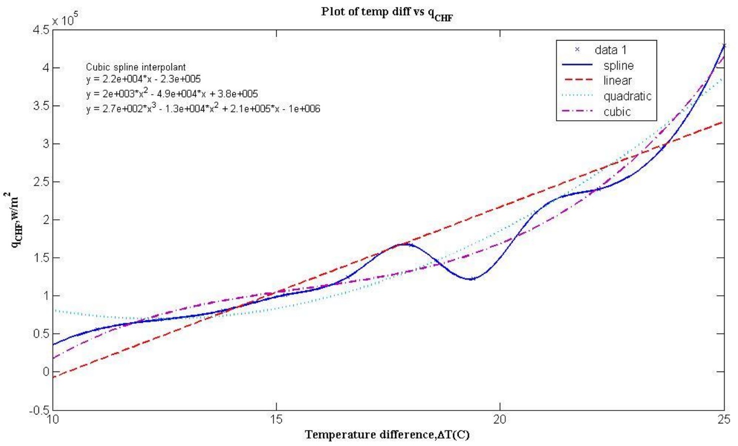

Figure 16.Plot between temperature difference and qCHF.

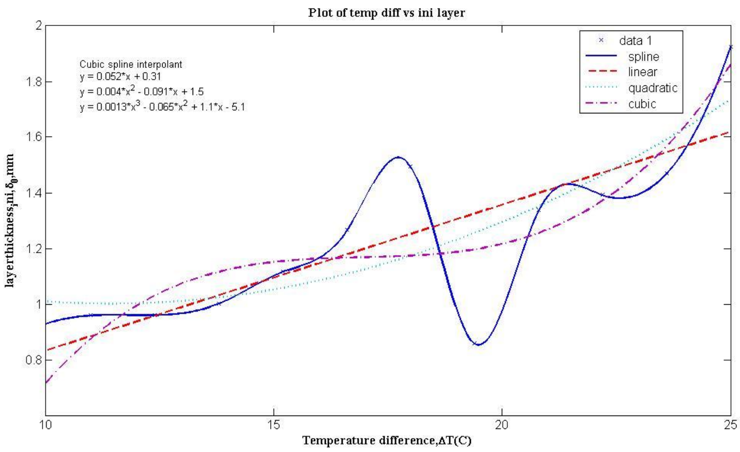

Figure 17. Plot between temperature difference and Initial layer thickness.

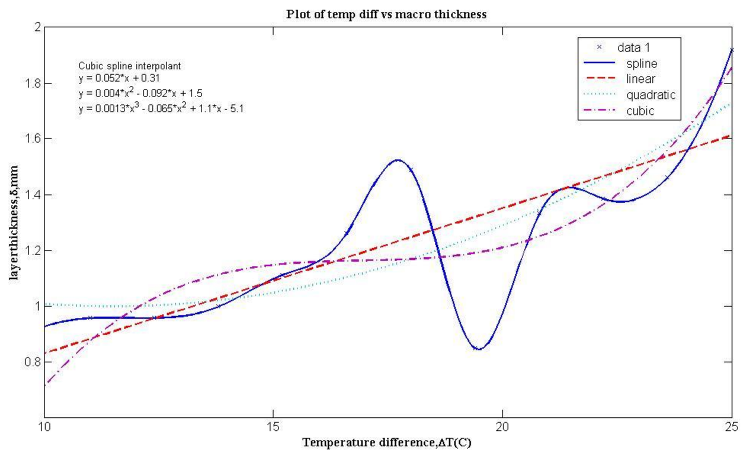

Figure 18. Plot between temperature difference and Macro layer thickness.

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4.2 Comparison with previous research works

The present work is validated with previous research works and the comparison graph is shown below for different parameters

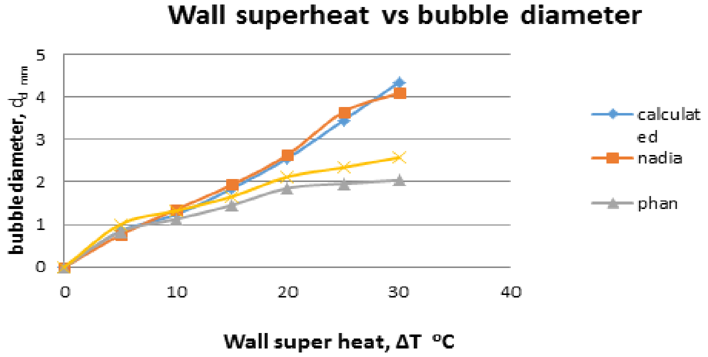

Figure 19. Comparison between calculated values and models for bubble diameter.

The calculated values of bubble diameter is evaluated with the past research works and has good covenant with them. The present study is showing a same pattern which is clear from the above graph.

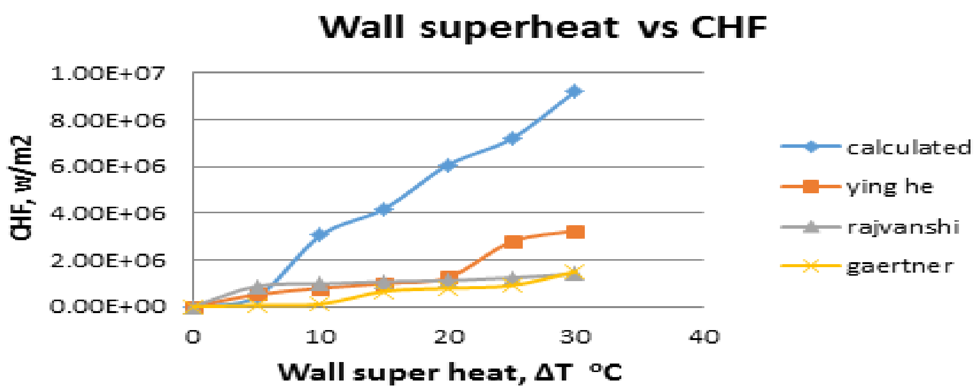

Figure 20. Comparison between calculated values and models for CHF.

The value of CHF is compared and shows a slight increase in the value when the temperature difference exceeds the value of 20ºC. This is due to occurrence of macrolayer thickness at higher temperature difference.

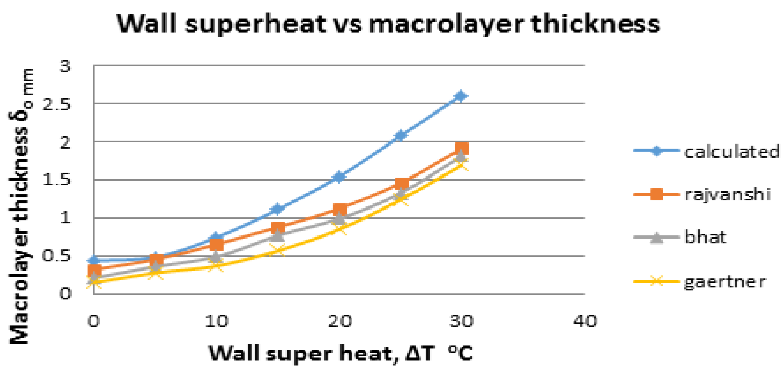

Figure 21. Comparison between calculated values and models for macrolayer thickness.

The value of macrolayer thickness is compared and shows a slight variation at higher temperature difference. The maximum value is slightly varying with 10% error on comparing with other literatures.

4.3 Results

Table 3. Comparison between experimental results and previous literature results

Parameters	**Experimental Results**			**Results From Literature**		
Base temperature	**30ºC**	**40ºC**	**50ºC**	**30ºC**	**40ºC**	**50ºC**
d_d	3.14 - 0.8791 mm	4.35 - 0.74 mm	3.21 - 1.43 mm	3.21- 0.75 mm	4.10 - 0.78 mm	3.85 - 0.81 mm
CHF	4.7515e6- 1.5526e6 w/m^2	9.2251e6 - 0.6644e6 w/m^2	4.2873E6 - 0.5622E6 w/m^2	9.35e6 – 0.785e6 w/m2	8.35e6 – 0.682e6 w/m2	7.35e6 – 0.56e6 w/m2
δ_o	1.8840 - 0.5275 mm	2.6100 - 0.4440 mm	1.9260 - 0.9600 mm	1.7453 - 0.4987 mm	2.5987 - 0.3945 mm	1.8754 - 0.8753 mm
δ	1.8737 - 0.5107 mm	2.6055 - 0.4304 mm	1.9198 - 0.9519 mm	1.7214 - 0.4873 mm	2.5321 - 0.3754 mm	1.8432 - 0.8549 mm

4.4 Inferences

The values of Initial layer thickness, Macro layer thickness and CHF are obtained by calculation. The maximum value and its range for the experiment is summarised as follows:

In this analysis the range for the initial layer thickness is from 0.4303 mm to 3.3420 mm and maximum value is 3.3420 mm. The range for the macro layer thickness is from 0.4303 mm to 3.3381 mm and maximum value is 3.3381 mm. The range for the CHF is from 0.4201e6 W/m^2 to 9.2251e6 W/m^2 and maximum value is 9.2251e6 W/m^2. Also it was observed that the value of CHF increases as the base fluid temperature increases. Initial macro layer thickness increases as the base fluid temperature increases.

The values of macro layer thickness and initial layer thickness gradually increases and drops at certain point and then gradually increases till the nucleation site. The contact angle has 5 percent deviation with the experimental values.

The bubble departure diameter has 10 percent lapse with the experimental values. The critical heat flux has 8% error in the experimental data. The initial layer thickness has 10 percent inaccuracy with experimental result. The experimental value of the CHF, initial layer thickness and macrolayer thickness of water was found to have a good agreement with literatures.

5 Conclusion

From the above calculated value it is inferred that the macrolayer thickness value decreases from the initial layer thickness as suggested by Rajvanshi[7]. Also it was found that there is a change in all values when the base temp of the fluid is changed. Initial macro layer thickness also increases when the base fluid temp increases. Thus the calculated Values of CHF, Initial layer thickness and macrolayer thickness for water using this method was found to be in agreement with various literatures.

5.1 Future work
The work can be extended to study the pool boiling characteristics of other fluids like ethylene glycol and nano fluids. The work can be validated by comparing the Results with ANSYS fluent.

Bibilography

d_b Bubble departure diameter

q_{CHF} Critical Heat Flux

H_{fg} Latent heat of vaporisation

L_c Correction factor

Greek symbols
δ_o Initial layer thickness
δ Macro layer thickness
ρ Density
Superscripts
v vapour
l liquid

6. References

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