POOL BOILING OF WATER OVER A STAINLESS STEEL FLAT PLATE HEATER

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Abstract- The purpose of this experiment is to study heat transfer characteristics of water through pool boiling over a flat stainless steel plate heater. The present experimental data of water is in good agreement with Stephen and Abdelsalam correlation (1980) with the given heat flux range 30-750 kW/m^2. Without any modification in the Stephen and Abdelsalam correlation (1980), it is observed that the experimental data of water are within an error band of ± 20 percent, this is because of the Stephen and Abdelsalam correlation (1980) predicts their own data in an error band of 11.3 percent. In order to minimize the error band, the pool boiling experimental data of water have been analyzed by regression analysis using Stephen and Abdelsalam correlation (1980) and the powers and coefficient of the terms in the correlation are modified and the optimum values of the power index and coefficient which gives the minimum error band of ± 10 is obtained.

I. INTRODUCTION

The fluids play a major role in heat transfer. Conventional fluids such as water, oil and ethylene glycol are widely used as cooling fluids, which are of most significance to many industrial sectors. From the past few decades, extensive investigations have been carried out to study the pool boiling of water. Recently the pool boiling studies have drawn attention of scientist and engineers owing to growing demand of high energy dissipation in electronic equipment and computing machines earlier, Rohesnow [1] and Cornwell and Houston [2] reported the boiling heat transfer coefficient of water over various heating surfaces, through mathematical approach based in the principles of physics and by conducting experiments as well. Later Pioro [3] experimentally determined the heat transfer of water under the plates. They found the experimental data has an under prediction due to high bubble dynamic. Nucleate pool boiling heat transfer characteristics and the critical heat flux condition were investigated W. R. McGillis et al., [4] for a wide range of rectangular fin geometries, for several surface finishes for at low pressure and the results are found much different from pool boiling at atmospheric pressure. An investigation on Pool boiling heat transfer over finned tubes was conducted by E. Hahne et al. [5] Based on the theory proposed by Mikic and Rohsenow for plain tubes and developed a new theory for finned tubes. This new theory considers bubble dynamics and interaction between the heat transfer mechanisms of boiling and natural convection, as well as the effect of the tin geometry.

R. J. Benjamin et al., [6] was studied the effect of the nucleation site density in pool boiling of saturated pure liquids experimentally by varying the surface micro roughness and surface and liquid properties. They developed a correlation for

nucleation site density in terms of thermo physical properties of heating surface and liquid and the metrological properties of the surface. An observations of boiling behaviors and measurements of critical heat flux (CHF) for saturated water boiling on a horizontal, upward-facing plate at pressures from atmospheric to 7 MPa on a horizontal plate in saturated pool boiling of water at high pressures was investigated by Hiroto Sakashita and Ayako Ono., [7]. The experiment reveals that the following (i) primary bubbles diminish in size almost in inverse proportion to pressure and commence to coalesce in the very low heat flux region. (ii) The diameter of detached coalesced bubbles increases with increases in the heat flux and reaches about 10 mm even at a pressure of 5 MPa. (iii) Detachment frequency of the coalesced bubbles was unaffected by the heat flux and pressure. The CHF predicted based on the macro layer dry out model agrees well with the measured data. A new hydrodynamic model is developed, and analyses of CHF in fundamental boiling systems was

carried out by Y. Haramura and Y. Katto [8] by introducing Helmholtz instability on the vapor-liquid interface of columnar vapor stems distributed in a liquid layer wetting a heated surface. It is found that the vapor-liquid system was collapsed wholly by the instability, but due to the suppression of the solid surface, a thin liquid film including vapor stems is left stable on the surface with a certain definite thickness relating to the Helmholtz critical wavelength. A vapor blanket, thus formed on the liquid film, restricts the feed of liquid from the bulk region to the film, resulting in the disappearance of liquid from the heated surface, that is, the appearance of critical heat flux (CHF).

From the above literature survey it is concluded that the direct liquid cooling, which involves boiling heat transfer, is one of the plausible ways to maintain a low component temperature assuring a reliable operation of the unit. At very high heat fluxes, the regular nucleate boiling transmutes into the film boiling regime and thereby experiences a rapid temperature increase of substrate by several hundred degrees. With the employment of the enhanced boiling techniques, the critical heat flux (CHF) can be increased, which ensures continuous cooling of the component. The reliable and effective cooling in nuclear power reactors is of highest priority, where transition to film boiling can have devastating consequences. Here the enhanced boiling technique increases the safety margin in a significant manner.

II. EXPERIMENTAL SET-UP

The following Figure (1) show the schematic diagram of flat plate heater experimental set-up. The experimental set-up mainly consisted of a test-vessel with inbuilt vertical condenser, heater assembly with power supply, cooling arrangements and data acquisition system. The heater is the emery polished square stainless steel surface of 30 mm size and 0.44 mm thickness. The average surface roughness of the test heater was measured 0.167 μm. Two opposite sides of the test-section were brazed with the copper bus bar of 180 mm length and 30 mm x 5 mm cross section. The other ends of copper bars were connected to power supply unit through a step down transformer having a variable capacity of 10 kVA controlled through a dimmer stat. The test-section was polished using fine emery paper and then with velvet polish.

This arrangement was tightly inserted in to the slot made in the cylindrical teflon rod of 60 mm diameter through a silicone rubber disc. Five T-type thermocouples were tightly held at different position by the silicone rubber disc and these thermocouples were used to measure the bottom surface temperature of the stainless steel test-section. The thermocouple leads and voltage leads were taken out through five capillary holes made in the teflon rod and these leads were connected with data acquisition system. The contact of the thermocouple beads with test section was ensured by checking the connectivity between them using a multimeter.

This heater assembly was further inserted in the bottom side of the borosilicate glass vessel of inner diameter 60 mm and thickness 4 mm. The vessel has the provision with inlet, drainage, cleaning hole, one vertical reflux glass condenser and thermocouple to measure the bulk temperature of the test fluid. The vessel arrangement was mounted to an immovable base using mild steel rods of 6 mm

diameter, connecting the base and the pressure plate fixed above the vessel using the silicone rubber to make it leak proof. Finally the experimental set up was checked for any leakage.

III. POOL BOILING OVER PLATE HEATER

Prior to data acquisition, the vessel and test-section were thoroughly cleaned with soap water, acetone and finally with distilled water to remove any deposition and dirt. After cleaning, the test-section was filled with distilled water and thermally stabilized by heating it for 12 hours at a heat flux of 500 kW/m2. Subsequently the test-section was cooled down for 12 hours. At the beginning of data acquisition, the test-fluid was maintained at saturation temperature at a given heat flux of 50 kW/m2 and the steam generated in the process was allowed to pass through the crack valve of condenser to remove any dissolved gases in the test-fluid and in the test-vessel. Then cooling water circulation to the reflux condenser was started simultaneously, so that, any vapor generated by boiling of water was condensed and drained back to the liquid pool gravitationally. Data acquisition was done initially from 20 kW/m2 heat flux, which was then increased gradually to just before the burn out level. The entire tests were performed under atmospheric pressure.

The wall temperature of plate heater test-section was determined by the following equation (1)

$$T_w = \frac{\dot{q_g}}{2k_w}\delta^2 + T_b \qquad (1)$$

Tb is the average bottom surface temperature of test heater in oC determined from the following equation (2)

$$T_b = \frac{T_1 + T_2 + T_3 + T_4 + T_5}{5} \qquad (2)$$

Figure 1 Plate heater pool boiling experimental setup

where, T1, T2, T3, T4, and T5 are the bottom surface temperatures of the test heater located at different places. The average heat transfer coefficient was evaluated using the following equation (3).

$$h = \frac{Q}{A\left(T_{wo} - T_f\right)} \qquad (3)$$

Although all precautions were taken to minimize the errors in experimentation, yet some errors are likely to creep in. The error in measurement depends upon the accuracy of the measuring instrument. The various uncertainties associated with

the measurements have been evaluated by Kline and McClintock [9] method and quantification of uncertainty in the measured parameters is as follows. The percentage uncertainty in Area, heat transfer, heat flux, wall temperature and heat transfer co-

efficient has been found 1.67%, 1.097%, 1.995%, 0.203% and 2.99% respectively.
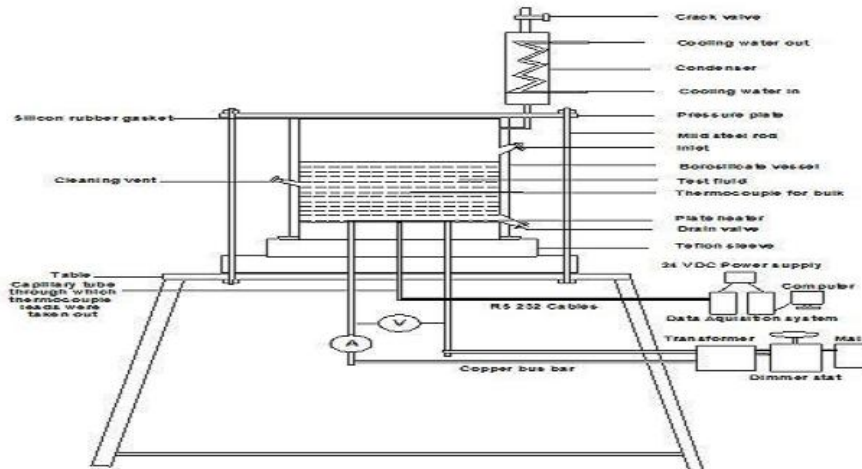

Figure 1 plae heater pool boiling experimental setup

IV. RESULTS AND DISCUSSION

Figure 2 shows the photographs of pool boiling of distilled water on the flat plate heater surface at various heat fluxes. Below the heat flux of 100 kW/m2, the free convection heat transfer is observed. From the given heat flux of 100 kW/m2 to CHF, nucleate boiling is observed. In this region the bubbles begin to form on the surface of the heater and are dissipated in the liquid after breaking away from the surface. Further increase of wall superheat, the bubbles are formed more vigorously and rise to the surface of the liquid, where they are dissipated. Eventually, bubbles are formed so rapidly that they blanket the heating surface and prevent inflow of fresh liquid from taking their place. At this point the bubbles coalesce and form a vapour film which covers the heating surface. Above CHF and upto the burnout of heater elements, the region represents film boiling. The sliding of bubbles is observed during the pool boiling of saturated water at atmospheric pressure. The bubbles formation, growth and detachment occurred on the same point on the surface of flat plate heater.

The data obtained from the boiling of distilled water over a flat plate test-heater, have been

analyzed in order to check the integrity of the experimental set-up. The results for the pool boiling of water have been compared with those predicted by

Cornwell-Houston correlation [2], Kutateladze (new) correlation [10], Kruzhilin correlation [11] and Stephan and Abdelsalam correlation [12]. The equations of the above correlations are given below

a. Cornwell-Houston correlation (1994)

$$Nu = 9.7 P_C^{0.5} F_p \operatorname{Re}^{0.67} \operatorname{Pr}^{0.4} \qquad (4)$$

$$F_p = 1.8 P_r^{0.17} + 4 P_r^{1.2} + 10 P_r^{10} \qquad (5)$$

Where, $P_r = \dfrac{P}{P_C}$

b. Kruzhilin correlation (1947)

$$\frac{h l_*}{k} = 0082 \left(\frac{h_{fg} \rho_g}{g T_s + 2735 (\rho - \rho_g)} \right)^{07} \left(\frac{(T_s + 2735) C_p \rho}{h_{fg}^2 \rho_g^2 l_*} \right)^{033} \operatorname{Pr}^{045} (6)$$

c. Kutateladze new correlation (1990)

$$h_b = \left[3.37 \, x10^{-9} \frac{k}{l_*} \left(\frac{h_{fg}}{C_p q} \right)^{-2} \left(\frac{\left(\frac{\sigma g}{\rho - \rho_g} \right)}{\left(\frac{p}{\rho_g} \right)^2} \right)^{-4} \right]^{\frac{1}{3}}$$

$$(7)$$

Where $l_* = \left[\dfrac{\sigma}{g(\rho - \rho_g)} \right]^{0.5}$

d. Stephen Abdelsalam correlation

$$h_{pred} = 0.248 \times 10 \left(\frac{k_L}{d}\right)\left(\frac{\dot{q}d}{T_s k_L}\right)^{0.673}\left(\frac{h_{fg}d^2}{\alpha^2}\right)^{-1.58}\left(\frac{Cp_s d^2}{\alpha^2}\right)^{1.26}\left(\frac{\rho_L - \rho_v}{\rho_L}\right)^{5.22}$$
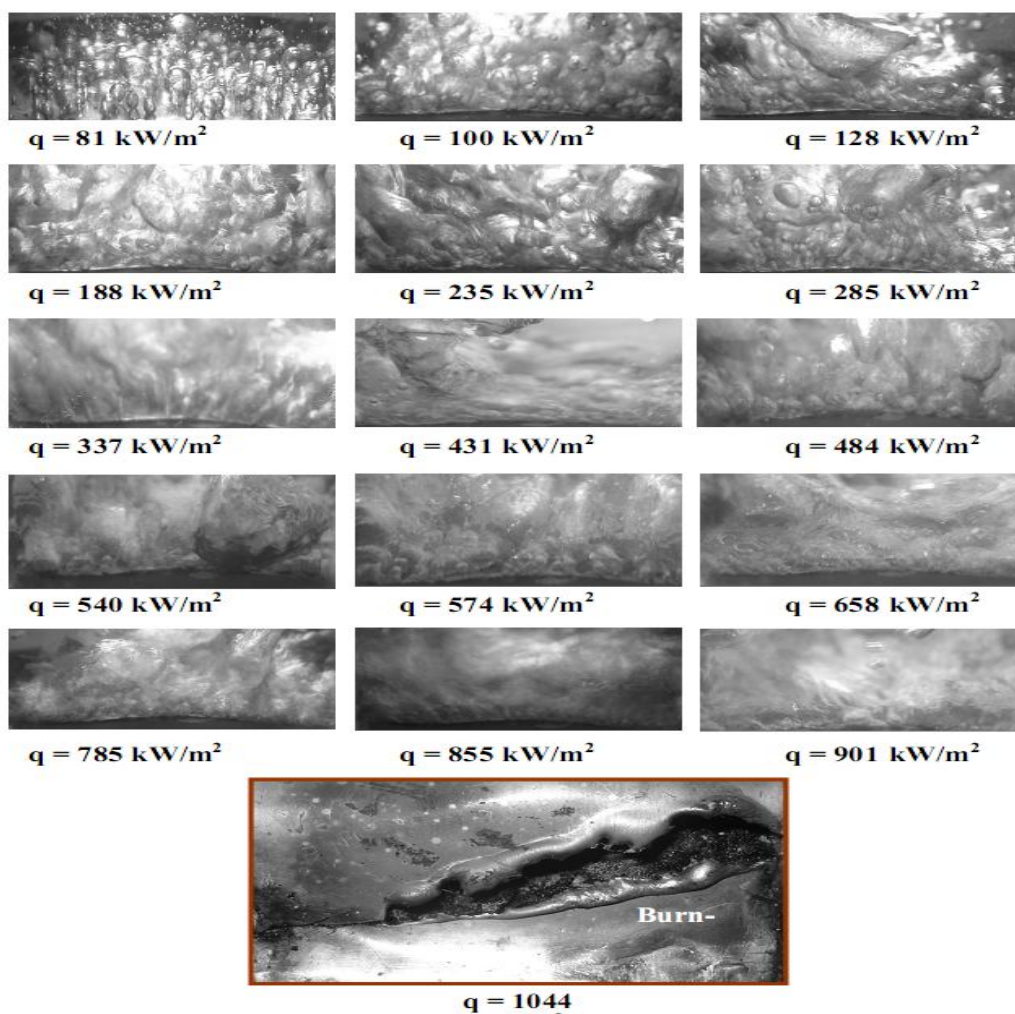
(8)

Figure 2 Boiling of water over the flat plate heater at different heat fluxes

Figure 3 shows that the present experimental data of water is in good agreement with Stephen and Abdelsalam correlation [12] with the given heat flux range 30-750 kW/m2 and further increase in heat flux, the boiling curve of experimental data has an under prediction due to high bubble dynamic. Figure 4

show the relation between present experimental heat transfer coefficient with that predicted by Stephen and Abdelsalam correlation [12]. Without any modification in the Stephen and Abdelsalam correlation[12], it is observed that the experimental data of water are within an error band of ± 20 percent, this is because of the Stephen and Abdelsalam correlation [12] predicts their own data in an error band of 11.3 percent (Figure 4). This agreement of experimental data with Stephen and Abdelsalam

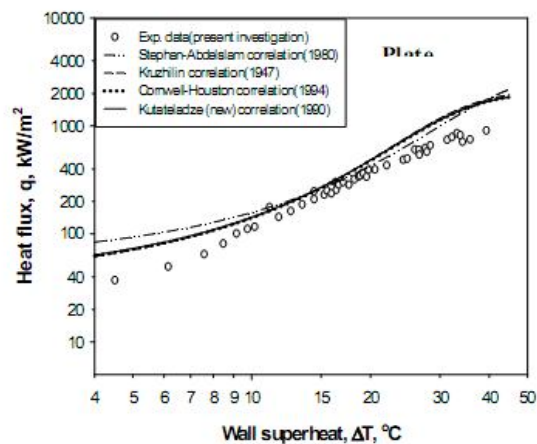correlation [12] establishes the integrity of experimental set-up.

Figure 3 Comparison of pool boiling experimental result of water with existing correlations

The experimental data for the boiling of distilled water are also be in good agreement with those predicted by Cornwell-Houston [2] , Kutateladze (new) [10], and Kruzhilin [11] correlation for the heat flux up to 400 kW/m2 and above which, the experimental data are under predictions by 30 percent. In fact, at higher heat fluxes, the heat transfer curve for experimental data converges towards the predicted values by the above said correlations due to high bubble dynamics (Figure 4). The results show that the test surface has better heat transfer performance in association with the more bubble nucleation and higher bubble generation frequency (Tsay et al. [13]).
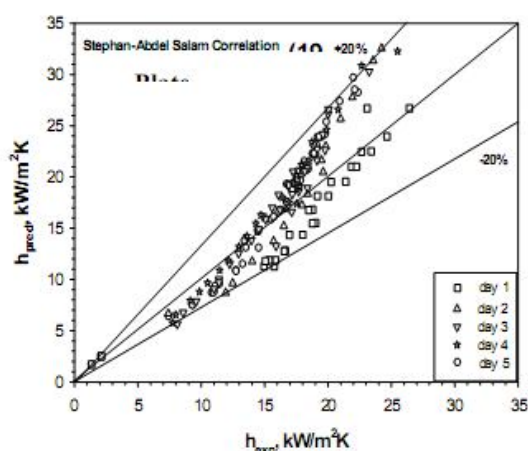

Figure 4 Variation of hexp with hpred by Stephen Abdelsalam correlation (1980)

In order to minimize the error band, the pool boiling experimental data of water have been analyzed by regression analysis using Stephen and Abdelsalam correlation [12] and the powers and coefficient of the terms in the correlation are modified and the optimum values of the power index and coefficient which gives the minimum error band are obtained. Equations 8 shows the actual correlation of Stephen Abdel salam [12] and equation 9 shows modified Stephen Abdelsalam correlation. Figure 5 shows the error band of experimental heat transfer coefficient of water with predicted heat transfer coefficient by
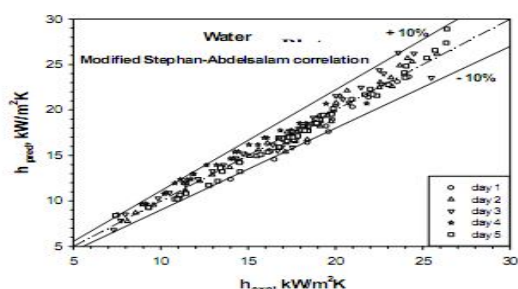

Figure 5 Comparision of hexp with hpred by modified Stephen

modified Stephen Abdelsalam correlation obtained by regression analysis and the error band is only ±10 percent.

Modified Stephen Abdelsalam correlation of water for present investigation

$$h_{pred}=0.559X10^7\left(\frac{k_L}{d}\right)\left(\frac{qd}{T_s k_L}\right)^{0.43}\left(\frac{h_{fg}d^2}{\alpha^2}\right)^{-1.58}\left(\frac{Cp T_s d^2}{\alpha^2}\right)^{1.26}\left(\frac{\rho_L-\rho_v}{\rho_L}\right)^{5.22}$$

Limitations of Present Experimental Study

The heat flux of the heater was controlled with the help of variac so that the input heat flux was varied from 20 kW/m2 to critical heat flux. The fine control of heating could not be achieved by means of variac. Therefore, readings could not be taken for exactly the same levels of heat flux for water as test fluid in different date's plate heater.

V. CONCLUSION

The pool boiling experiment of water over a flat plate stainless steel of 30 mm square plate is conducted and the following has been concluded

1. The experimental data for the boiling of distilled water are also be in good agreement with those predicted by Cornwell-Houston (1994), Kutateladze (new) (1990), and Kruzhilin (1947) correlation for the heat flux up to 400 kW/m2. And above which, the experimental data are under predictions by 30 percent.

2. At higher heat fluxes, the heat transfer curve for experimental data converges towards the predicted values due to high bubble dynamics. The results show that the test surface has better heat transfer performance in association with the more bubble nucleation and higher bubble generation frequency.

3. The modified Stephen Abdelsalam correlation obtained by regression analysis and the error band is only ±10 percent with that of this modified correlation.

VI. FUTURE SUGGESTION

In our future studies we are using the nano fluids in the replacement of water in the same pool boiling exprimental setup.

VII. NOMENCLATURE

A	Heated surface area, (m^2)
B	Full width at half of maximum intensity (FWHM) in radians
Cp	Specific Heat Capacity $(Jkg^{-1}K^{-1})$
I	Electric Current (ampere)
Nu	Nusselt Number $(hkfL^{-1})$
P	Pressure (Pa)

Pr	Prandtl number
Re_b	Boiling Reynolds Number ($qD\mu f^{-1} h_{fg}^{-1}$)
ΔT	Wall Superheat, T_w-T_{sat} (^{o}C or K)
V	Voltage (volt)
a	Side (m)
g	Acceleration due to Gravity (ms^{-2})
h	Heat transfer coefficient (Wm^{-2} K^{-1})
h_{fg}	Latent heat of vaporization (Jkg^{-1})
k, k_w	Thermal conductivity (Wm^{-1} K^{-1})
q	Heat flux (Wm^{-2})
$\overset{.}{q}_g$	Internal volumetric heat generation rate(Wm)

GREEK SYMBOLS

β	Contact angle (degree)
δ	Thickness of the plate
(m)μ	Dynamic viscosity (Pa-s)

SUBSCRIPT

b	boiling
c	critical
g	gas
l	liquid
m	mass
v	volume
w	wall, plate

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