

AN EXPERIMENTAL STUDY OF POOL BOILING HEAT TRANSFER ENHANCEMENT IN DEIONISED WATER USING ADDITIVE

Miss. Vipashana K. Meshram¹, Prof. Prashant R. Walke²

¹M.Tech Student (Heat Power Engineering), BIT, Ballarpur, Maharashtra, India

²Assistant Professor (Guide) Mechanical Engineering Department, BIT, Ballarpur, Maharashtra, India

Abstract - Pool boiling is of interest in heat transfer applications because of its potential for removing large amount of heat resulting from the latent heat of evaporation and little pressure drop penalty for circulating coolant through the system. Boiling is an important phase change phenomena as it plays a crucial role in the design of high heat flux system like boilers, heat exchangers, heat transfer devices. However boiling process is limited by critical heat flux. At critical heat flux material of heated surface suffers physical damage due to lower heat transfer resulting from thin film formed over the surface. Critical Heat Flux creates inconvenient compromises between economy and safety in most industries, related to thermal systems such as nuclear power plants. Application of this technique results in a decrease of heated surface temperature and a more uniform temperature of the heated surface, both effects are important in immersion cooling of electronic equipment.

Key Words: Critical Heat Flux (CHF), Pool Boiling, Flow Boiling, Deionized Water (DI)

1. INTRODUCTION

Heat transfer is a very important issue in many industrial applications. Heat transfer in the nucleate boiling regime, the latent heat of vaporization during the change from liquid to gas phase can be exploited, and is the most effective way of cooling thermal systems running at high temperatures. However, the boiling heat transfer is limited by the critical heat flux (CHF). This is the highest heat flux where boiling heat transfer sustains its high cooling performance. When the surface reaches CHF, it becomes coated with a vapor film which isolates the heating surface and the fluid, and the heat transfer decreases dramatically. In these conditions, the wall temperature rises quickly, and if it exceeds the limits of its constituent materials, system failure occurs. For this reason, every system incorporates a safety margin by running at a heat flux lower than CHF, but this approach reduces system efficiency. This compromise between safety and efficiency is a very serious problem in the industry. For this reason, a vast amount of work has been carried out to understand heat transfer mechanisms in nucleate boiling and CHF conditions, and to increase the CHF point [1].

When a surface immersed in a liquid is maintained at a temperature higher than the saturation temperature of the liquid, boiling may take place. The type of boiling depends upon the difference between these two temperatures. These

are briefly described as follows. Natural convection boiling occurs at low temperature differences. The motion of the liquid is essentially due to natural convection. Nucleate boiling occurs at high temperature differences. Bubbles of vapour are formed at certain locations on the solid surface. These grow in size, detach from the solid surface, and rise to the liquid surface. Film boiling occurs at still higher temperature differences. The rate of evaporation becomes greater than that required to form bubbles. Hence, the bubbles coalesce and blanket the surface with a vapour film. This phenomenon begins at the peak heat flux. Dissipation of large heat fluxes at relatively small temperature differences is possible in systems utilizing boiling phenomenon as long as the heated wall remains wetted with the liquid. With the wetted wall condition at the heated surface, heat is transferred by a combination of two mechanisms: (i) bubbles are formed at the active nucleation cavities on the heated surface, and heat is transferred by the nucleate boiling mechanism, and (ii) heat is transferred from the wall to the liquid film by convection and goes into the bulk liquid or causes evaporation at the liquid-vapor interface. The large amount of energy associated with the latent heat transfer (compared to the sensible energy change in the liquid corresponding to the available temperature potential in the system) in the case of nucleate boiling, or the efficient heat transfer due to liquid convection at the wall, both lead to very high heat transfer coefficients. Removal or depletion of liquid from the heated wall therefore leads to a sudden degradation in the heat transfer rate. Critical Heat Flux condition represents the upper limit of heat flux (in heat flux controlled systems) followed by a drastic rise in wall temperature, or considerable degradation in heat flux with an increase in wall temperature (in temperature controlled systems) in the nucleate boiling heat transfer. A vapor blanket covers the heated surface separating the surface from the liquid [3].

1.1 Literature Review

1. Baines PI al. presented an alternative mechanistic model for CHF which applied for wall jets and falling films. They maintained that, even when the film separates from the hot wall during severe boiling, adequate cooling of the wall is still possible by droplets that are ejected from the separated film. AS the heat flux is increased, the separation angle of the film will also increase, ejecting droplets further downstream on the surface. CHF

occurs when most of the droplets are ejected beyond the downstream edge of the heater.

2. Katto 151 presented a comprehensive review article on CHF models and correlations for pool and forced convection boiling, which included several studies on thin film boiling systems. The article discusses a CHF model developed earlier by Haramura and Katto 161 for saturated pool and forced convection boiling systems. The model is based on the assumption that, in the high heat flux nucleate boiling region, vapor jets leaving the boiling surface are rendered hydrodynamically unstable due to the Helmholtz instability and a large vapor blanket is formed at the heated wall. They postulated that cooling of the wall is limited by the supply of liquid to a thin liquid layer trapped between the blanket and the wall. In this paper, data taken with Fluorinert FC-72 (product of 3M company) flowing films are reported. The study was conducted to assess the feasibility of using free-falling dielectric fluids to cool vertically mounted electronic chips. Results of extensive photographic studies which depict the mechanistic role of flow parameters on CHF are presented. A CHF model based on subfilm dryout is used as a basis for correlating the experimental data.
3. Roach et al. 10 studied the CHF associated with flow boiling of subcooled water in circular tubes with diameters of 1.17 mm and 1.45 mm $L/D=110$, mass velocities from 250 kg/m² s to 1000 kg/m² s, exit pressures from 345 kPa to 1035 kPa, and inlet temperatures from 49°C to 72°C. They observed the CHF condition at very high exit qualities around 0.8 indicating dryout. CHF increased with increasing channel diameter, mass flux, and pressure. They found that in both the tube sizes for pressure around 690 kPa and mass flux about 800 kg/m² s, CHF did not occur at all, and a smooth transition from nucleate to film boiling took place. The deviation for the smaller tube from the Bowring correlation was about 35% for most heat flux values; it should be noted that the Bowring correlation was based on data with diameters from 2 mm to 45 mm.

2. EXPERIMENTAL APPARATUS & PROCEDURE

2.1 Working of project

- The apparatus consists of a specially designed Borosilicate Glass Cylinder.
- An arrangement above the Cylinder in the form of wooden plate is provided to place the main Heater and the Nichrome wire heater arrangement.
- The base is made of MS and wooden platform given to place the Glass cylinder.
- Heater regulator to supply the regulated power input to the heater.

- Voltmeter and Ammeter to measure power input of the test heater.
- Thermometer placed at suitable position to measure the temperatures of body and the air.
- Digital Temperature Indicator to measure the temperatures.
- The whole arrangement is mounted on an aesthetically designed sturdy frame made of MS frame with all the provisions for holding the tanks and accessories.

To conduct experiments, an experimental set up as shown in Fig. 2.1 is used. It includes a Borosilicate Beaker, Two copper thin cylindrical rod, Test heater and measuring instruments, like ammeter, voltmeter, thermometer, Autotransformer etc.

The Beaker capacity was 3000 ml. The experiment has been conducted at atmospheric pressure. The glass beaker has been used to observe bubble dynamics on the tube. The copper rod was immersed vertically inside a beaker of working fluid and was supported with the help of clamp. Usually Three working fluids used in this experiment is Battery Water, Bore well water and Deionized water. Fluid is heated up by the test surface (copper) which is submerged in the liquid, boils and evaporate. Heating tube are laid vertically in the beaker in such a manner that their closed ends remain floating in liquid pool. Different types of water is filled in the Beaker up to the height of 3000 ml one by one. A voltage regulator modulates input voltage to the test heater. At steady state condition readings of all Thermometer, Digital Temperature Indicator, Ammeter and Voltage regulator readings are noted.

One Wooden sheet (cover) of thickness 10 mm used. Top Wooden cover was used to cover the top side of the glass container so that the vapor will not leave the container. It has a hole at the centre to fix the heater. Heater is used to maintain the saturated condition in the pool. Given electric power supply to the system.

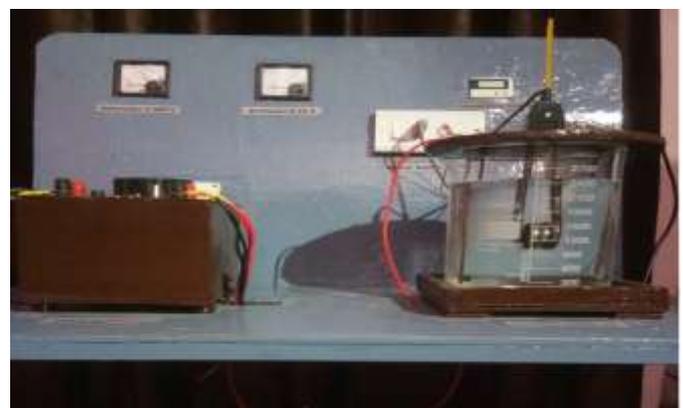


Fig -2.1: Experimental Setup

Inner Wooden disk was inserted inside the container to hold two copper electrodes. Top cover was having small holes for thermometer and wire to supply current to copper electrodes. A heater of 500W was used to heat the different types of water to the saturation temperature. The CHF of those types of water was measured with a NiCr wire of 41 SWG (0.1 or 0.2 mm diameter) vertically submerged in the test fluid at atmospheric pressure. Length of test wire was 110 mm. Two copper electrodes were used having diameter 5mm. Two copper electrodes were used to supply measured AC power to test wire. Both ends of the NiCr wire heater were tightly secured to the clamps of the copper electrodes. These copper electrodes were bolted to the inner Wooden plate inside the container firmly. The pool temperature was measured with a thermometer. All pool boiling experiments were conducted saturated temperature (100°C). heater was heated to saturation temperature. Once the saturation temperature of test fluid was reached. The heater was switched off and the AC power supply to the NiCr wire was switched on. The experiments were conducted by increasing the electric power supply to the wire (test wire). As the wire was becoming red hot the AC supply was increased in smaller steps using Voltage regulator. For each incremental step Voltage and current were recorded during test. At particular Voltage and current NiCr wire breaks, corresponding Voltage and current just before burn out point is recorded and used to calculate CHF of test fluid.

For every test, all types of water with additive was used to ensure it was free from contaminants. Water is chosen because of its well known fluid properties, and minimal risk handling the fluid, compared to a refrigerant. The water is allowed to be boiled sufficiently in order to reduce the effects of any dissolved air within the fluid. Periodically during the tests, more water is added to the pool to replenish the evaporated water vapor. The water is allowed to reach steady-state before any data is collected. The average of five readings was used to determine the difference between wall and bulk temperature for each thermometer.

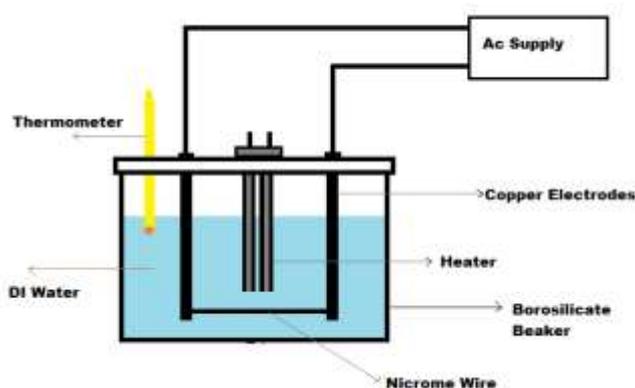


Fig -2.2: Schematic diagram of pool boiling experimental setup

2.2 Testing And Analysis

Experimental work was undertaken to investigate the process by which pool-boiling critical heat flux (CHF) occurs using a camera to measure the local temperature and heat transfer coefficients on a heated surface.

The encouragement for heat transfer enhancement is discussed, and the principles later than compact heat exchangers are summarized. Next, various methods for comparing different types of heat transfer enhancement devices using first or second law resolution are presented. Heat transfer enhancements of both experimental and analytical studies have been reported in view of their industrial and domestic significance. The heat transfer enhancement can be increases by both active and passive method. In that we focus mainly on active method, they require external power, such as electric or audile fields and surface vibration. The way to improve heat transfer achievement is referred to as heat transfer enhancement nowadays a forceful number of thermal engineering researchers are seeking for new enhancing heat transfer methods between surfaces and the surrounding fluid. Due to this phenomenon, enhancement of heat transfer is divided as active or passive methods. Those which require external power source to maintain the enhancement mechanism are named active methods. Examples of active enhancement methods are well stimulating the fluid or vibrating the surface. The principal active methods, i.e. methods involving the supply of external energy, are then detailed. The physical mechanisms growing to heat transfer enhancement are pick out from the analysis.

Critical heat flux (CHF) in pool boiling is an interesting phenomenon. if one controls the input heat flux, there comes a point where as the heat flux is increased further the heater surface temperature undergoes a drastic increase. This increase originally was not well understood. Kutateladze (1951) offered the analogy that this large abrupt temperature increase was caused by a change in the surface geometry of the two phases. In fact, Kutateladze first empirically correlated this phenomenon as analogous to a gas blowing up through a heated porous plate cooled by water above it. At a certain gas volumetric flowrate (or superficial velocity, $j_g = v_g/A$) the liquid ceases to contact the heated surface and the gas forms a continuous barrier. Kutateladze concluded this by measuring the increasing electrical resistance between the plate and water as a function of the increase gas flowrate. Thus, pool boiling CHF may be thought of as the point where nucleate boiling goes through a flow regime transition to film boiling with a continuous vapor film separating the heater and the liquid. More generally, one may say CHF is the condition where the vapor generated by nucleate boiling becomes so large that it prevents the liquid from reaching and rewetting the surface.

Consider this final physical picture of the critical heat flux, \dot{q}_{CHF} , where the liquid is

prevented from reaching the heater surface by the flow of vapor generated by boiling,

$$q_{CHF} = \rho_g i_{fg} V_{crit}$$

where V_{crit} is that critical superficial velocity preventing the liquid flow. A simple force balance on the liquid as droplets, D_f , is given by,

$$C_d \left(\frac{\rho_g V_{crit}^2}{2} \right) \frac{\pi D_f^2}{2} = (\rho_l - \rho_g) \frac{\pi}{6} D_f^3$$

where D_f is assumed to be determined by the characteristic Taylor wavelength (Equ. 2.11), which results in a velocity,

$$V_{crit} \sim \left(\frac{g \Delta \rho}{\rho_g^2} \right)^{1/4}$$

Combining these relations one obtains a general expression for CHF in pool boiling,

$$q_{CHF} = C_o \rho_g i_{fg} \left(\frac{g \Delta \rho}{\rho_g^2} \right)^{1/4}$$

where the constant, C_o , is found to be in the range of 0.12 to 0.18; e.g., Zuber (1958) theoretically estimated $C_o = \pi/24$, Kutateladze (1951) correlated data for $C_o = 0.13$, and Lienhard (1976) correlated data for $C_o = 0.15$.

All of these previous discussions focused on the case where the liquid pool was at its saturation temperature. If the stagnant pool is maintained at a temperature below saturation, subcooled, the vapor bubbles can condense before they get very far from the heater surface. Thus, the heater power can go into directly heating the liquid and actual vapor superficial velocity is decreased; thus increasing the allowable heat flux before CHF occurs. Ivey and Morris (1962) correlated this subcooling effect as a multiplicative correlation to \tilde{q}_{CHF} ,

$$\frac{q_{CHF_{sub}}}{q_{CHF_{sat}}} = \left[1 + 0.1 \left(\frac{\rho_l}{\rho_g} \right)^{3/4} \frac{C_{sub} \Delta T_{sub}}{i_{fg}} \right]$$

where ΔT_{sub} is the degree of subcooling in the liquid.

The final point to emphasize is the location of the CHF point on the pool boiling curve. Critical heat flux appears as a horizontal line of the pool boiling curve and its intersection with the nucleate boiling curve indicates the temperature at which CHF occurs.

2.3 Preparation of fluid

In this work, Distilled water was used as the base liquid, and NaCl particles were used as additives. The NaCl particles were procured from lab having 99% purity. Stirring was

performed for few second just before pool boiling experiments.

Concentrations of NaCl water fluids were as follows.

1. 25 mg of NaCl particles in 2.5 liter of distilled water.(i.e 10ml/liter)
2. 50mg of NaCl particles in 2.5 liter of distilled water.(i.e 20ml/liter)
3. 75 mg of NaCl particles in 2.5 liter of distilled water.(i.e 30ml/liter)
4. 100mg of NaCl particles in 2.5 liter of distilled water.(i.e 40ml/liter)
5. 125mg of NaCl particles in 2.5 liter of distilled water.(i.e 50ml/liter)

In beaker of 3000ml capacity, 2500ml distilled water was taken. Required mass of NaCl particles was taken by weighing on a digital electronic balance. NaCl particles were added into the distilled water very slowly and stir it by wooden strip. Through this preparation temperature of the fluid was increased slowly. Then this solution was poured into beaker of capacity 3 liter having 2500 ml of distilled water and was stirred for few min. This prepared fluid was used in pool boiling experiment. NaCl particles were white in color; hence fluids formed were white in color.

2.4 Calculation

1. Surface Area of the Wire, A

$$A = \pi DL \text{ mm}^2 \\ = \pi * 0.2 * 1100 \\ = 691.15 \text{ mm}^2$$

where d = diameter of Test Wire. L = Length of Test Wire.

2. Heat Input, Q

$$Q = V \times I \text{ Watts.} \\ = 100 * 2.5 \\ = 250 \text{ W}$$

Where, V = Voltage in Volts. I = Current in Amps.

3. Heat Flux, q

$$q = Q/A \\ = 250/691.15 \\ = 0.3617 \text{ W/mm}^2$$

4. Heat Transfer Co - efficient, h

$$h = q/A * \Delta T \\ = 250/691.15 * ((101-99)+273) \\ = 99.47 \text{ W/mm}^2\text{k}$$

Where, q = Heat Flux

5. Temperature Excess, ΔT

$$\Delta T = (T_w - T_{sat}) \\ = (101-99) + 273 = 275\text{K}$$

3. RESULT AND DISCUSSION

- **Influencing parameter.**

The most important parameters of influence on pool boiling heat transfer of fluids are heat flux (q), saturation pressure and properties of the boiling fluid. Additional influences result from material and surface roughness of the heating elements, from their arrangement (inclination to gravity; geometry), and from operating conditions of the evaporators (impurities of the fluid). The pool boiling heat transfer relations can apply to smooth surfaces. As the rate of heat transfer in the nucleate boiling regime strongly depends on the number of active nucleation sites on the surface and the rate of bubble formation at each site. It is observed that irregularities on the heating surface, including roughness and dirt, serve as additional nucleation sites during boiling. The first bubbles are likely to form at the scratches on the heating surface. These scratches act like nests for the bubbles to form and thus increase the rate of bubble formation. Such surfaces are reported to enhance heat transfer in the nucleate boiling regime. High heat transfer rates cannot be sustained for long since the effect of surface roughness is observed to decay with time and the heat flux to drop eventually to near the values encountered on smooth surfaces.

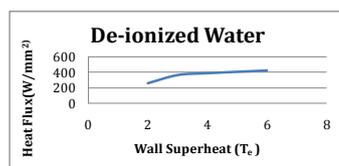
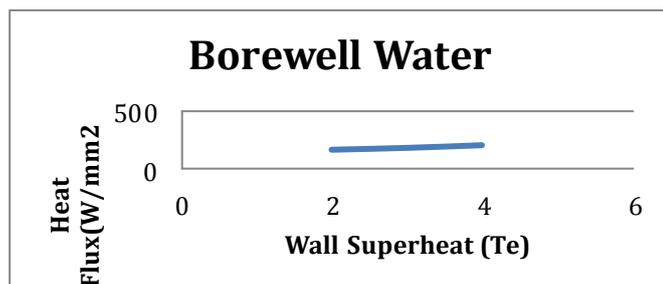
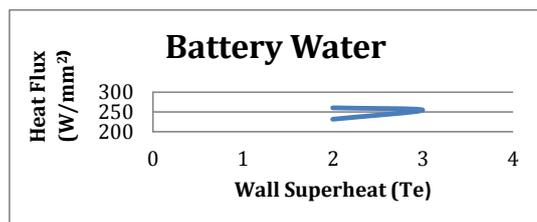


Chart -1: Comparison of Different types of water with NaCl Additive in pool boiling heat transfer.

- **CHF of fluid at different concentration.**

In the present experimentations, concentration of fluid was varied from 10ml/liter to 50 ml/liter. At each concentration CHF values were determined by performing five experiments. CHF values for that particular concentration was considered as average of four experiments. Measured CHF values of NaCl-water fluid at different particle concentrations. From pool boiling experiments results it is clear that CHF of NaCl- water fluid is greater than that of water.

- **Surface roughness of heater surface used in pool boiling of fluid.**

When additive is added to base fluid CHF enhancement occurs in pool boiling. CHF enhancement increases with fluid concentration from 10 ml/liter to 40ml/liter fluid particle concentration, then for 50 ml/liter particle concentration CHF enhancement decreases. Likewise, Surface roughness of wire surface increases when it is used in increased fluid particle concentration up to 40 ml/liter concentration then for 50 ml/liter concentration surface roughness value decreases as compared to 40ml/liter fluid particle concentration. These results clearly indicates that in pool boiling of fluid particle deposits on heater surface forms a porous layer and causes surface roughness change of heater surface. Due to this porous layer trapping of liquid near heater surface takes place which leads to delay in occurrence of CHF.

Also, these porous layer causes breaking of voids near heater surface and prevent the formation of vapor blanket on the heater surface, thus CHF enhancement occurs. Fluid particle deposition increases nucleation site density. Due to increase in nucleation site density bubble departure diameter decreases. Due to this, coalescence of bubble decreases and vapor blanketing on the heater surface decreases. Also, reduced bubble departure diameter causes increased bubble departure frequency as small size bubble forms. Irregularity due to roughness allows bubble to leave heater surface more easily.

The use of NaCl-water fluid in pool boiling experimentation has an effect on the heater surface roughness. When the NaCl-water fluid evaporates at the boiling surface, it leaves behind fluid particles that adhere to the boiling surface. This builds up of fluid particle layer on the boiling surface. Thus, surface roughness changes. Also, a rougher surface increases nucleation site density, the physical locations at which the boiling process begins. The effect of fluid particle concentration on surface roughness of wire is needed to find out. Hence surface roughness of wire surface before pool boiling and wire used in pool boiling of NaCl-water fluid at different concentration is measured. More specifically surface roughness is defined as the measurement of vertical deviation of a real surface from its ideal surface.

- **Considering boiling curve.**

With the same heating area, the boiling curve for with NaCl-water solution it has been observed that the enhancement of heat flux is much higher than that of Water. Surface tension is generated due to the attractive forces present in a fluid with respect to air. Since surface tension of NaCl-water solution is higher than that of Water and latent heat of evaporation was even smaller, when Sodium Chloride was used as working liquid, the microlayer at the bottom of coalesced bubbles was more liable to be dried out. Heat transfer deterioration appeared in part of the area, and the global effect of heat transfer enhancement was poorer than that of water. Through experiments it has been observed that the size of the bubble in case of NaCl solution increases due to its greater volume expansion co-efficient than that of water. With increase in bubble size, frequency of bubble formation decreases which results in reduced heat transfer.

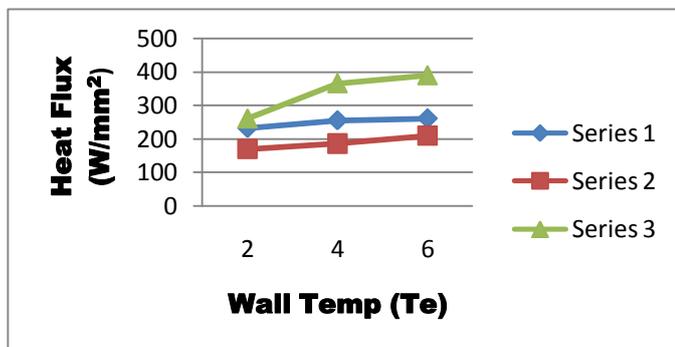


Chart- 2 Variation of heat flux of Additive with different Waters with wall superheat in pool boiling,

- **Variation of heat flux with time.**

Since bubble growth depends on a sufficient superheating of the surrounding liquid, fluid properties, and available superheat. Bubble growth is expected to take place from an active cavity (cavity with residual gasses or vapor) when the surrounding liquid reaches the required superheat. An appreciable time may be required to reheat the liquid in the vicinity of the wall to a superheated state and initiate subsequent bubble growth. Time required for the surface of heater to be superheated in definite heat input here referred as Time of Superheat. Time to be superheated is largely depends on the rate of bubble growth and departure as they act as energy mover. The stirring and agitation caused by the entrainment of the liquid to the heater surface is primarily responsible for the increased heat flux. The length of time from the beginning of bubble growth to bubble departure, depends on how large the bubble must become for release to occur. This interval therefore depends on the rate at which the bubble grows to departure size. The departure bubble size is determined from the net effect of forces acting on the bubble as it grows on the surface. Surface tension holds the bubble down.

- **Variation of heat transfer coefficient with heat input.**

The variation in convective heat transfer coefficient for the different values of heat input has been shown in Fig. 8.3. It is observed that it is strongly dependent on the heat input, as expected. It varies from 65 to 120 W/mm² k for the heat input range from 180 to 294 W. These results are in accordance with those reported in the literature. The increasing trend in the values of *h* with the increase in the heat input may be due to a higher surface temperature and the rapid formation of vapour bubbles at the surface liquid interface. It is further noted that the heat transfer rate is increasing with (*T_s — T_{sat}*) at low values of heat input.

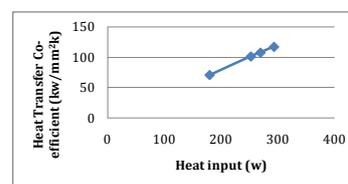


Chart- 3 Variation of heat transfer co-efficient with heat input in pool boiling heat transfer.

4. CONCLUSIONS

An experimental observation has been established for pool boiling of deionized water from a copper tube with vertical orientation. The following conclusions can be reported.

[1] In the pool boiling experiment, considerable amounts of additive are deposited on the nichrome wire. Thus, the surface wettability, which is important parameter for CHF enhancement, is changed and the CHF is also enhanced.

[2] Heat transfer coefficients and critical heat flux are strongly dependent on the fluid properties. Fluids with a low surface tension, such as alcohols, NaCl etc. will wet a given surface better and have a lower contact angle than higher surface tension fluids such as water.

[3] Pool boiling experiments has been performed on three types of liquids.

[4] At higher heat flux levels time of super heat decreases, and the number of active nucleation sites and the frequency of bubble departure increases. As the flux increases, the heat flux in boiling becomes less fluctuating.

[5] In pool boiling from a cylinder the wall superheat is established in the bottom surface earlier than top surface.

5. FUTURE SCOPE

- Additive like Sodium Chloride particle deposits on heater surface forming layer on heater surface. The exact thickness of this layer on heater surface up to which CHF enhancement can occur needs to be found out. This porous layer causes breaking of voids near heater surface and prevents the formation of vapor blanket on the heater surface, thus CHF enhancement occurs.
- If bubble size increases, frequency of bubble formation decreases which results in reduced heat transfer.

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BIOGRAPHIES



Miss. Vipashana Kishor Meshram pursuing M. Tech from BIT, Ballarpur (M.S.) India. Her research interest are in Heat & Mass Transfer.



Prof. Prashant R. Walke working as assistant professor in Mechanical Engineering Department, BIT, Ballarpur (M.S.) India. His research interests are in Heat & Mass Transfer.