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EXPERIMENTAL INVESTIGATION OF POOL BOILING HEAT TRANSFER ENHANCEMENT USING POROUS SURFACE

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***Abstract**- An experimental investigation was carried out to determine the pool boiling heat transfer coefficient of water and to enhance the pool boiling heat transfer. Here, pool boiling was done by electrically heated copper tube with porous surface at atmospheric pressure. The diameter of each pore around the copper tube was 3 mm, depth of each pore was 3 mm and distance between them was 1 cm. The tank in which pool boiling was done consists of stainless steel. This was a close tank and a condensing system was attached to it for system safety. The length and diameter of the heater was 11.36 cm and 2.6 cm respectively. Here natural convection and nucleate boiling regions were identified. The heat transfer coefficient in case of plain surface heater was found between a range from 0.37 kW/m^2 ℃ to 1.25 kW/m^2 ℃. The maximum heat transfer coefficient was found 1.25 kW/m^2 ℃ at the critical point of boiling curve at atmospheric pressure. The heat transfer coefficient in case of porous surface heater was found to be at a range from 0.36 kW/m^2 ℃ to 1.30 kW/m^2 ℃. The maximum heat transfer coefficient was found 1.30 kW/m^2 ℃ at the critical point of boiling curve at atmospheric pressure.*

Keywords: Porous surface, Pool boiling, Copper rod, Forced water cooling.

1. Introduction

Boiling occurs at the solid liquid interface when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid. In pool boiling, the heated surface is submerged below a free surface of fluid. There is no bulk fluid motion. Any motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy.

The rate of heat transfer between a solid surface and a fluid per unit surface area and per unit temperature difference is called convective heat transfer co-efficient.

We are born in an era where there is scarcity of energy. For this reason Pool boiling heat transfer enhancement is needed to reduce the loss of energy. Because by enhanced heat transfer production of vast amount of vapor by using less energy or work is possible. This is the sole objective of this experiment. Other objectives are:

- To design and fabricate an experimental setup for determining boiling heat transfer co-efficient of liquid.
- To increase the pool boiling heat transfer.
- To make sure that boiling begins at high pressure with respect to fluids saturation temperature so that we can have our desired fine steam particles.
- Finding out suitable heating material and suitable surface of material for specific fluid.

A fair amount of study was conducted on pool boiling heat transfer by using different types of fluids and heating surface. It has been proved that the increased number of nucleation sites may enhance the heat transfer by providing more convection heat transfer from increased bubble agitation. The geometry of the micro-cavity containing trapped vapor/gases was directly related to the bubble nucleation process. Re-entrant type cavities were stable, easily activated boiling sites. The primary enhancement mechanisms for re-entrant type enhanced surfaces were: enhanced nucleation from the larger embryonic bubbles, increased thin film evaporation due to the large internal surface area of the porous structure, and two-phase convection within the porous structure. [1][2]

Electroplating the heating surface was also done to enhance the heat transfer. Where, cold water with porous copper rod gave the best performance. [3][4]

Abrasive treatment was also done to enhance the heat transfer rate. Because of the severe aging effects, there has been little sustained interest in this method. [5]

Boiling with using open groove surface was also done in different researches. Those researches results were also pretty suitable. [6][7]

Pool boiling heat transfer coefficient using wired heater was 1.213 kW/m^2℃ and Wall Temperature of heater was 151℃. A table of heat transfer which indicates properties of saturated water was used to measure the heat transfer co-efficient. [8][9]

2. Experimental Setup

The experimental setup has various materials and components. Following materials was used in the setup as shown in fig. 1 and fig. 2.

Heater: An electric heater was used here for water heating as shown in fig. 1.
Tank: It was made of stainless steel plate as shown in fig. 3.
Boiling liquid: In this experiment, boiling liquid was water as shown in fig. 3.
Multi-meter: It was used to measure the voltage and current and get power of heater as shown in fig. 2.
Thermocouple: K type thermocouple was placed between heater and copper tube to get the reading as shown fig. 2.
Voltage regulator: It was used to regulate or change the power of heater as shown in fig. 2.
Copper rod: Porous surface copper rod was used here. The diameter of each is pore was 3 mm and depth was 3 mm and the distance between them was 1 cm as shown in fig. 3 and 4.

At first copper rod was drilled by lathe machine and also porous surface on copper rod was created by drill machine. The diameter of each is pore was 3 mm and depth was 3 mm and the distance between them was 1 cm. It was done on workshop. Then this copper rod was attached with stainless steel tank properly. Korean putty was used to make the setup leak proof. At higher temperature continuous flow of water through the condenser was ensured for the safety of this setup because this setup was a closed setup. The heater was placed inside the copper rod. K type thermocouple was placed in between the heater and copper rod for wall temperature. Then voltage regulator was used to control the voltage flow. Voltmeter and ammeter was connected to the setup for voltage and current reading. A thermometer was used to measure the temperature of the water.

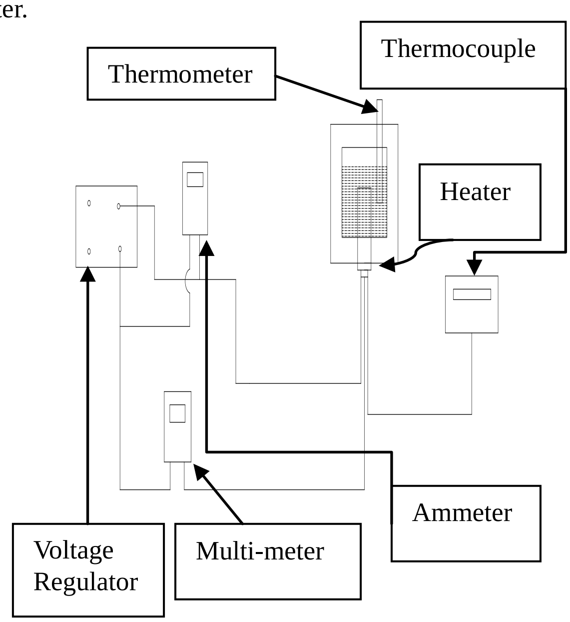

Fig. 1: Schematic diagram of setup.

Fig. 2: Final experimental setup.

Fig. 3: Formation of bubbles.

Fig. 4: Porous copper rod for extended heating.

3. Data Calculation

Natural convective and boiling heat transfer co-efficient theoretically can be calculated by some empirical relation. For natural convective heat transfer the characteristic dimensions to be used in Nusselt and Grashof numbers depends on the geometry of the problem. For the boiling heat transfer, it depends on the nature of nucleation, which is difficult to predict. This complication made it difficult to develop theoretical relations for heat transfer and for this reason relations are based on experimental data.

Newton's law of cooling

Convective heat flux is proportional to the difference between the surface and fluid temperatures. This is expressed as equation (1),

$$q = \frac{Q}{A} = h(T_w - T_\infty) \qquad (1)$$

Theoretically free convective heat transfer depends on film temperature, Prandtl number, Nusselt number, Grashof number, Thermal conductivity etc.

It is the arithmetic average of the surface and liquid temperature. The fluid properties are usually evaluated at the film temperature expressed as equation (2),

$$T_f = \{(T_w + T_L)/2\} \qquad (2)$$

The nusselt number is a dimensionless number that measures the enhancement of heat transfer from a surface that occurs in real situation, compared to the heat transferred if just conduction occurred. It is the ratio of convective heat transfer to the conductive heat transfer. Rayleigh number is dimensionless number associated with the heat transfer within the fluid. When the Rayleigh number is below the critical value for that fluid, heat transfer is primarily in the form of conduction; when it exceeds the critical value, heat transfer is primarily in the form of convection. Rayleigh number is defined as the product of the grashof number and prandtl number. Where, prandtl number defined as viscous diffusion rate to thermal diffusion rate.

Data Collection Method:

- A heating capacity of 30.6W for plain heater and 10.2W for porous heater was set at the start of the experiment.
- Heating capacity was increased by regulating voltage regulator up to 370.6W
- After certain interval of time data was taken from voltmeter, ammeter, thermometer and thermocouple.

Data Collection:

- Outside diameter of the heater, D = 0.026 m
- Length of the heater, L = 0.1136 m
- Heater surface area, $A = \pi L D = .009279\ m^2$
- Liquid : Water
- Boiling point at 1 atm 100°C
- Surface tension of liquid-vapor interface for water at saturation temperature, σ = 0.0588 N/m
- Value of co-efficient, C_{sf} = 0.013 and s = 1.0 for water-copper (polished)

Necessary Equation for Calculation Process

Outer surface area of the heater, $A = \pi L D$ ………….. (1)
Heat transfer rate, $Q = h A (T_w - T_L)$ ………………… (2)
Heat flux, $q = Q / A$ …………………........................ (3)
Heat transfer co-efficient, $h = q / (T_W - T_L)$ ……… (4)
Film temperature, $T_f = (T_W + T_L) / 2$ ……………… (5)
Rayleigh number, $Ra_x = g\beta\rho^2 Cp(T_W - T_L)D^3/\mu k$ … (6)
Nusselt number, $Nu = .59 \times (Ra_x)^{1/4}$ $10^4 \le Ra_x \le 10^9$. (7)
Theoretical Heat transfer coefficient, $h = Nu \times k / D$... (8)
For nucleate boiling,
Heat flux, $q = \mu_l \times h_{fg} \times \left(\frac{c_{pl}}{h_{fg} \times pr_l^s \times C_{sf}}\right)^3 \times (T_W - T_{sat})^3 \times \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{0.5}$ ……………………………………….. (9)
Heat transfer co-efficient, $h = q / (T_W - T_{sat})$ …….. (10)

4. Result and Discussion:

For plain heater:

In this experiment, two different boiling regions are found, they are

- Natural convection region and
- Nucleate boiling region.

In natural convection region,

T_{excess} = 0 to 7 °C
h_{exp} = 0.66 to 0.76 kW/m²°C

The nucleate boiling region is divided into sub regions:

- Bubbles collapse in the liquid:
  T_{excess} = 7 to 21 °C
  h_{exp} = 0.76 to 1.14 kW/m²°C
- Bubbles rise to the free the surface:
  T_{excess} = 21 to 27 °C
  h_{exp} = 1.14 to 1.25 kW/m²°C

Maximum heat transfer coefficient, h_{max} = 1.25 kW/m²°C at atmospheric pressure.
The wall temperature T_w = 127 °C at critical point.

For porous heater:

In natural convection region,

T_{excess} = 0 to 4 °C
h_{exp} = 0.66 to 0.70 kW/m²°C

The nucleate boiling region is divided into sub regions:

- Bubbles collapse in the liquid:
  T_{excess} = 4 to 19 °C
  h_{exp} = 0.70 to 1.11 kW/m²°C
- Bubbles rise to the free the surface:
  T_{excess} = 19 to 24 °C
  h_{exp} = 1.11 to 1.30 kW/m²°C

Maximum heat transfer coefficient, h_{max} = 1.30 kW/m^2°C at atmospheric pressure.
The wall temperature T_w = 124 °C at critical point.

Heat transfer coefficient: In case of natural convection, the heat transfer coefficient increased slowly with respect to heat flux. When the nucleate boiling started, the heat transfer coefficient increased rapidly. But this increasing rate slowed down and finally started to decrease after the critical heat flux was obtained. This occurred due to the blanketing of heater surface with vapor film as shown in figure 5.
Heat flux: In case of natural convection, heat flux increased slowly with respect to T_{excess}. In case of nucleate boiling, the heat flux increased rapidly with increasing temperature until the peak heat flux was reached as shown in figure 6. If burnout point of the heater is reached within this time frame, heat flux reduction is necessary. In this experiment this circumstances didn't required.

There was variation in heat transfer co-efficient between plain and porous heater. Because plain heating surface couldn't be able to produce vast amount of bubble as porous surface due to lack of uneven surface. That's why intense porous surface helped to get high heat transfer co-efficient compared to plain surface. Although, maximum heat transfer co-efficient 1.30 kW/m^2°C was quite low. Because a cooling system was given to this setup for safety as it was a closed system. The amount of heat taken away by this cooling system was not included in calculation. For this reason, heat transfer co-efficient was quite a bit low.

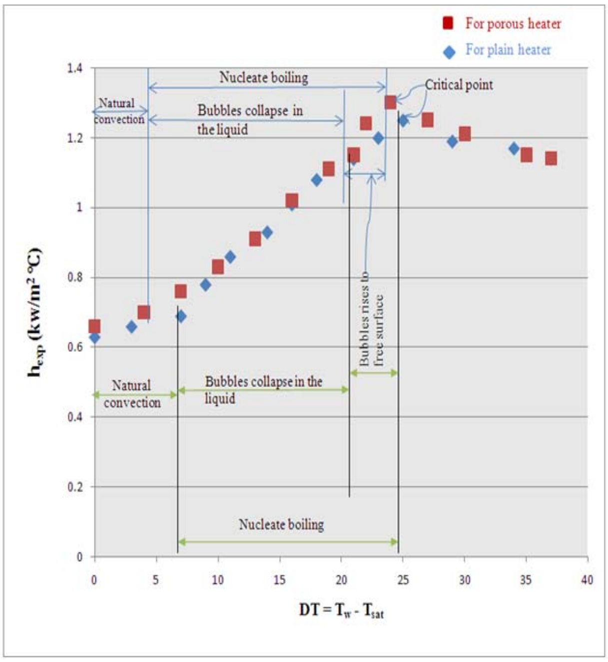

Fig. 5: Representation of heat transfer coefficient (experimental) and temperature difference of wall and saturation temperature of water for plain and porous heater.

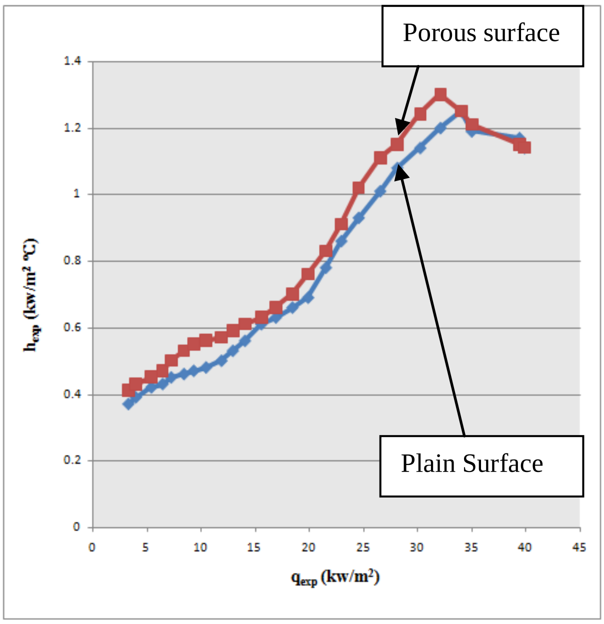

Fig. 6: Representation of heat transfer coefficient (experimental) and heat flux for plain and porous heater.

5. Conclusion

Boiling Heat transfer coefficient measurement is a theoretical analytical experiment. By this setup the experimental and theoretical coefficients have been measured. The maximum heat flux in critical point was not similar to the theoretical maximum heat flux due to heat loss from the experimental setup. A certain amount of heat lost through the periphery of the tank. The voltage regulator was fluctuating. That caused problem in data taking. Higher heat transfer coefficient was gathered in this experiment because of two reasons,

- The boiling tank was closed and well sealed.
- For the use of porous surface of the heater.

6. References

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7. Nomenclature:

Symbol	Meaning
A	Surface area of heating tube (m^2)
h	Convective heat transfer coefficient($W/m^2/°C$)
d	Diameter of the heating tube(m)
L	Length of the heating tube(m)
Q	Rate of heat transfer(W)
q	Heat flux(W/m^2)
T_w	Wall temperature of heating tube($°C$)
T_L	Temperature of liquid($°C$)
T_{sat}	Temperature of saturation($°C$)
dT	Wall and liquid temperature difference
Texcess	Wall and saturated temperature difference
Csf	Value of co-efficient for water-copper(polished)
h_{fg}	Enthalpy of vaporization(J/kg)
g	Gravitational acceleration(m/s^2)
n	Experimental constant that depends on fluid

Greek letters	Meaning
μ	Viscosity of the liquid(Kg/ms)
ρ_l	Density of the liquid(kg/m^3)
ρ_v	Density of vapor(Kg/m^3)
σ	Surface tension of the liquid-vapor interface (N/m)

Dimensionless Number	Meaning
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Ra_x	Rayleigh number