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EXPRIMENTAL INVESTIGATION OF POOL BOILING & OPTIMIZATION OF CRITICAL HEAT FLUX BY USING Al2O3 NANOFLUID

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ABSTRACT

This work performed the experimentation to study the pool boiling and optimization analysis of critical heat flux using nanofluid. Phenomenon of boiling heat transfer plays a crucial role in the design of high heat flux system like boilers, heat exchanger, microscopic heat transfer devices. This works uses the Al_2O_3 nanoparticles for experimentation. The experiments covered the following range: Nanofluid concentration (NF_C) 6 gm/lit, 9 gm/lit and 12 gm/lit, surface area of heater (A_S) 94.79 mm^2, 129.90 mm^2 and 193.17 mm^2 and mass flow rate of condenser water (M_f) 6 kg/min, 12 kg/min and 18 kg/min. Critical heat flux (CHF) and surface roughness (Ra) considered as performance parameters. The factorial method of design of experiment (DOE) with 3 factors and 2 levels is used for the sequence of experimental trails. The correlations are used for determining theoretical critical heat flux for distilled water. The experimental results for distilled water are compared with theoretical results obtained from correlation equations. There is a good agreement between theoretical and experimental results which gives validation of experimental test rig. The analysis is done with regression method and D'optimal method is used for response optimization.

Keywords: Critical Heat Flux, Pool Boiling, Nanofluid, Concentration, Surface Roughness, Factorial Method.

I. INTRODUCTION

The rapid advancement in the field of nuclear and fossil energy, electronic chips, electric power generation, compact computing devices etc. which gives tremendous impetus to study the heat transfer phenomenon. Heat transfer associated with phase change has gained lot of attention by engineers and researchers throughout the world aimed at improving the heat transfer performance. This rapid heat transfer is possible due to removal of heat from the surface as a combined effect of heat of vaporization and sensible heat, and motion of bubbles leading to rapid mixing of the fluid. This phenomenon of boiling heat transfer plays a crucial role in the design of high heat flux systems like boilers, heat exchangers, microscopic heat transfer devices, thermal ink jet printers etc [1]. Therefore, it is important to predict and enhance the CHF value for improved safety and cost effectiveness. Improved CHF allows operation at thermal power levels higher than those possible in present power plants. The effect of improving CHF in several power plants was considered to be nearly as beneficial as building a new nuclear power plant but obviously without the construction costs. It is important to enhance the CHF in order to improve the safety margin and economic performance in a thermal system. Heat transfer to boiling liquids is a convection process involving a change in phase from liquid to vapor. The phenomena of boiling heat transfer are considerably more complex than those of convection without phase change because in addition to all of the variables associated with convection; those associated with the phase change are also relevant. In liquid phase convection, the geometry of the system, the viscosity, the density, the thermal conductivity, coefficient of expansion and specific heat of the fluid are sufficient to describe the process. In boiling heat transfer, however, the surface characteristics, the surface tension, the latent heat of vaporization, pressure, density and possibly other properties of the vapor play an important part [2]. This has forced the researchers to focus on cooling fluids enhanced heat transfer characteristics. With the surge of nanofluids as potential candidates for cooling fluids, many studies have been reported on enhancement of CHF using nanofluids.

II. EXPERIMENTAL SET-UP

Experimental Set-up consists of various components such as Glass Beaker, Bakelite Covers, Fluid Heater, Test Wire, Copper Electrode, Thermocouple, and Condenser. A glass beaker has capacity of 3000 ml having size 15 cm diameter and 21.5 cm height. Material of glass beaker is Borosilicate. It can sustain temperature up to 350°C. Two Bakelite sheets are used in test rig. Top Bakelite cover is also having small holes for thermocouple and wire to supply current to copper electrodes. There is one inner Bakelite disk is inserted inside the container to hold four copper electrodes. These Bakelite top cover and inner Bakelite disk are bolted each other firmly. To avoid the escape of vapour silicate paste is pasted on bottom of top Bakelite cover so that the flexible layer will form on bottom side of top Bakelite cover and after bolting top Bakelite to the base steel frame, the vapour will not escape from side. Bakelite sheet has thickness 15 mm. In this experimentations plate heater is used. A plate heater of 1000 W is used to heat the water and nanofluid to the saturation temperature. The plate heater is attached to the copper electrode. This plate is having 110 mm diameter and small thickness. Test wire used is Nichrome wire. Wire is of SWG (standard wire gauge) 24, 28, and 32.

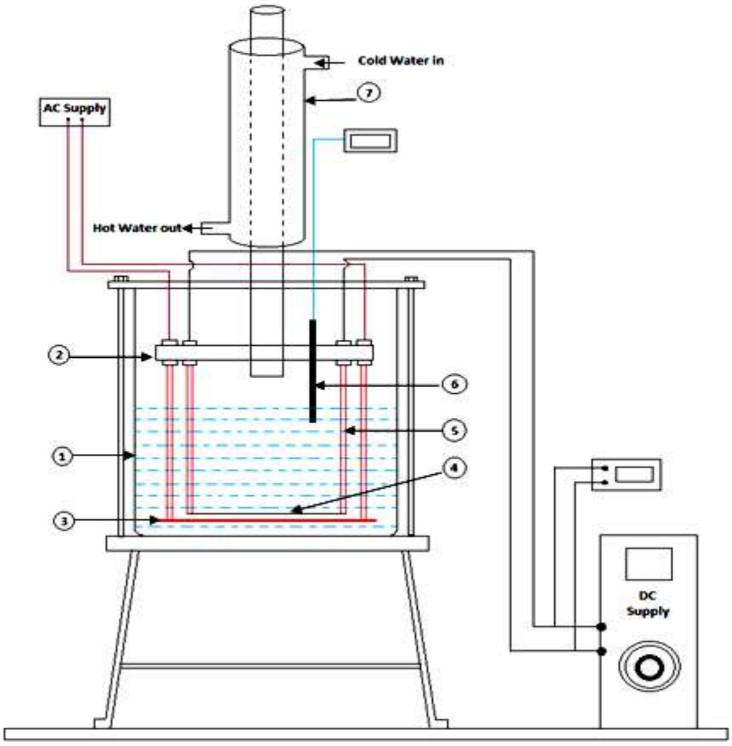

Fig. 1: Schematic of Experimental Set-up: (1) Glass Beaker (2) Bakelite Covers (3) Fluid Heater (4) Test Wire (5) Copper Electrode (6) Thermocouple (7) Condenser

A plate heater of 1000 W is used to heat the water and nanofluid to the saturation temperature. The plate heater is attached to the copper electrode. This plate is having 110 mm diameter and small thickness. Test wire used is Nichrome wire. Wire is of SWG (standard wire gauge) 24, 28, and 32. The diameter of wire is taken according to the standard gauge and length of test wire is selected as 110 mm. Four copper electrodes are used having diameter 5 mm. Two copper electrodes are used to supply current to fluid heater. Other two Copper electrodes are used to supply measured DC power to test wire. The distance between two copper electrodes on which test wire is mounted is 110 mm. K-type thermocouple is used to measure the temperature of the fluid. This thermocouple is calibrated at temperature 50°C, 100°C, and 150°C having uncertainty 4.5 %. The diameter of thermocouple is 8 mm and length is 75 mm having 2 m wire. The temperature range of the thermocouples is from 0°C to 200°C. Condenser is used to condense the water vapors which are formed due to boiling condenser is having one central hole of 20 mm diameter through which vapors can pass. Surrounding this 20 mm hole water jacket is provided. Water jacket is having length 300 mm diameter 30 mm. Cold water supply arrangement is provided. Two the tubes are attached to condenser supply cold water and take hot water from condenser. Central hole of condenser ensure atmospheric condition inside the container. This condenser is fixed on Bakelite top cover.

Table 1: Operating Conditions Tested in Experimentation

Sr. No	**Parameters**	**Values**		
		Low	**Medium**	**High**
1	Concentration of Nanofluid (NF_c)	6 gm/lit.	9 gm/lit.	12 gm/lit.
2	Surface Area of Heater (A_S)	94.79 mm^2	129.90 mm^2	193.17 mm^2
3	Mass Flow Rate of Condenser Water (M_f)	6 kg/min.	12 kg/min.	18 kg/min.

In the present investigation, experiments have performed on the basis of the design of experiments (DOE) technique. Factorial design of experiment has employed for experimentation in order to improve reliability of result and to reduce the size of experimentation without loss of accuracy. The design chosen has a two level factorial design 2^3 which gives 8 runs of experiment. The process parameters selected for the experimentation is concentration of nanofluid (NF_c), surface area of heater (A_S) and mass flow rate of condenser water (M_f). Critical heat flux (CHF) and surface roughness (Ra) has taken as response variable.

III. DATA PROCESSING

3.1 Critical Heat Flux and Surface Roughness

Experimental critical heat flux is determined by following formula

$$q''_{\text{experimental}} = \frac{V_{CHF} \times I_{CHF}}{A} \tag{1}$$

A = Surface area of heater surface
A = π × D × L
V_{CHF} = Voltage at CHF
I_{CHF} = Current at CHF

The value of surface roughness (Ra) for heater surface is directly obtained from surface roughness testing machine. The sample of each experiment is tested on surface roughness Tester MarSurf M400.

3.2 Experimental Uncertainties

The main sources of uncertainty of the applied voltage and current are due to contact resistance between the wire heater and electrodes [6]. In addition, there is uncertainty associated with the length and diameter of the NiCr wire heater. The measurement uncertainty is calculated using the method by Holman as given in Equation (2).

$$\frac{Uq''}{q''} = \sqrt{\left(\frac{U_I}{I}\right)^2 + \left(\frac{U_V}{V}\right)^2 + \left(\frac{U_D}{D}\right)^2 + \left(\frac{U_L}{L}\right)^2} \tag{2}$$

The uncertainties in the Voltage, Current, Length and diameter of wire measurement are 3.44%, 3.98%, 1.81% and 5.32% respectively. The maximum estimated uncertainty of the heat flux measurement is 7.69%.

IV. RESULT AND DISCUSSION

4.1 Validation of Experimental Set-up

In order to have a basis for the evaluation some experiments were carried out with distilled water. CHF in pool boiling are compared with the most widely accepted Zubers correlation. It is given by:

$$q''_z = 0.131 \times h_{fg} \times \left[g \times \sigma \times \rho_v^2 (\rho_l - \rho_v)\right]^{\frac{1}{4}} \quad (\text{W/m}^2) \tag{3}$$

The predicted value of critical heat flux of distilled water at 100°C by using Zubers correlation is $1.11 MW/m^2$. Critical heat flux is determined for distilled water at saturated temperature by performing ten pool boiling experiments. Average value of CHF is determined by taking average of CHF of ten experiments. Average critical heat flux for experimental method is 1.1891 MW/m² which is 7.12% more than theoretical critical heat flux predicted by Zubers correlation. In all the experiments critical heat flux is deviated from theoretical critical heat flux in acceptable range. Hence experimental test rig is validated.

4.2 Critical Heat Flux Analysis

The experimentation is carried out according to set of experiment obtained from two level full factorial design of experiment. The analysis of results is done by analyzing factorial design, analysis of variance (ANOVA), estimated effects and coefficients and main effects plots, normal plot of standardized effects are drawn for each point. The p-value for all the input parameters such as concentration of nanofluid (NF_c), surface area of heater (A_S) and mass flow rate of condenser water (M_f) are 0.032, 0.084 and 0.043 respectively. In which nanofluid concentration (NF_c) and mass flow rate (M_f) shows significant effect on critical heat flux value because p value lower than 0.05. Figure 2 shows normal plots indicates the percent effect of each parameter on critical heat flux, there are three significant effects ($\alpha \leq 0.05$).

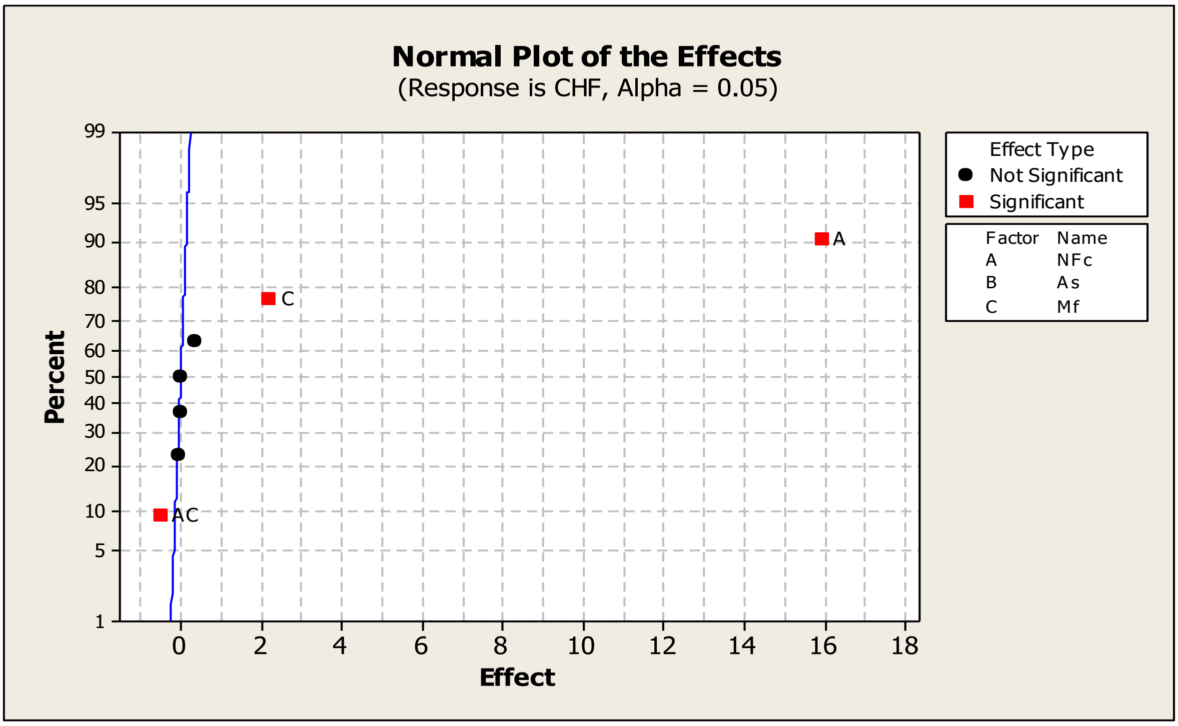

Fig. 2: Normal Plot Showing the Percent Effect of Each Parameter on Critical Heat Flux

These significant effects includes two main effects, concentration of nanofluid (NF_c) and mass flow rate in condenser water (M_f) and one effects from 2-way interactions, which are (NF_c*M_f). All three parameters have largest effect because it lies furthest from the line. In which concentration of nanofluid (NF_c) shows 90.54% effect, Mass flow rate of condenser water (M_f) shows 77.02 % effect and for 2-way interactions (NF_c*M_f) shows 9.45% effect. In addition, the plot indicates the direction of the effect, out of three parameters two parameters i.e. NF_c and M_f shows positive effects because they reside to the right of the line and NF_c*M_f shows negative effect on response because it resides to left of the line.

4.3 Surface Roughness Analysis

The p-value for all the input parameters such as concentration of nanofluid (NF_c), surface area of heater (A_S) and mass flow rate of condenser water (M_f) are 0.005, 0.036 and 0.023 respectively which indicates that all input parameters shows more significant effect on surface roughness. All the input parameters shows the p-value lower than 0.05. Hence, all the input parameter shows significant effects on surface roughness. Figure 3 shows normal plots indicates the percent effect of each parameter on surface roughness, there are three significant effects ($\alpha \leq 0.05$). These significant effects includes all three main effects, nanofluid concentration (NF_c), surface area of heater (A_S), and mass flow rate of condenser water (M_f). All three parameters have largest effect because it lies furthest from the line. There is one significant effect of parameters included in 2-way interaction.

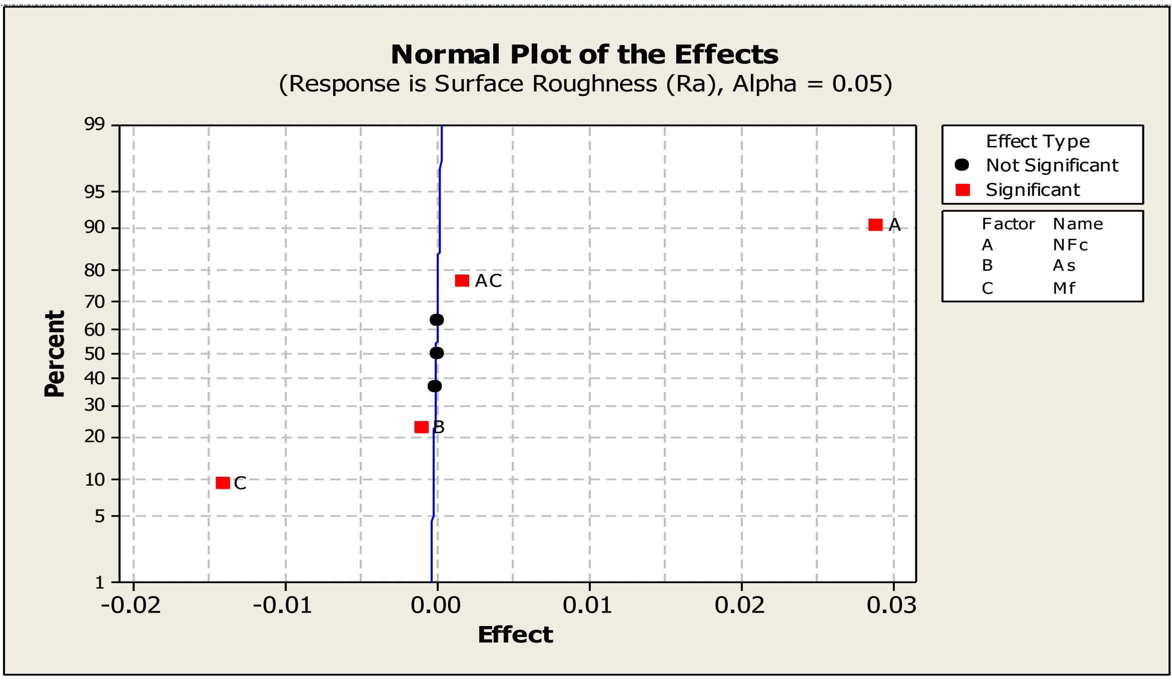

Fig. 3: Normal Plot Showing the Percent Effect of Each Parameter on Surface Roughness

This is interaction of nanofluid concentration (NF_c) and mass flow rate of condenser water (M_f). In which concentration of nanofluid (NF_c) shows 90.40% effect, surface area of heater (A_S) shows 23.54% effect, Mass flow rate of condenser water (M_f) shows 9.55 % effect and for 2-way interactions (NF_c*M_f) shows 78.22% effect. In addition, the plot indicates the direction of the effect, out of three parameters one parameter concentration of nanofluid (NF_c) shows positive effects because they reside to the right of the line and two parameters surface area of heater (A_S) and mass flow rate of condenser water (M_f) shows negative effect on response because it resides to left of the line. Also one interaction of nanofluid concentration (NF_c) and mass flow rate of condenser water (M_f) i.e. (NF_c*M_f) shows positive effect because it reside to the right of the line.

4.4 Response Optimization

Response optimization is carried out to determine the optimum input set of experiment from all 8 sets of input parameters. Table 1 shows input data for optimization which used to determine optimum set of parameters. The optimization is carried out by using 'D' optimal method of optimization with the help of Minitab software.

Table 2: Input Data for Response Optimization

Responses	Goal	Lower Value	Upper Value	Weight	Import
Critical Heat Flux	Maximize	173.80	205.30	1	1
Surface Roughness	Minimize	0.507	0.715	1	1

Figure 4 shows the response optimization plot. Parameters levels with red colour indicate the optimum level of parameters for optimum responses. From the response optimization plot it is clear that, the nanofluid concentration (NF_c) should be 7.8792 gm/lit. It means that optimum value for nanofluid concentration should be 65.66 % of high level. Surface Area of Heater (A_S) should be at low level; i.e.94.79 mm^2 and mass flow rate (M_f) should be at low level; i.e. 6 kg/min.

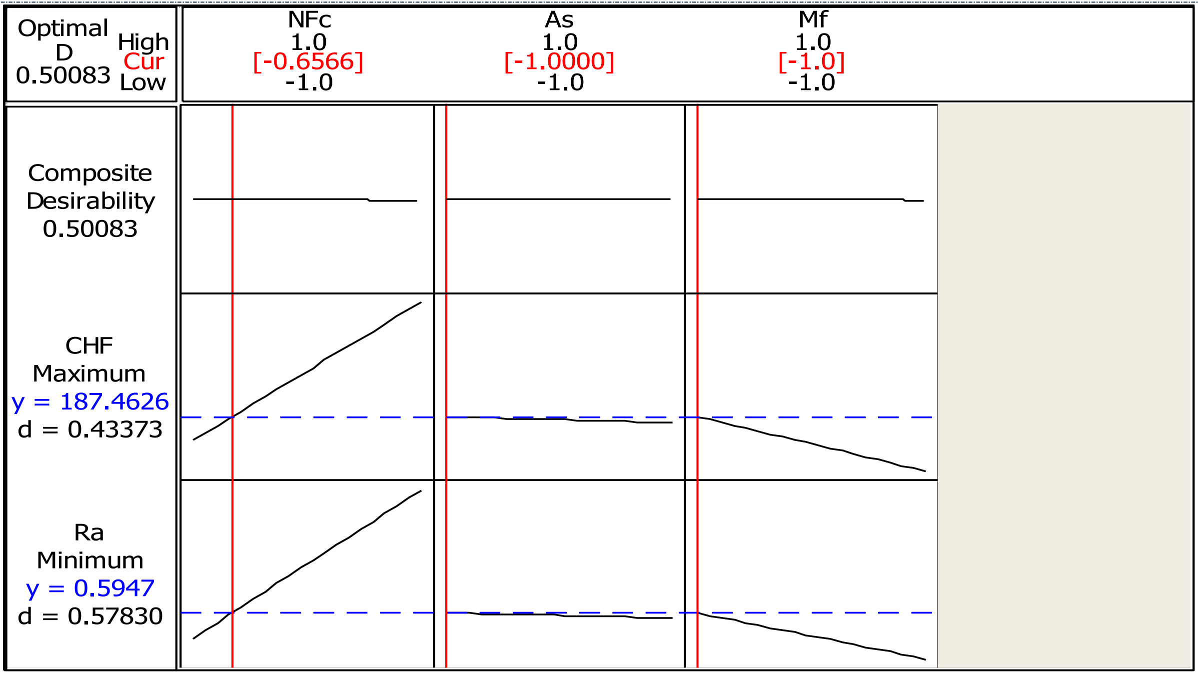

Fig. 4: Response Optimization Plot

V. CONCLUSIONS

In this study, following conclusions are drawn for effective critical heat flux and surface roughness and summarized as:

1. **Development of Experimental Set-up:** In this work design and development of experimental test rig are carried out for desired investigation of critical heat flux (CHF) and surface roughness.
2. **Validation of Experimental Set-up:** Validation of experimental set up is carried out with well-known equations for critical heat flux. The average percentage error of experimental and theoretical critical heat flux is 7.12%. Hence experimental set-up is validated.
3. **Critical Heat Flux Investigation:** The higher values of input parameters such as nanofluid concentration (NF_c =12 gm/lit), mass flow rate of condenser water (M_f =18 kg/min), and lower value of heater surface area (A_S = 94.79 mm^2) provided the maximum value of critical heat flux which is equals to 205.30 W/cm^2.
4. **Surface Roughness Investigation:** The lower value of input parameter such as nanofluid concentration (NF_c = 6 gm/lit), and higher values of heater surface area (A_S = 193.17 mm^2) and mass flow rate of condenser water (M_f =18 kg/min), provided the minimum value of surface roughness which is equals to 0.507
5. **Response Optimization:** It is observed that maximum critical heat flux and minimum surface roughness are obtained simultaneously by employing NF_C= 65.66% of higher value i.e. 7.8792 gm/lit, A_S = 94.79 mm^2 and M_f = 6 kg/min

VI. REFERENCES

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