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ORIGINAL ARTICLE

Experimental prediction of flow boiling heat transfer coefficient of Water and Copper Oxide nanofluid using ANNOVA technique

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Abstract

In the present work the flow boiling charecteristics of CuO/water nanofluid were studied experimentally and the statistical as well as regression analysis were conducted to asses the flow boiling heat transfer coefficient and the influencing parameters. For this, CuO/water nanofluid was prepared by two step procedure for the particle concentration of 0.001%, 0.005%, and 0.01 % respectively. The experiments were conducted by varying the heat flux and mass flux ranging from of 50-200 kW/m2 and 380-955 kg/s-m^2, respectively for water and CuO/water nanofluids. All the experiments were conducted for the same temperature of water at heater inlet. A full factorial multi-level design approach was used to design the experiments by considering the heat flux, mass flux and particle concentration are key influence parameters. Results showed that the boiling heat transfer is increases with mass flux and heat flux for both water and nanofluids. Furthermore, increasing the nanoparticle concentration enhances the flow boiling heat transfer rate and lowers the wall temperature. It is observed that at a mass flux of 954.29 kg/s-m^2, the maximum decrease in wall superheat is 18.66 % for 0.01% CuO/water nanofluid. From statistical analysis, it is noticed that the aforementioned factors were statistically significant. Furthermore, heat flux has a considerable influence on the boiling heat transfer coefficient, which is followed by mass flux and particle concentration. The heat transfer coefficient was predicted using a simplified quadratic model, which was found to be in good agreement with the experimental results.

Keywords: *CuO/water Nanofluid; Flow Boiling Curve; Heat Flux; Mass Flux; Heat Transfer Coefficient; Particle Concentrations.*

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INTRODUCTION

Whenever fluid undergoes a phase transition, it transfers more heat through latent heat of vaporization. Hence boiling heat transfer is undoubtedly the most effective heat transfer mechanism, as evidenced by its great latent heat transport capability, and is employed in a variety of applications including nuclear power production, thermal energy plants, heat exchangers, and radiators. Rapid growth in science and technology had resulted in rise of high heat concentration in devices. Therefore there is a need for an efficient cooling system with superior critical heat flux (CHF) and superior heat transfer coefficient (HTC). In boiling heat transfer systems, the enhancement of HTC makes the boiling systems better energy efficient, resulting in miniature systems.One of the well-known techniques for increasing HTC and CHF is the use of nanofluids instead of base fluid. The use of nanofluids in heat transfer has piqued the curiosity of many researchers. At first, Choi [1] introduced nanofluids, which are colloidal suspensions or

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spreading of nano-scale particles (nanoparticles) in the base liquid. Following discovery of several beneficial nanoparticles properties, such as an elevated surface-to-volume ratio, low inertia and small mass that can result in synergies such as increased mass-to-energy conversion rates, increased colloid stabilization, and low erosion, the intriguing idea of developing new cooling media was introduced.

Initially, the researchers are focused on single phase heat transfer in nanofluids. For example Experimental investigation was carried out by Talebi *et al.* [2] wherein they studied the forced convection of Cu/Fe_3O_4, Fe_3O_4 and Cu and hybrid nanofluid in the laminar regime under constant heat flux for volume fraction of 1, 2, 4% and three Reynold number of 600, 1200 and 1800. They found out that HTC increased with the increase in the volume fraction of nanoparticles and Reynold number and for Cu/water the increase in HTC is 7.8 %. Experimental investigation was carried out by Mortenza *et al.*[3] to study the heat transfer of Fe_3O_4 nanofluid in a helical coil. They found out that increase in heat transfer rate along spherical coil is due to alternating magnetic field. Considering pure water as the base fluid ferrofluid with an alternating magnetic field of 50 Hz, 5 Hz, and ferrofluid without a magnetic field and with a constant magnetic field the increase in the heat transfer was 43%, 33%, 26%, 19%, and respectively.

Empirical investigation was carried out by Hossein *et al.* [4] wherein they studied the fully developed forced convection of Fe_3O_4 nanofluid under the effect of magnetic field. They found out that at a constant Reynolds number, the local heat transfer coefficient increased with the increase in frequency of the alternating magnetic field. H. Kargarsharifabad et al [5] conducted a numerical research to investigate the forced convective heat transfer of an aqueous ferrofluid passing through a circular copper tube in a laminar flow with uniform heat flux. They found out that the convective heat transfer is enhanced by alternating magnetic field.

In recent times, research on nanofluids in boiling heat transfer has grabbed attention. Studies available in open literature reveals that nanofluids are successfully used in boiling process [6] [7][8][9]. In this context, some of the most significant contributions from the literature are discussed here.

Experimental investigation was carried out by A. Zangeneh *et al.* [10] to study the influence of heat flux, sub cooled temperature, mass flux and nanoparticle concentration on heat transfer for the CuO/ water nanofluid (0.005, 0.01, 0.02 vol%) under flow boiling condition. The heat transfer coefficient (HTC) increased with the increase in heat flux and fluid flow rate, according to findings. It was observed that as the subcooling temperature increased, the heat transfer coefficient decreased. Boiling heat transfer was reduced at first as nanoparticle concentration increased, but with the further increase in concentration, heat transfer improved. Experiments were done by Mayank *et al.* [11] to study the heat transfer characteristics of CuO/water nanofluid jet on a hot surface. Experiments were carried out by varying Reynolds numbers and nanoparticle concentrations ranging from 0.15 to 0.6 % by volume.They noticed that the Nusselt number increased as nanoparticle concentration and Reynolds number increased. Also they postulated a relationship between Reynolds number, Nusselt number, nanoparticle concentration and Prandtl number. Experimental investigation was carried out by M. M Sarafraz *et al.* [12] to study the heat transfer of CuO/water nanofluids (0.1, 0.2, 0.3 vol%) inside a vertical annular space under flow boiling condition.They found that the (HTC) rose with the increase in fluid flow rate under flow boiling condition. The authors observed that the bubble diameter increases with fluid flow rate and heat flux, but it is not influenced by inlet temperature.

An experimental investigation was accomplished by Heris *et al.* [13] to study heat transfer characteristics of CuO/water nanofluid under uniform heat flux through square duct in laminar flow. It was found that for CuO/water nanofluid (1.5 vol %) 20.7 % enhancement in Nu is achieved. Guanbin *et al.*[14], in a flow loop with continuous heat flux, investigated the laminar convective heat transfer behaviour of CuO nanoparticle dispersions in glycol. As the mass fraction of CuO/ water Nanofluid increased, the Nusselt number and HTC increased, but the wall temperature decreased. The pressure drop, heat transfer, and properties of CuO/water Nanofluid inside a horizontal tube were investigated experimentally by Sahin *et al.*[15].They discovered that local Nusselt number increased with the increase in particle volume fraction up to 1 vol % and for the values higher than 1 vol % increase in the partial volume fraction decreased the local Nusselt number. The convective heat transfer of a dilute CuO/water water-based nanofluid was examined experimentally by Nikkhah *et al.* [16]. They discovered that when the concentration of nanofluid in the convective zone grew, so did the HTC, whereas they observed that in the nucleate boiling region there was a deterioration of HTC. . Experimental investigation was carried out by Xue-FeiYang *et al.* [17] in evaporator section of a thermosyphon loop. They discovered that introducing CuO nanoparticles enhanced the heat transfer in flow boiling, with the largest enhancement in HTC occurring at the optimum mass concentration of 1 wt percent.

An experimental examination was conducted by Abedini *et al.*[18] in a circular vertical channel for water-based low concentration nanofluids (0.1 percent, 0.5 percent, 2.5 percent by vol.) containing oxide nanoparticles (CuO, Al_2O_3, TiO_2) for various heat and mass fluxes for the single phase and subcooled flow boiling conditions. In the monophasic regime, they discovered that the convective heat transfer coefficient is improved for nanofluid. However, as the concentration of nanoparticles and the size of the nanoparticles rise, the heat transfer rate decreases. Experimental investigation was carried out by Chidanand *et al.* [19] to evaluate the thermal characteristic of laminar and transition phase forced convective flow with Al_2O_3/water and CuO/ water for wide range of Reynold number between $500 < Re < 3000$. They found out that maximum heat transfer enhancement with alumina/water nanofluid was found to be 52 % and for CuO/water it was 60 %.

Experimental investigation was carried out by S. Zeinali Heris *et al.* [20] on CuO and Al_2O_3 nanofluids with different concentrations. It was found that for both the nanofluids increase in Peclet number and nanoparticle concentration, HTC is enhanced.Experimental investigation was carried out by Rameshbabu *et al.* [21] to study the influence of cold fluid inlet temperature, particle concentration, power input on heat transfer and fluid flow behaviour of CuO, Al_2O_3, SiO_2 and water nanofluids. They found out that with increase in particle concentration, power input, and with decrease in cooling water temperature the average Nusselt number increases.

Experimental investigation was conducted by M. M. Sarafraz *et al.* [22] to study the pressure drop characteristics and heat transfer of carbon nanotube therminol 66 (0.1 and 3wt %) under subcooled flow boiling condition. They found out that the addition of CNT caused enhancement in viscosity in the therminol 66 which induced high value of pressure drop. They found out that when the mass concentration of nanofluid increased, heat flux, mass flux and thermo-hydraulic performance index increased.

Patra *et al.* [23] investigated the parametric effect of particle volume fraction and heat flux on bubble dynamics and determined bubble behaviour for the flow boiling of TiO_2 – water and Al_2O_3 – water nanofluids using high-speed visualization in a vertical annulus with a concentric catridge heater (0.001 vol percent and 0.01 vol percent). It was observed that nanofluids had a delayed DNB compared to DI water. Experimental studies were accomplished by Patra *et al.*[24] on the heat transfer of silica/water and alumina/ water nanofluids (0.001 vol% and 0.01 vol%) by varying the heat flux and wall temperature until flow oscillation under flow boiling condition. It was found that HTC of nanofluid is enhanced compared to DI water, but HTC enhancement decreased with the increase in concentration.

Under subcooled conditions, Mukherjee *et al.*[25] investigated the heat transfer and thermophysical properties of Al_2O_3 / water nanofluids under flow boiling condition. They observed how the HTC was affected by surface roughness, flow rate, heat flux, and concentration. They observed that increasing the concentration from 0.01 to 0.5 wt percent enhanced the HTC. They also noticed that the maximum enhancement of HTC was 26 % with the nanofluids at 0.5 wt%. Experimental investigation was carried out by Sudheer *et al.*[26] to study the flow boiling of Al_2O_3 water nanofluid in a vertical pipe. They determined that at a mass flux of 905.42 $kg/s\text{-}m^2$ and for particle concentration of 0.01%, 0.005 %, and 0.001 %, the average improvement in HTC is 29.97 %, 21.75 %, and 12.11 %. Nanofluid has a higher HTC than water, according to their findings. Experimental study was done by Nagareddy *et al.* [27] to study the thermohydraulic behavior of Al_2O_3 nanofluid in natural circulation Loop. They found out that Grashof number and Nusselt Number increases with particle concentration. It was observed that as concentration increased from 0 to 5 % Nusselt Number doubled.

Azgandhi *et al.* [28] performed experiment to study heat transfer characteristics of multiwalled carbon nanotubes. (MWCNTs) nanoparticle with water as a base fluid with a nanofluid weight concentration of 0.1-0.145 wt % for turbulent condition in a counter flow plate heat exchanger. It was found that as Reynold number increased the HTC improved. Experimental investigation was carried out by Lakhawat *et al.* [29] to study the effect of concentration of nanoparticle (1 ,2 ,3 vol % of ZnO nanofluid) and temperature on viscosity and HTC in a heat exchanger. It was found out that when the concentration of nanoparticle and operating temperature increased HTC increased. Prajapati *et al.*[30] carried out experiments to study the heat transfer characteristics of ZnO/water nanofluid. The HTC increased by 126 percent over water with a constant mass flux of 400 kg/m^2s and heat flux (0–400 kW/m^2). Sethoodeh *et al.* [31] conducted experiments to investigate the boiling of alumina water nanofluid (0.25 vol. percent) in a subcooled flow along a channel with a hot spot. Experimental results indicated that there was an increase in flow boiling performance by the addition of nanoparticle by 56%, 59% and 79% for surface roughness of 15.1, 4.4, and 0.65 µm respectively.

Experimental investigation was carried out by Wael M. El-Maghlany *et al.*[32] to study the thermal performance of Cu-water nanofluid in horizontal double-tube counter-flow heat exchanger. It was found that NTU of Cu-water nanofluid was enhanced by 23.4 % compared to base fluid. Zhenping Wan [33] experimentally investigated the influence of nanofluid on the thermal characteristics of specially designed mL HP. They found out that HTC of nanofluid enhanced by 19.5% compared to base fluid. Higher the subcooling temperature lower the corresponding heat flux related to ONB. Experimental investigation was carried out by M. M Sarafraz [34] to determine the heat transfer coefficient of Al_2O_3 nanofluids (0.5, 1, and 1.5 vol%) under flow boiling condition. They found out that with the rise in heat and mass fluxes HTC increased. R. Aghayari [35] experimentally investigated the heat transfer in Fe_3O_4 nanofluid. They found out that average variation of Nusselt number for heat exchanger without twisted tape inserts at concentration of 0.12 and 0.2 vol % was found to be 5.3 and 8.10 % respectively.

Experimental investigation was carried out by M. M. Sarafraz *et al* [36] on heat transfer of MWCNT nanofluid(0.1, 0.2, 0.3 vol %) under flow boiling condition. They observed heat transfer improvement in MWCNT nanofluids with increase in mass flux, heat flux and concentration of nanofluid.

Experimental investigation was carried out by Y.Wang *et al.*[37] on γ-Al_2O_3/H_2O nanofluid to analyse_the heat transfer in a vertical tube.They found out that average enhancement rates of Nusselt Number for nanofluids are 45% and 23% and for 0.5 vol.% and 0.1 vol.%. Experimental investigation was carried out by Abedini *et al.*[38] on subcooled flow boiling in horizontal and vertical tube for TiO_2 nanofluid. They found out that in subcooled flow boiling regime the HTC of nanofluid deteriorated,_and the deteroration was observed to be more pronounced with the increase of nanoparticle concentration.

From the literature, most of the studies focused on nanofluid boiling heat transfer behaviour for various nanofluids at different operating conditions by varying the operating parameters of heat flux, nanoparticle concentration, mass flux and inlet subcooling temperature etc. From the literature it was observed that studies available on CuO/water nanofluids are few. However, all these studies were done at higher concentrations. As the nanoparticle concentration increases the sedimentation of nanoparticles in the base fluid is observed. Also from the literature it is noted that with increase in concentration beyond certain limits, the sedimentation causes the (boiling heat transfer coefficient) BHTC to decrease. Considering the stability aspects and sedimentation issues the present work focused on the flow boiling behaviour of CuO/water nanofluid at lower concentrations of 0.001%, 0.05%, and 0.01%. The experiments are carried out by varying mass flux (381.72-954.29kg/s-m^2) and the heat flux (45-190 kW/m^2). Experiments are designed based on the full factorial multi-level design of experiments approach. ANNOVA is done to analyse the results and find out the impact of operating parameters such as particle concentration and heat flux and mass flux on boiling heat transfer in terms of HTC.

EXPERIMENTALS

Preparation of the nanofluid

The process for preparing nanofluids is described in the following section.A surfactant, CTAB, is initially added to the base fluid and sonicated for 30 minutes. Shimdzu digital electronic scale (Fig.

Fig. 1. Weighing measurement device.

Fig. 2. Ultrasonicator.

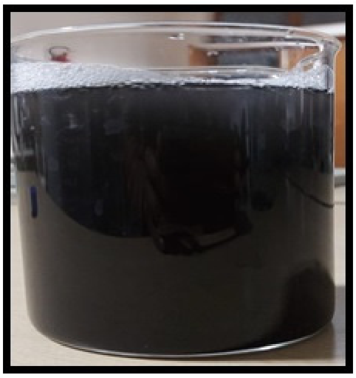


Fig. 3. CuO/water nanofluid (0.01 %).

Table 1. Thermo physical properties of nanofluids.

Temperature	Fluid	Density (kg/m^3)	Specific heat (kJ/kg-K)	Thermal conductivity (kW/m-K)
	0.001 % CuO/water	965.33	4.2056	0.7168
	0.005% CuO/water	965.56	4.2046	0.7169
	0.01% CuO/water	965.83	4.2033	0.7170
	Water	965.28	4.2058	0.6921
95 °C	0.005% CuO/water	961.14	4.2108	0.7201
	0.001% CuO/water	961.91	4.2107	0.7200
	0.01% CuO/water	962.41	4.2085	0.7202
	water	961.86	4.21093	0.6951

1) is used to measure the weight of nanoparticles. A weighed amount of CuO nanoparticle is added to the base solution and sonicated for 5 hours with a cycle duration of 10 minutes and an idle time of 2 minutes using a sonicator (Fig. 2).A Well diffused CuO/water nanofluid (Fig. 3) is obtained after sonication. Thermophysical properties of CuO/water nanofluids are shown in Table 1.

Experimental setup

The schematic representation and pictorial view of the flow boiling apparatus are as shown in Figs. 4(a) and (b). The experimental apparatus contains a reservoir tank with submerged heaters. A thermostat is attached to maintain the specific required temperature in the reservoir tank with the help of submerged heaters. The flow of working fluid is accomplished through a submersible pump (ESP) and a bypass valve adjusts the flow rate. A calibrated rotameter is used to measure the mass flow rate of the working fluid. The working fluid initially enters into the preheater for the necessary subcooling. The preheater is made up of SS-316 steel pipes with inner and outer diameters of 8 and 12 mm respectively. Two 53.5 ohm Nichrome resistance wires were wounded along the preheater. A 50 mm thick glass wool is wrapped around the preheater to reduce convective losses and radiation. Thereafter, the subcooled working fluid enters the main heater (test section). The main heater section is made up of stainless steel pipe with 8 mm in internal diameter and 12 mm outside diameter. Two 54.4 ohm nichrome wires were uniformly wounded along the length of pipe. Similar to the preheater section, a 50 mm thick glass wool is wrapped around the main heater to reduce convective losses and radiation. A variable transformer controls the amount of heat applied to the main heater. To measure the bulk fluid temperature, two sets of two thermocouples (k-type) are placed at the exits of the main heater section. To measure the outside wall temperature, twelve k type thermocouples are placed on the main heater section pipe outer wall. To avoid short circuit, the thermocouples are electrically insulated. Temperature data was recorded using Agilent Data Acquisition System. Two pressure tapings are provided at the extreme exits of the main heater section. These tapings are connected to a U tube manometer to record the two phase pressure drop. A slight glass is attached to the outer end of the test section to visualize the flow. Then the working fluid enters the condenser

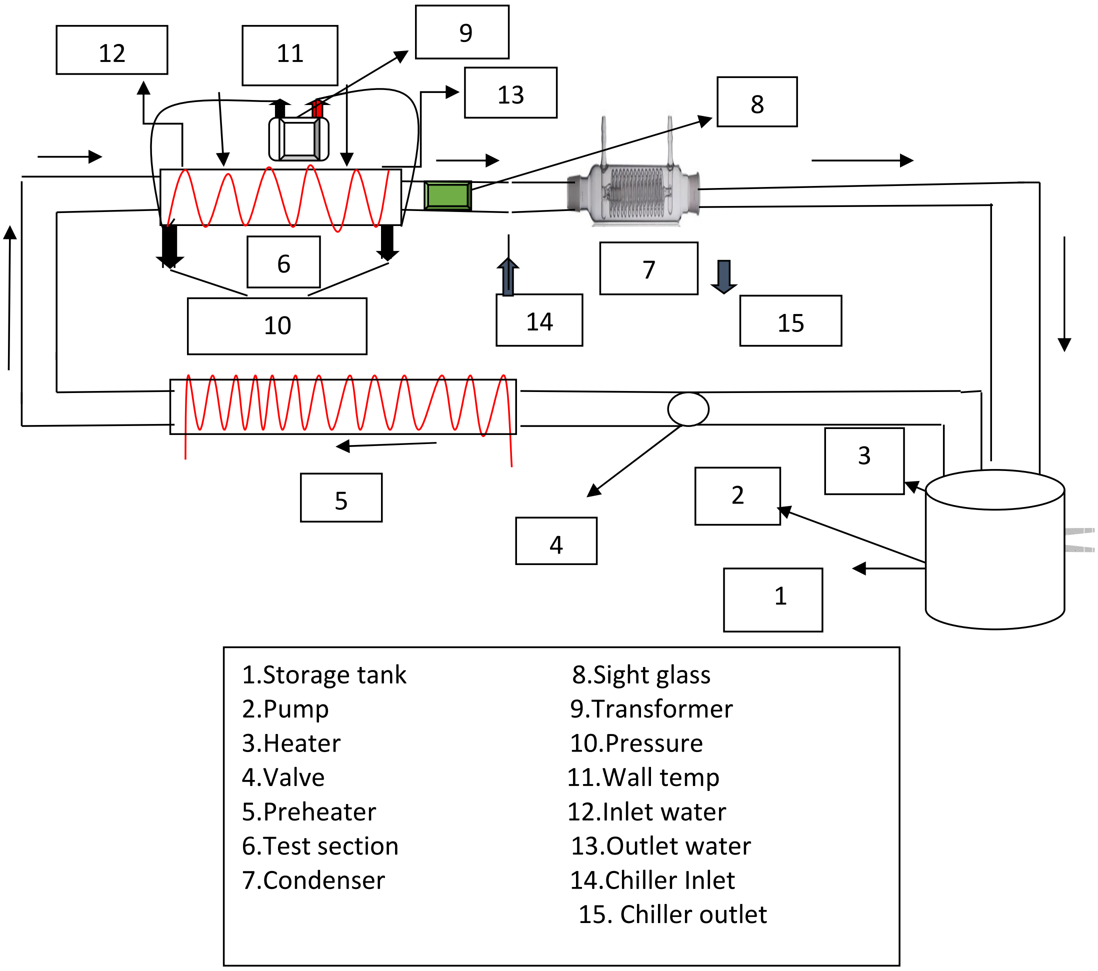


Fig. 4. (a) Schematic view of flow boiling experimental apparatus.

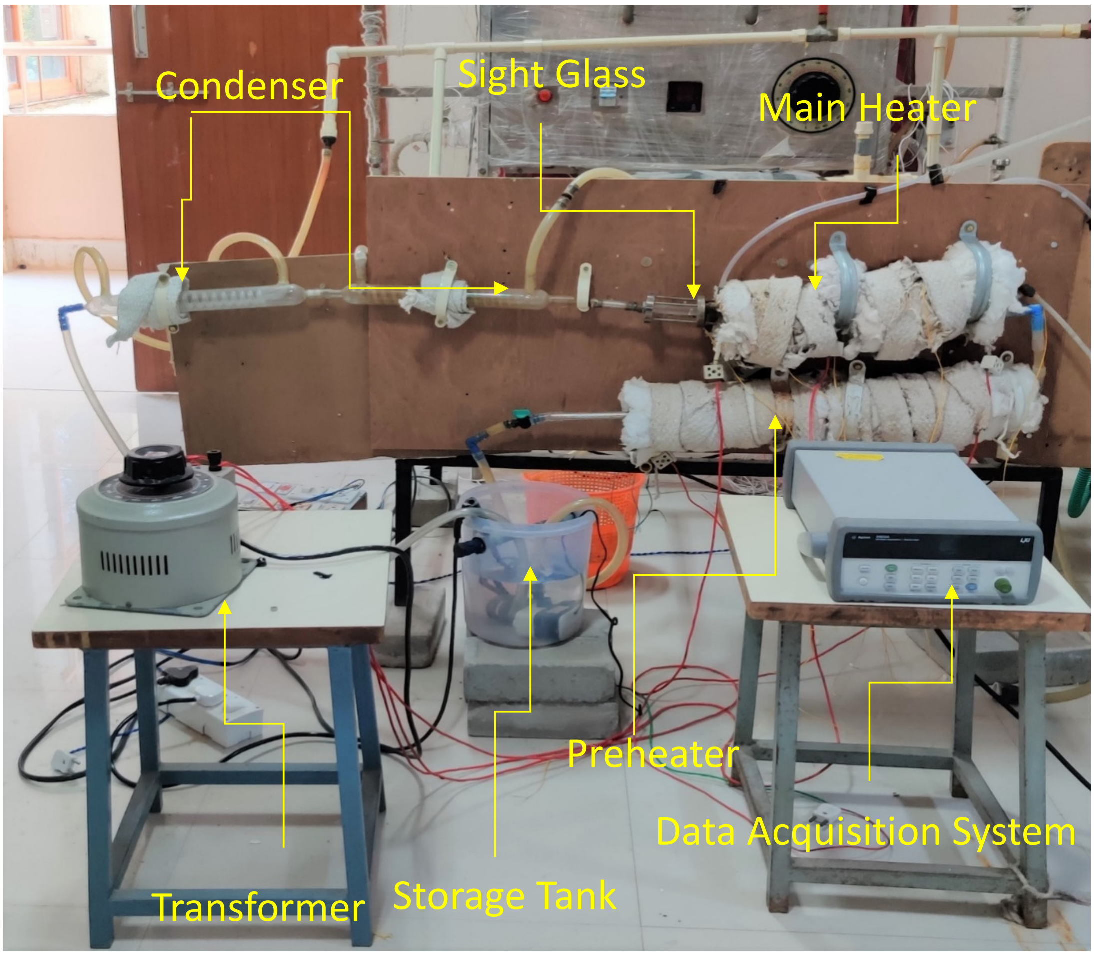


Fig. 4(b) Pictorial view of experimental setup.

which is connected to the chiller. The working fluid is condensed in the condenser and returned to the reservoir tank.

Experimental procedure

The dissolved gases have a significant impact on boiling heat transfer, hence the working fluid (water/nanofluid) must be degassed before each experiment. The working fluid is boiled vigorously for more than one hour in the reservoir tank with the aid of submerged heaters. Internal fluid circulation is provided using a pump to minimize nanoscale deposition on the immersed heaters. After degassing, power is supplied to the necessary components. Once the required flow rate and inlet subcooling is achieved, primary heater power is switched on and known heat flux value is imposed with the help of variac transformer. Sufficient time was given to reach steady state condition by observing all temperature readings to be within ±0.5 °C for about 2 minutes and then required data was noted down. With the use of the variac transformer, the heat flux is increased in steps and the chiller conditions are altered to get the same inlet subcooling. Repeat the same procedure for all the test runs.

Data reduction and uncertainty analysis

The local heat transfer coefficient can be estimated by using the eq.(1)

$$h_z = \frac{q_{net}}{T_{inner\ wall,z} - T_{f,z}} \tag{1}$$

Z is the axial location along the heater section.

q_{net} is the net imposed heat flux to the main heater section and is estimated by using eq. (2)

$$q_{net} = \frac{Q_{net}}{\pi D_i L} \tag{2}$$

Where Q_{net} is net heat supplied to the main heater section after accounting the convection and radiation losses that can be estimated as follows:

$$Q_{net} = Q - \left(Q_{Conv} + Q_{rad}\right) \tag{3}$$

The Q, Q_{Conv}, Q_{rad}, are the heat supplied to the main heater section and heat transfer to the surrounding due to convection and radiation respectively. These terms are estimated by using eq. (4 a, b, and c).

$$Q = V \times I \tag{4.a}$$

$$Q_{conv} = h \times A_s \left(T_{surf} - T_{amb}\right) \tag{4.b}$$

$$Q_{radiation} = \sigma \times A_s \left(T_{surf}^4 - T_{amb}^4\right) \tag{4.c}$$

Uncertainty analysis

Uncertainty analysis is performed to evaluate the errors obtained during the experiments. The Uncertainty of the instrument used in this test setup is summarised in Table 2. In the present work uncertainties of several parameters such as voltage, current, temperature of the wall and bulk fluid and mass flow rate etc. are estimated. Table 3 depicts the highest potential uncertainties included in the experimental analysis.

RESULT AND DISCUSSION

Validation

To see the precision and validity of the experimental setup and procedure, comparisons have been done with existing Shah Correlation [14]. The fabricated experimental setup and adopted procedure accurately generate the data that can be verified/cross checked in terms of boiling heat transfer coefficient (BHTC). Fig. 5 depicts the closeness of the experimentally estimated BHTC with predicted results. This shows that the fabricated experimental setup and adopted procedure precisely generate the results for nanofluids.

Flow boiling curve

In general the flow boiling heat transfer mainly depends upon the nucleate boiling mechanism and forced convection heat transfer mechanism. The nucleate boiling mechanism is influenced by the imposed heat flux whereas the mass flux influences the forced convection heat transfer. Therefore in the present work, flow boiling behaviour of CuO/water nanofluids (having particle concentrations of 0.001%, 0.005% & 0.01%) was analysed by varying mass flux (381.72-954.29 kg/s-m^2) and the heat flux (45-190 kW/m^2).

Fig 6 (a-d) depicts the relation between the wall superheat and the applied heat flux for CuO/water nanofluids and water (flow boiling curve) at different mass fluxes. The wall superheat is measured at the exit of heater section. It is observed that the wall superheat increased with the increase in the applied heat flux. Also it is

Table 2. Uncertainties of the instruments.

Measuring parameter	Measuring unit	Uncertainty
Length	Verniercaliper	± 0.02 mm
Diameter	Multimeter	± 0.02 mm
Temperature	Thermocouple	0.242%
Mass flow rate	Rotameter	1.8%
Current	Ammeter	0.2 %
Voltage	Voltmeter	0.32 %

Table 3. Uncertainties of the estimated data.

S.No	Variable name	Uncertainty (%)
1	Heat transfer coefficient	0.448
2	Heat flux	0.378
3	Surface area	0.028
4	Mass flux	1.5

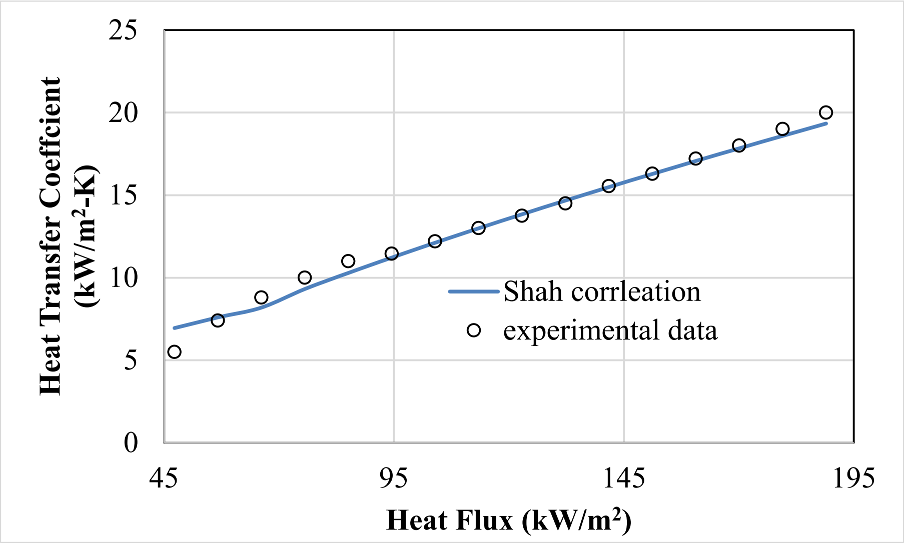
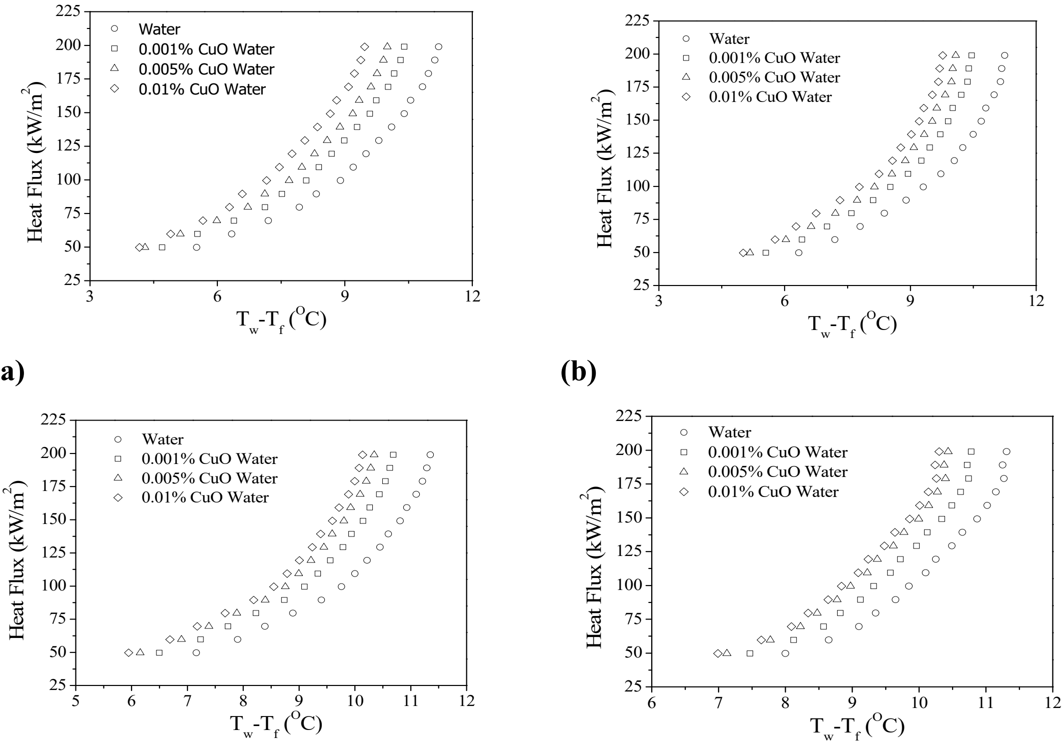


Fig. 5. Comparison of classical two-phase heat transfer correlations with experimental data.



(a)

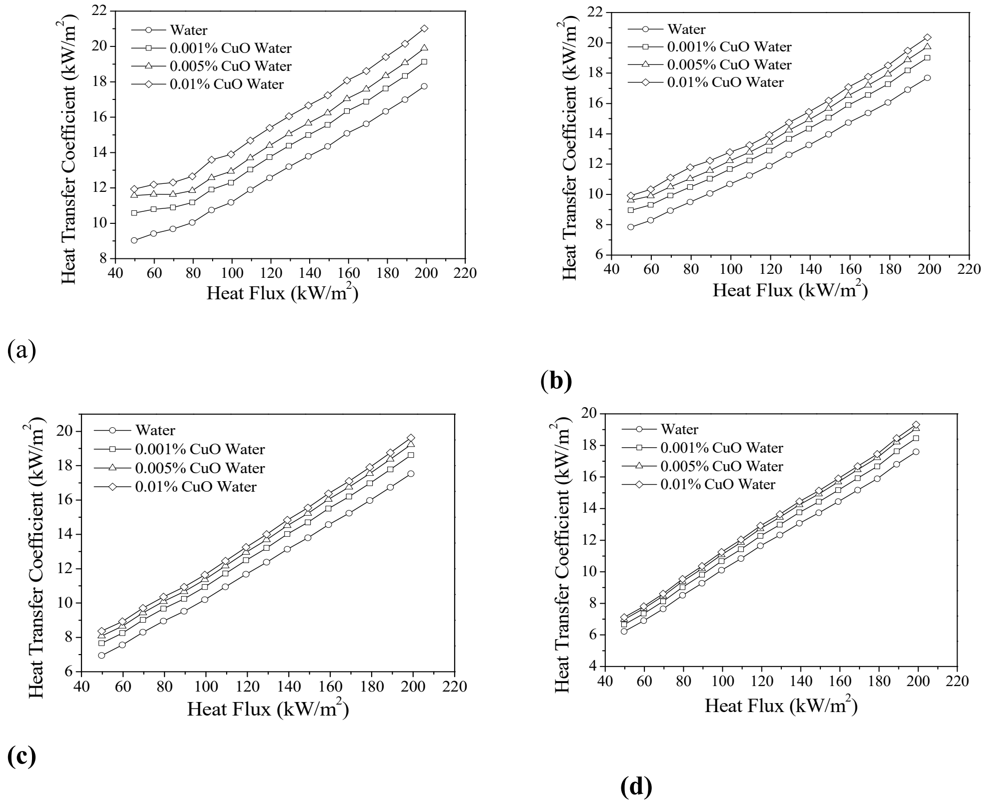
(b)

(c)

(d)

Fig. 6. (a) Mass flux 954.29 kg/s-m², (b) Mass flux 763.43 kg/s-m², (c) Mass flux 572.57 kg/s-m², (d) Mass flux 381.72 kg/s-m².

noticed that with the increase in applied heat flux, the rate of increase of wall superheat decreases. The limited variation is due to the dominance of the convective heat transfer process. The wall superheat variation w.r.to imposed heat flux for the CuO/water nanofluids and water are similar



(a)

(b)

(c)

(d)

Fig. 7. (a) Mass flux 954.29 kg/s-m^2, (b) Mass flux 763.43 kg/s-m^2, (c) Mass flux 572.57 kg/s-m^2, (d) Mass flux 381.72 kg/s-m^2.

in nature at all mass flow rates. The slope of the boiling curve shift towards left for the CuO/water nanofluids,and as the CuO particle concentration increases more shift of the curve is observed. It means for the imposed heat flux, CuO/water Nanofluids have a lower wall superheat than water, and as CuO particle concentration increases, the wall superheat further decreases. For example at the mass flux of 954.29 kg/s-m^2,for nanofluids with particle concentrations of 0.001 %, 0.005 %, 0.01 % the average wall superheat is reduced by 9.13 %, 13.67 %, and 18.66 % respectively. The low wall superheat for the same heat flux indicates the increase in boiling heat transfer and results in lower wall surface temperature.

A similar trend is observed for other mass fluxes. It is also observed that the slope of the boiling curve changes, which indicates the transition of heat transfer phenomena. This was observed for water and CuO/water nanofluids. At the mass flux of 954.29 kg/s-m^2 water, 0.005% & 0.001% nanofluids boiling curve slope changes at the heat fluxes of 159.15kW/m^2 (transition of forced convection heat transfer from bubble flow to slug flow) and 89.52 kW/m^2 (transition of forced convection heat transfer (stratified flow) to nucleate boiling heat transfer (plug/annular flow)) respectively. For 0.01 percent nanofluids, the boiling curve slope changes at lower heat fluxes of 79.57 (transition of forced convection heat transfer from bubble flow to slug flow), 159.15 kW/m^2(transition of forced convection heat transfer (stratified flow) to nucleate boiling heat transfer (plug/annular flow)). For the other mass fluxes, similar behaviour is found in nanofluids and water. This indicates the transition of heat transfer phenomena occurred at lower heat fluxes for the nanofluids as nanoparticle concentration increases.

Heat transfer coefficient

Relation between heat transfer coefficient and heat flux as function of the nanoparticle volume concentration is depicted in Fig7 (a-d). From Fig 7, it is noticed that for all the range of heat flux and mass fluxes the nanofluids have a

Table 4. Boiling heat transfer coefficient enhancement.

Mass flux	**Nano particle concentration**		
(kg/s-m^2)	0.001%	0.005%	0.01%
954.29	10.12	15.99	23.07
763.43	9.17	14.3	18.91
572.57	7.27	11.47	14.2
381.72	5.53	9.51	11.14

Table 5. Independent operating variables.

Level No	Operating Variables		
	Heat flux (kW/m^2)	**Mass flux (kg/s-m^2)**	Particle concentration (%)
1	49.7358	954.29	0
2	59.68296	763.43	0.001
3	69.63012	572.57	0.005
4	79.57729	381.72	0.01
5	89.52445		
6	99.47161		
7	109.4188		
8	119.3659		
9	129.3131		
10	139.2602		
11	149.2074		
12	159.1546		
13	169.1017		
14	179.0489		
15	188.9961		
16	198.9432		

high heat transfer coefficient. It was observed that the boiling heat transfer was enhanced with the increase in nanoparticle concentration. The average enhancement of heat transfer coefficient for the nanoparticle concentrations of 0.01%, 0.005%, 0.001% of CuO/water nanofluid are 23.07%, 15.99 %, & 10.11% respectively, for the mass flux of 954.29 kg/s-m^2.

Table 4 depicts the enhancement in boiling heat transfer coefficients with increase in CuO particle concentration. The boiling heat transfer process is improved by adding CuO nanoparticles in the water, this is due to enhanced heater surface properties or altering the bubble formation mechanism. Similar results are obtained for Al_2O_3/water nanofluid at lower concentrations. Nanoparticles are deposited on the heater surface during boiling process and due to this surface of heater has been modified (1: more microcavities/nuclei sites, 2: forms an adsorption layer on the surface of heater causing the reduction of the adjacent thermal boundary layer of the heater surface), this strongly influences the bubble dynamics such as nucleation site density, bubble departure diameter, frequency and evaporation of the macro-and micro-layer beneath the growing bubbles. Similarly, the process of bubble generation is affected by the presence of nanoparticles in the fluid's liquid phase. The suspended nanoparticles alter the net force balance at the interface, altering dynamics of bubble such as bubble departure volume, frequency and contact angle, this results in overall improvement in boiling heat transfer.

Prediction of HTC

ANNOVA is done to know the impact of major operating parameters like particle concentration, heat flux and mass flux on boiling heat transfer coefficient. Table 5 represents the levels of the influence parameters. To analyse the boiling heat transfer coefficient, a quadratic model was proposed. The aforementioned model assesses the relationship between the response (boiling heat transfer coefficient) and the independent variables (mass flux, heat flux, and particle concentration), as well as their interactions. Minitab software is used to do ANNOVA (variance analysis), the results are presented in Table 6.

Table 6. Analysis of variance.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of con.
Model	9	2964.03	329.34	3856.02	0	99.30
Mass flux	1	135.93	135.93	1591.51	0	4.55
Heat flux	1	2527.21	2527.21	29589.7	0	84.66
Particle concentration	1	120.18	120.18	1407.15	0	4.03
Mass flux*Mass flux	1	2.54	2.54	29.76	0	0.09
Heat flux*Heat flux	1	5.2	5.2	60.86	0	0.17
Particle concentration*Particle concentration	1	12.02	12.02	140.76	0	0.40
Mass flux*Heat flux	1	24.95	24.95	292.16	0	0.84
Mass flux*Particle concentration	1	11.04	11.04	129.23	0	0.37
Heat flux*Particle concentration	1	1.09	1.09	12.76	0	0.04
Error	246	21.01	0.09			0.70

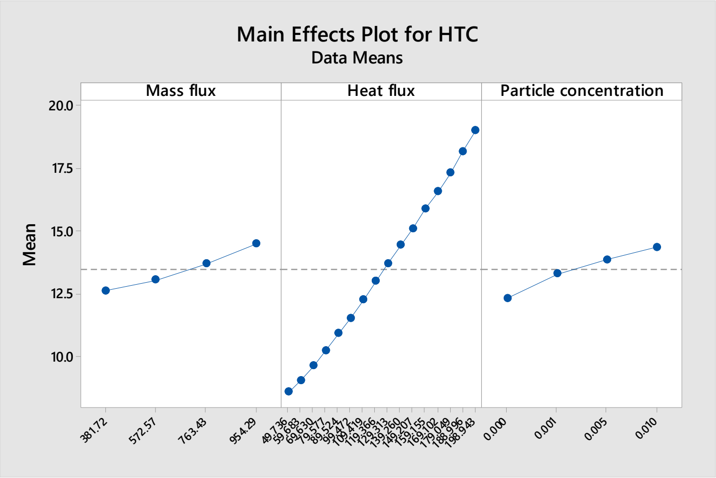


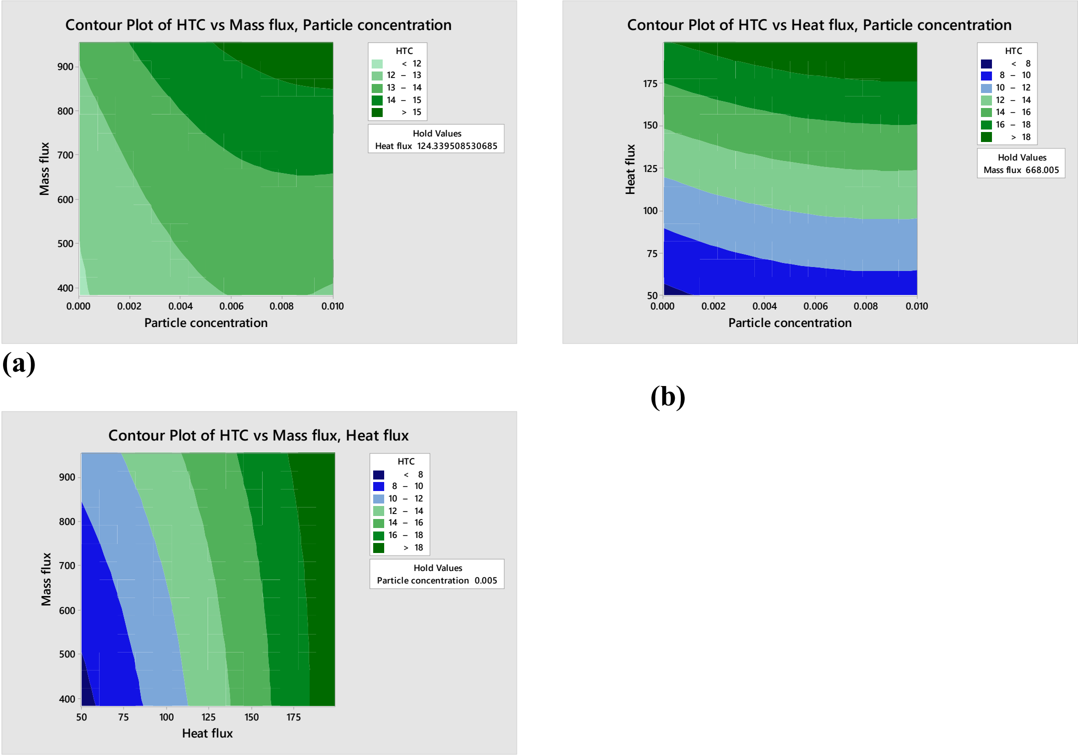
Fig. 8. Mean effect plot for HTC.

The probability value of model (p-value) is zero, which indicates that model which is proposed is quite useful in forecasting the HTC (Note that the model is significant if the p-value is less than 0.05). In this analysis, influencing operating parameters (mass flux, heat flux, and particle concentration) and their interactions are significant. Among all operating parameters heat flux have a major influence and is followed by mass flux and particle concentration.

Fig.8 depicts the influence of considered operating parameters on HTC. The influence of the heat flux parameter is greater than that of mass flux and particle concentration, according to the HTC mean plot. The maximum HTC is obtained at higher levels of the operating parameters.

Fig. 9 (a-c) depicts the contour plots of the considered operating parameters on the HTC. By fixing the one operating parameter as constant and varying the other two parameters these plots are obtained. It is noticed that at low heat flux and low mass flux the increase in particle concentration has a lower impact on the HTC. Significant variation in the HTC is observed with the increase of mass flux/heat flux w.r.t particle concentration. Heat and mass flux have a linear relationship for a given particle concentration of nanofluid, as shown in Fig. 7.

The relationship between operating parameters on HTC is modelled by a polynomial equation (5) with the second order. The regression equations are obtained together with determination coefficients (R^2 adjacent-99.27% and R^2 predicted -99.23%). The HTC model is given by equation (5). The proposed model predicts up to the accuracy of 99.3%.



(a)

(b)

(c)

Fig. 9 (a, b, c). Contour plot for HTC.

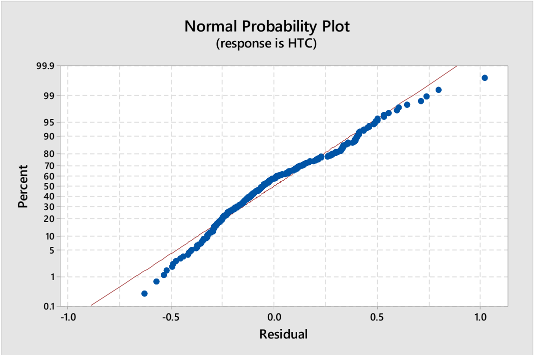


Fig. 10. Residual plot for HTC.

$$\begin{aligned}\text{HTC} = {} & 1.965 + 0.002600\ \text{Mass flux} + 0.07125\ \text{Heat flux} + 176.3\ \text{Particle concentration} \\ & + 0.000003\ \text{Mass flux*Mass flux} + 0.000076\ \text{Heat flux*Heat flux} \\ & - 21226\ \text{Particle concentration*Particle concentration} - 0.000032\ \text{Mass flux*Heat flux} \\ & + 0.2472\ \text{Mass flux*Particle concentration} + 0.361\ \text{Heat flux*Particle concentration} \qquad (5)\end{aligned}$$

The diagnostic checking of the model has been carried out by the examination of the residuals. Fig. 10 shows the residual analysis data for the HTC. From that, it is observed that errors are normally distributed as the residuals fall on a straight line. The regression plot shows the goodness of the developed equation to forecast the HTC.

CONCLUSIONS

The flow boiling heat transfer of CuO/water nanofluid is investigated experimentally. Constant inlet subcooling at the heater inlet and Atmospheric pressure are the conditions followed in the experiments. The major operating parameters are mass flux and heat flux. In addition, the concentration of nanoparticles in the nanofluid was chosen as an influencing parameter on the boiling heat transfer. The following are the study's principal findings:

1. Flow boiling heat transfer increases with mass flux for both water and nanofluids.
2. The boiling curve of Nanofluid shifts to the left when compared to water. This is because, as compared to water, nanofluids produce a lower surface temperature for the same heat flux input. For a mass flux of 905.42 kg/s-m2, the average reduction in wall superheat is 9.13 percent, 13.67 percent, and 18.66 percent for 0.01 percent, 0.005 percent, and CuO nanofluids, respectively.For the mass flux of 905.42 kg/s-m^2

   the average reduction of wall superheat for 0.01%, 0.005% and 0.001%, of CuO nanofluids are 9.13%, 13.67 % and 18.66 % respectively.
3. When compared to water, nanofluids have a high boiling HTC, which increases as the volume concentration increases. For a mass flux of 905.42 kg/s-m^2, the average augmentation in HTC for the 0.001%, 0.005%, and 0.01% nanofluid is 10.11%, 15.99%, and 23.07 %, respectively.
4. The boiling heat transfer process is improved by the presence of nanoparticles in the fluid. This is due to an improvement in heater surface properties or an amendment in the bubble formation mechanism.
5. The aforementioned factors (particle concentration, heatflux and massflux) were statistically significant, according to statistical analysis. Heat flux is the most important contributor to the heat transfer coefficient.
6. A simplified quadratic model was proposed to predict the heat transfer coefficient data. The model and the experimental data were in good agreement.

NOMENCLATURES

T	Temperature, K
Z	axial location along the heater section,m
Qnet	heat supplied to the main heater,kW
h	heat transfer coefficient,W/m^{2}K
As	surface Area m^2
V	oltage Applied, Volts
I	Current, Ampers
Qconv	Heat transfer by convection,kW
Qrad	Heat transfer by radiation,kW

ABBREVIATIONS

CHF	critical heat flux
BHTC	boiling heat transfer coefficient
MWCNT	multi-walled carbon nanotubes
CNT	Carbon Nanotube Therminol
DNB	Departure from Nucleate boiling
ANNOVA	Analysis of Variance
ESP	Electrical Submersible Pump
HTC	Heat Transfer Coefficient

CONFLICTS OF INTEREST

The authors do not have any conflicts of interest.

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