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ORIGINAL

Effect of boiling surface vibration on heat transfer

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Abstract Experimental investigation of effect of forced vertical surface vibration on nucleate pool boiling heat transfer of saturated water at atmospheric pressure is presented in this paper. Vertical vibration was induced externally to the circular copper test surface on which boiling took place, using a vibration exciter. Frequency was varied in the range 0–25 Hz and amplitude of vibration was varied in the range 0–5 mm. Boiling takes place at much lower superheats for the same heat flux, slope of boiling curve decreases remarkably, when the surface is given external excitation. High frequency and high amplitude oscillations lead to more intensive heat transfer. There are some combinations of frequency and vibration amplitude, which cause up to two times increase in heat transfer coefficients.

List of symbols

- a Amplitude of vibration (mm)
- f Frequency of vibration (Hz)
- h Heat transfer coefficient (kW/m^2 °C)
- q Heat flux (kW/m^2)

1 Introduction

In recent years, improvement in two phase heat transfer, where phase change from liquid to vapor significantly increases the level of heat transfer when compared to the single phase heat transfer, has been the basis for advances in heat transfer technology. High heat loads are removed from a device while maintaining relatively low surface temperatures with nucleate pool boiling. In recent years efforts are made to enhance boiling heat transfer. Methods to improve two phase heat transfer can be grouped as active and passive techniques. Active techniques include mechanical aids, surface vibration, fluid vibration, electrohydrodynamics. Passive techniques include surface treatments, roughening and modification of the surface, surface extension, displaced enhancement, swirl flow techniques, alteration of surface tension, and the inclusion of additives to the coolant. A combination of any of these techniques is termed as compound technique. The passive techniques require special surface geometries (such as rough surface, extended surface etc.), hence they lead to manufacturing difficulties and cost. They also increase the pumping power since the surface modifications obstruct the flow of the liquid [1]. Modified surfaces may also invite the problems of scaling and fouling. For a module with spatial limitation, active cooling technique is often more practical than passive cooling. Therefore recent technologies include the use of fluid/surface vibration to achieve high cooling rates. Sufficiently intense oscillations can improve heat transfer in liquids both by applying surface vibration usually lower than 1000 Hz or inducing vibration in the fluid itself. The two mechanisms operate quite differently. The vibration of a surface obtained by an electro-dynamic vibrator or a motor driven eccentric mainly breaks the boundary layer, moving the particles of the fluid in the vicinity of the surface. This can induce a "forced" convection in a region otherwise of free convection [2].

There have been many prior attempts to enhance pool boiling heat transfer by vibration. A critical review of the state of the art of the works known in the literature and concerned with the influence of vibrations of structures of plants and artificially initiated vibrations in working

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liquids on the processes involving boiling is given in [3]. Prisnyakov et al. [4] have shown that the value of the heat fluxes removed from a vibrating surface substantially depends on the prehistory of the process and more prominently on the presence or absence of boiling on the surface. They observed that in the convection region, a successive increase or decrease in the heat loads leads to inverse changes in the thermal conditions in the volume. They obtained a twofold increase in heat transfer with vibrating heat source and the increase in heat transfer was more proportional to the amplitude of vibrations and to the frequency of pulsations. Antonenko et al. [5] detected the hysteresis phenomenon in passage from convection to boiling under vibration actions while studying heat transfer on a surface of small size. They explained that vibration gives rise to jet pulsating flows which favors the thinning of the thermal boundary layer on a cooling surface and growth in the heat transfer coefficients. Quantitative data on the dependence of the superheats of a liquid in water boiling on a wire are reported by Markov [6]. Considerable effect of the action of vibrations on the boiling process (at frequencies of 75 and 100 Hz) was detected which substantially increased the heat transfer coefficient (nearly twofold).

Navruzov et al. [7] reported the results of an experimental study of the mechanisms of heat exchange between a vibrating heat source and a free surrounding liquid. It was found that heater vibration significantly intensifies the convective heat exchange. It was also shown that vibration effects can produce substantial changes in the mechanism of steam bubble evolution both during their growth on the surface and on their detachment from the surface. The results of an investigation into subcooled ethanol boiling under conditions of low frequency heater vibration are described in [8]. Heat transfer enhancement at low heat fluxes was observed. The analysis of hysteresis phenomena under conditions of heater vibration after an increase in and subsequent removal of the heat load was carried out. Visual observations of the boiling process on the vibrating surface by synchronized illumination revealed essential changes in the internal boiling characteristics.

Zitko and Afgan [9] did experimental research on water pool boiling heat transfer occurring during the vibration of a heating surface and the liquid in contact with it at atmospheric pressure. Experiments were performed on a vibrating table with equipment made specifically for this purpose, and with the aim of measuring the heat transfer coefficient at the boiling point. Measurements were made by varying thermodynamic parameters such as: heat flux $q = 0–85 \times 10^{-4}$ W/m^2, amplitude $a = 0.1–2.0 \times 10^{-3}$ m and frequency f = 0–70 Hz. They concluded that the heat transfer coefficient increases with the value of heat flux and with the increase of frequency and amplitude, the heat transfer coefficient increased up to 25 %. In another work [10], they presented the experimental study of the ethyl alcohol boiling heat transfer from the vertically and horizontally vibrating surface. Parameters varied in the experimental program were: heat flux q = 9.8–53.5 W/cm^2; pressure-atmospheric; vibration frequency f = 0–70 Hz; vibration amplitude a = 0–2 mm.

A 13 % increase in the heat transfer coefficient was obtained in the experiments with tubes of small size (d = 18 mm) in the case of vibrations with an amplitude of 1.2 mm and a frequency of up to 1450 Hz by Ugryumova et al. [11]. Chekanov and Kul'gina [12] investigated the effect of harmonic oscillations on bubble detachment frequency and its dispersion. The experiments were performed at frequencies from 20 to 100 Hz, at oscillation amplitudes of $0–0.4 \times 10^{-4}$ m. It was established that vibration leads to a decrease in detachment frequency and dispersion.

Vibration effects of different frequencies and amplitudes on water heat pipes were studied in [13]. The boundary frequency bands and amplitudes at which heat and mass transfer in heat pipes and thermosyphons is improved and degraded were determined.

As seen from the literatures mentioned above, the problem of the influence of vibrations on heat and mass transfer, including those in heat pipes and thermosyphons, have been studied experimentally and theoretically. There is inconsistency and ambiguity in the results of effect of vibration on heat and mass transfer in these papers. Hence further experimental studies are needed. Also, there is little information on effect of surface vibration on pool boiling heat transfer especially in nucleate boiling regime. Hence this study focuses on the effect of vertical vibration on the nucleate pool boiling heat transfer coefficient of water at atmospheric pressure.

2 Experimental setup and procedure

The experimental setup shown in Fig. 1 consisted of 200 × 200 × 350 mm square boiling chamber made up of SS 316 fitted with SS 316 flanges at the top and at the bottom. The top flange had provisions for liquid charging, condenser cooling water inlet and outlet, pressure transducer. Bottom flange had provisions for test section and drain. The vessel was fitted with two sight glasses to observe the boiling phenomena. Condenser is made up of coiled copper tube which is connected to the cooling water tank through a motor and PID. An auxiliary heater of 500 W capacity provided through the side wall maintained the water at constant saturation temperature during experimentation. An electrical heating element of 500 W capacity was inserted in a cylindrical copper rod of 15 mm diameter to give heat input to the test surface as shown in Fig. 2. The rod heater was mounted vertically within the boiling vessel. High temperature nylon

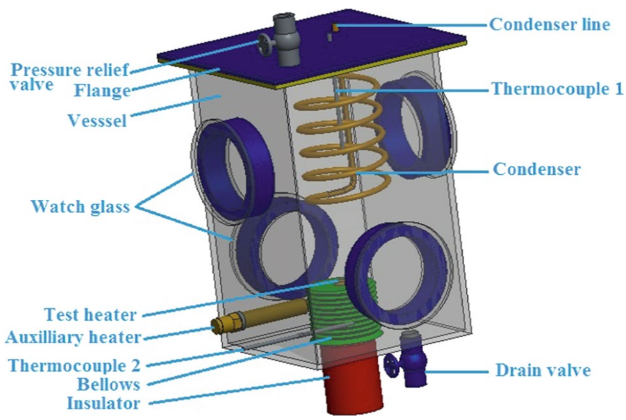

Fig. 1 Experimental setup

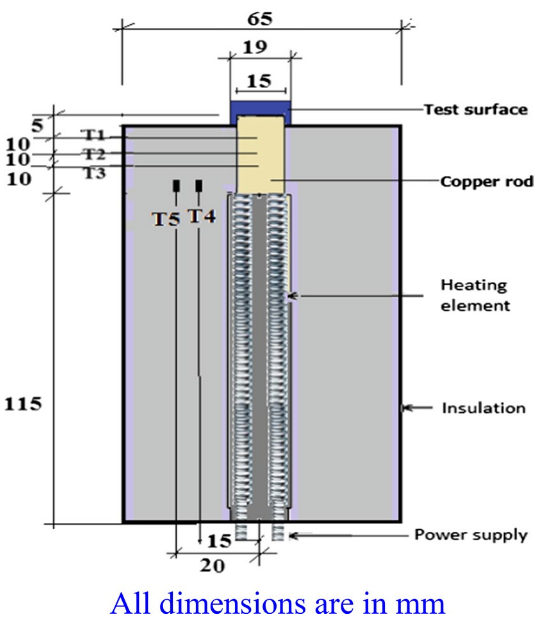

Fig. 2 Details of heater assembly

insulators were wrapped around the copper heater to reduce the heat losses. The insulator-heater assembly thus formed was inserted into the vessel through the bottom lid with a portion of the assembly remaining outside the vessel. Gaskets were used to provide leak proof assembly. On top of the heater rod replaceable circular test piece of 19 mm diameter and 7 mm thickness was placed. The replaceable test piece had a groove of 15.7 mm diameter and 3 mm depth which exactly fits on the 15 mm diameter heater rod. To reduce the thermal contact resistance between the test surface and the heater rod thermal grease was used. Boiling takes place on this test piece. The heating element was connected to a wattmeter to read the power supplied to it.

Three thermocouples were set inside the boiling vessel, two in the liquid pool to measure the saturation temperature

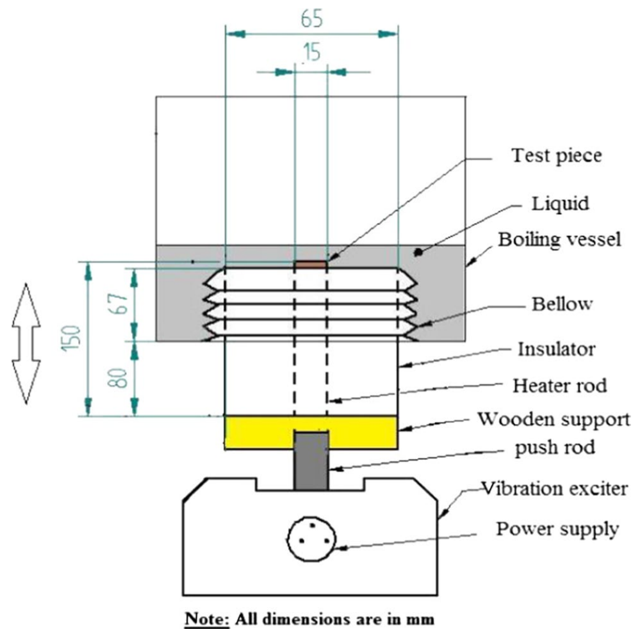

Fig. 3 Vibration arrangement

of the liquid and other in the vapour region. These liquid and vapour temperatures confirm that the system is being maintained at the saturation state during the experiments. Three thermocouples were provided along the length of the heater rod at a distance of 10 mm each close to the heating surface as shown in Fig. 2. These thermocouple readings were used to calculate the temperature gradient and then heat flux. The test piece surface temperature was calculated by extrapolation. Two thermocouples were provided on the insulation at a radial distance of 15 and 20 mm. these two thermocouple readings were used to calculate the radial heat loss.

A vibration exciter (Vector Force: 100 N, Total stroke: ±4 mm, Frequency range: 1–400 Hz) was used to vibrate the test surface vertically as shown in Fig. 3. Heater assembly was mounted on a wooden support which consists of a groove at the bottom. The pushrod of the vibration exciter fits into this groove and transmits the vertical vibration to the heater assembly. Upper portion of the insulator-heater assembly which is inside the boiling vessel is enclosed in a bellow to prevent leakage as well as to aid in vibrating the heater rod smoothly. Frequency of vibration was measured using a power oscillator. Amplitude was measured using an accelerometer.

2.1 Experimental procedure

In order to start the boiling tests, the boiling vessel should be filled with the water. Before filling the chamber with the water, it was evacuated using a vacuum pump. The pressure of the boiling vessel was read on the logger display. Once the evacuation process was completed, the boiling vessel was filled with water. The amount of water was chosen so as to maintain a fixed level in all experiments. The test pressure was set in the logger. When the system was ready, the tests were started by giving heat input to the test surface. The magnitude of the heat input was known from the wattmeter. After equilibrium was reached, the saturation temperature, test surface temperature was noted down for different heat flux. Vibration was imposed to the test surface through the vibrator and frequency and amplitude of vibration were noted. Experiments were conducted by varying the frequency and amplitude of vibration. The set pressure is maintained constant throughout an experiment by the combination of the cooling water pump, pressure transducer and a proportional integral derivative (PID) pressure controller. The PID senses the pressure level in the boiling chamber through pressure transducer and compares it with the set value fed to it by the researcher. To go from a higher pressure level to a lower pressure level, the PID sends a signal to cooling water pump to open the suction line and pump water through the condenser coils.

2.2 Calculation

Local heat transfer coefficient between the surface and the water was calculated by applying Newton's law of cooling

$$h = \frac{q}{\Delta T} = \frac{q}{T_w - T_s} \quad \text{where } q = k\frac{dT}{dx}, \tag{1}$$

where T_s is the saturation temperature of the water at the corresponding pressure, T_w is the surface temperature of the test surface and k is the thermal conductivity of material of heater rod.

To estimate the heat losses, cooling water calorimetry was performed by measuring the flow rate, inlet and outlet temperatures of cooling water during a fixed time. The amount of heat transferred calculated using this data was around 8 % less than the input heat. This difference is attributed to heat loss from the boiling vessel and the heater rod to the surroundings.

2.3 Experimental uncertainty

The uncertainty in temperature measurement was ±0.1 °C. Uncertainty in distance measurement was ±0.1 mm. Propagation of error method was used to estimate the uncertainty for the derived quantities. The resulting maximum uncertainty in the heat flux was 1.14 %. The maximum uncertainty in the wall superheat values was 0.13 %. The maximum uncertainty in the heat transfer coefficient was 1.46 %.

3 Experimental results

3.1 Validation of experimental setup

The surface roughness of the test surface was measured with the help of Mitutoyo Surftest. The test surface had an average roughness value of 0.84 µm. The test surface was polished with the emery paper before each trial to maintain the surface roughness constant. Figure 4 shows the boiling curve for stationary surface. Both heat flux versus wall superheat and heat flux versus heat transfer coefficient (h v/s q) are plotted in the same graph. It has been well established that nucleate boiling data exhibit power law of the form $q = a\Delta T^n$. Where n is an empirically determined constant. There is no general agreement on the value of exponent n. In the various power laws cited in the literature the value of the exponent varied from 3 to 4 [14]. In Fig. 4, the line passing through the experimental data (curve 1) represents the power law fitted to the experimental data in the nucleate boiling regime. Value of the exponent n obtained is 4.18. There were also efforts in the literature to represent the nucleate boiling data in the form $h \propto q^m$. The value of m was approximately 0.7 [14]. Similar presentation of the present experimental data is given in Fig. 4 by curve 2. The value of the exponent is 0.77. It should be noted that the numeric value of the constant of exponents obtained for the present experimentadata matches well with that in literature. The small difference is probably due to different material having different surface roughness, working fluid and experimental conditions in literature and this work. Thus, the test experiments can verify the authenticity of techniques and

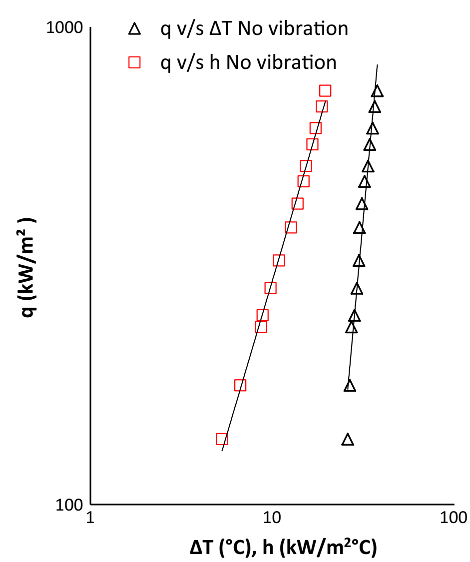

Fig. 4 Boiling curve for stationary surface

the reliability of the data and the accuracy of the experimental setup to carry out the experiments with induced vibration. Thus the q v/s ΔT and q v/s h curves of Fig. 4 may be considered basic and subsequently, he effect of vibration will determined by comparing the results with the base data.

3.2 Effect of vibration

Experiments were conducted on the same test surface with external induced vibration in the vertical direction. Effect of vibration on boiling curve is shown in Fig. 5. q v/s ΔT curve for vibration frequency of 2 Hz and amplitude 2 mm lies to the left of that without vibration (significantly at lower heat flux) indicating that boiling takes place at much lower superheats for the same heat flux when the surface is given external excitation. q v/s h curve for the same condition falls to the right indicating increase in heat transfer coefficient. It is also observed that slope of boiling curve decreases remarkably, indicating stronger dependence on the heat flux than the wall superheat. The value of exponent n is 1.7. Similar observations were done by Prisnyakov [4] and they attribute this to the transformation patterns of growth and separation of vapor bubbles from the vibrating surface. Pressure pulsations created due to excitation, force the bubbles to detach early and fill the cavities with the liquid for the formation of next bubble. Bubbles departing from the surface (vapour carried by the bubbles) during boiling mainly contribute to the amount of heat removed from the surface and thus the amount of heat removed is proportional to the size and frequency of the bubble and the nucleation site density. Change in any of these parameters due to vibration results in change in boiling characteristics. Visual observation revealed that the bubble remained attached to the surface for longer time and departed mostly after coalescing with the neighboring bubble in the horizontal direction on the stationary surface. Bubble quickly departed from the vibrated surface and the diameter at departure was smaller.

3.3 Effect of frequency and amplitude of vibration

High frequency and high amplitude oscillations lead to more intensive heat transfer. This is clear from Fig. 6 which shows greater shift in boiling curve (q v/s ΔT) to the left relative to the values obtained by absence of vibrations. It can also be observed that heat flux also plays a major role. At lower heat flux, there is only shift in the boiling curves to the left, however at higher heat flux the slope of the boiling curve changes remarkably. At higher flux, heat flux itself is influencing parameter, so the effect of vibration is not remarkable. Average value of exponent n in the relation $q = a\Delta T^n$ is 2.8 when excitation of frequency 2 Hz and amplitude 1 mm was given and is 1.3 when surface was vibrated with frequency 10 Hz and amplitude 1 mm.

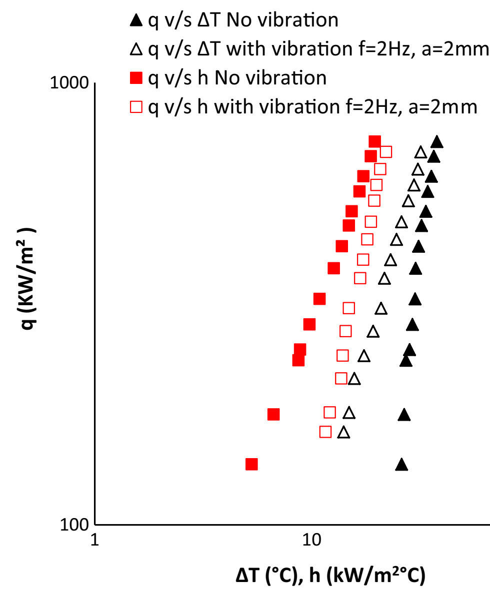

Fig. 5 Effect of vibration on boiling curve

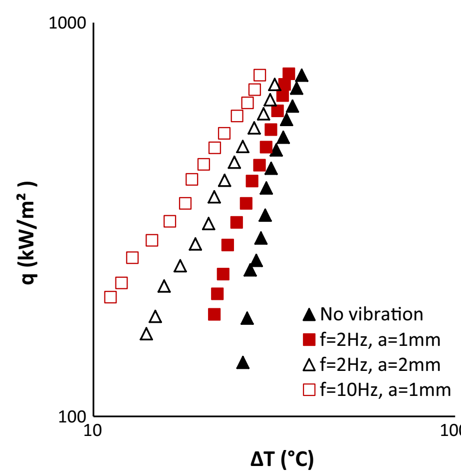

Fig. 6 Effect of frequency and amplitude of vibration on boiling curve

3.4 Intensification of heat transfer

To determine the intensification of heat transfer from vibration excitement, heat transfer coefficient was plotted against frequency of vibration for two different constant values of heat flux at various values of amplitude. Figure 7 shows the maximum value of heat transfer coefficients obtained for each series of tests, depending on the level of amplitude. Noteworthy is the presence of several distinct maxima at each heat flux and amplitude. As can be seen, there are some combinations of frequency and vibration amplitude, which cause considerable (up to 2 times) increase in heat transfer coefficients. It is mentioned in

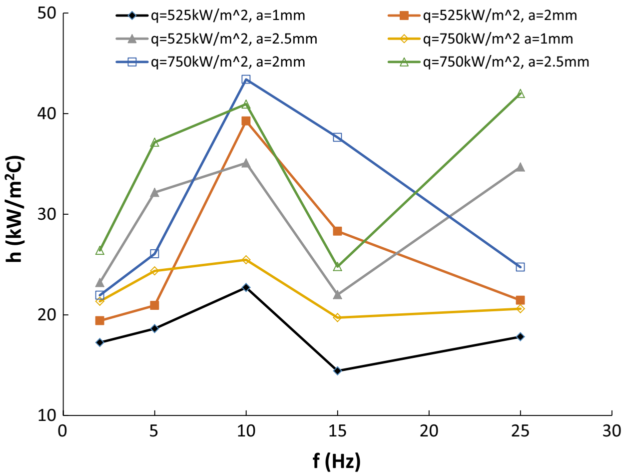

Fig. 7 Intensification of heat transfer

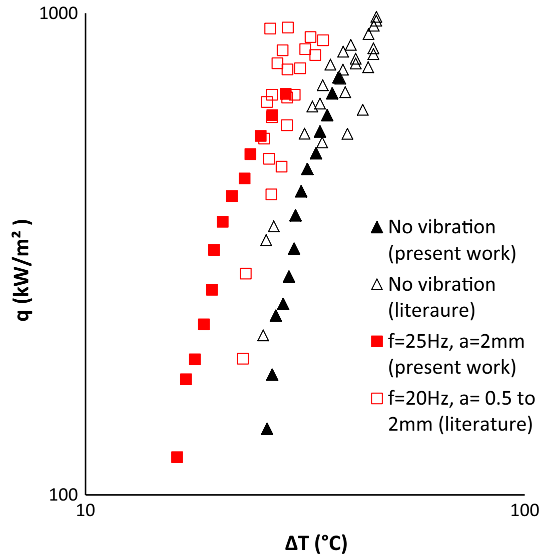

Fig. 8 Comparison of present experimental data with literature data

literature that there are two opposing factors responsible for this extremum value: alternating pressure pulsations due to the induced surface vibration results in pulsating flows in the thermal boundary layer leading to the disturbance of the equilibrium of vapour nuclei inside the pores of the heating surface which will decrease the wall superheat and increase the heat transfer coefficient. The turbulence created due to vibration induced mixing decreases the thickness of the thermal boundary layer that hinders the activation of nucleation sites, which increases the wall superheat and decreases heat transfer coefficient. Depending on which of these two effects is dominant, heat transfer coefficient may be maximum or minimum. Another possible reason for this extrema in intensification of vibration actions is the ratio of the dimensions of the inductor and of the working chamber. When their dimensions are close, an extra static pressure develops in the system, in addition to the dynamic pressure, whose value depends on the inductor shape [3]. It is also believed that when the frequency of bubble formation becomes equal to the frequency of applied vibration extrema will be observed.

3.5 Comparison with literature data

Figure 8 shows the comparison between experimental data of present work with those of literature [4]. There is good agreement between present work and literature data for the stationary surface. For the vibrating surface there is slight deviation at low heat flux, at high heat flux present data match well with the literature. The deviation may be due to the difference in the working fluid (water in the present work, ethanol in the literature), shape and size of the heating surface, size of the container and inductor.

4 Conclusion

To investigate the effects of forced vibration on nucleate pool boiling heat transfer coefficient, pool boiling experiments were conducted at atmospheric pressure with water as the working fluid. Experimental results suggest that external excitation can enhance the boiling heat transfer and it depends on intensity of excitation. It was concluded that the effect of vibration is significant at low heat flux. The present work has also shown that the heat flux removed from the surface for a given surface temperature increases as the intensity of vibration increases. Increase in heat transfer is attributed to changes in bubble parameters. Comparison of the present experimental data with the literature data showed good agreement at high heat flux. Further study on bubble dynamics is required to clearly understand the boiling mechanism under the influence of external excitation.

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