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BUBBLE DYNAMICS AND BOILING HEAT TRANSFER FROM A VIBRATING HEATED SURFACE

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ABSTRACT

An experimental investigation was carried out to determine the effects of heat transfer surface vibration on nucleate pool boiling heat transfer coefficient of saturated water at atmospheric pressure. The circular copper test surface of 19mm diameter was electrically heated and vibrated vertically using a mechanical vibrator at frequencies ranging from 0 to 25Hz and amplitude from 0 to 5mm. An improvement in heat transfer coefficient up to a maximum of 123% was observed with the highest amplitude and frequency of vibration in the investigated range. Visualisation of boiling phenomenon showed that frequency of bubble formation increased with decreased bubble departure diameter when surface vibration was induced.

Keywords: bubble dynamics, enhancement, mechanical vibration, visualisation

1 INTRODUCTION

Many engineering devices are commonly subjected to oscillations, pulsations and vibrations during their operations. The intensity of heat transfer in any fluid flow is influenced by the vibrations of structural elements which are caused by flow fluctuations. Many industrial heat transfer equipment like steam generators, condensers, piping systems and nuclear fuel rods, are subjected to high axial or cross flow which could often cause vibration problems, resulting in wear and damage to these systems. For example, in a steam generator, a bundle of tubes vibrates with a frequency of 200-500 Hz due to the existing hydrodynamic pulsations. Many efforts were devoted to study the influence of the vibration or

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oscillation on the flow and heat transfer characteristics in common heat transfer devices. An overview of vibration analysis procedures and recommended design guidelines was presented by Pettigrewa and Taylorb [1]. This work pertained to nuclear steam generators, reboilers, coolers, condensers, and moisture-separator-reheaters. The most serious vibration problems are due to fluid elastic instability, vortex-shedding resonance and response to turbulence excitation.

In order to gain an understanding of the relationship between critical heat flux (CHF) and flow induced vibration (FIV), Lee *et al*, [2] conducted an experimental investigation with vertical round tube at the atmospheric pressure. The CHF was enhanced by tube mechanical vibration. They conclude that to take advantage of vibration in heat transfer facilities, it is necessary to find an optimal design to enhance the CHF while preventing FIV problems. Khulief *et al*, [3] used numerical modeling to predict the FIV due to cross flow in the shell side of heat exchanger. The elasto-dynamic model of the tube array was modeled using the finite element approach, wherein each tube was modeled by a set of finite tube elements. The developed finite element numerical scheme demonstrated a good degree of accuracy in predicting the onset of instability associated with the FIVs in tubular heat exchangers. The developed scheme had the advantage of representing the fluid-elastic coupling forces in terms of a set of degrees-of-freedom distributed over the entire tube length, thus providing a more accurate prediction of such forces.

The process of bubble generation/growth that may occur at the nucleation site of heated surface during boiling of a liquid is sometimes accompanied by the noise and vibration of the heating surface. Celata *et al*, [4] used noise or vibration originating from the bubble growth and collapse to detect the subcooled boiling phenomenon covering the whole heat transfer regime on externally heated cylindrical channels from the single-phase up to the CHF. Nematollahi *et al*, [5] performed similar experimental study about intensive subcooled boiling induced vibration in annular flow channel and showed the influence of subcooling temperature, linear power density and flow rate on vibration.

Alternately there are efforts to intensify heat and mass transfer by artificially initiated vibrations. A great deal of experimental

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investigations has been performed to demonstrate the influence of vibrations/sound upon the rate of convective heat transfer from heated surfaces to fluids. The experimental works of Martinelli and Boelter [6], Takahashi and Endoh [7], Fand and Kaye [8], indicated that vibration enhances heat transfer capability from 5 to 400% in a free convective or pool boiling system and in a forced convective heat transfer system as well. Several correlations of forced convection to water with tube vibration were also developed (Deaver *et al* [9]; Saxena and Laird [10]; Zitko and Afgan [11]; Klaczak [12]).

And vibration is regarded as an alternative method of boiling heat transfer enhancement. But so far few relevant works could be found. Prisniakov *et al*, [13], studied the influence of vibration on heat transfer process in heat pipes, and found that for a heat pipe with a diameter of 6 mm or larger, the vibration with a frequency of about 100 Hz reduces the thermal resistance, the characteristic frequency grows with the reduction of the size of the heat pipe, so the influence of the size on the heat transfer characteristics of the oscillating heat pipe is strong. Shalaby *et al*, carried out an experimental investigation in order to study the heat transfer performance of a vibrated two-phase closed thermo syphon tube. The working fluid used was R143a. The effects of heat flux, filling percentage, the vibration dimensionless frequency, and the dimensionless amplitude were studied. The optimum filling percentage and the best dimensionless frequency values were 50% and 1.448, respectively. The Nusselt number had been correlated in a dimensionless form as a function of Kutateladze number, filling ratio, dimensionless frequency, dimensionless amplitude, and reduced pressure ratio. Boiling heat transfer enhancement by ultrasonic vibration is another active research area. The studies in this area mainly focused on measuring the heat transfer rate change with such experimental parameters as the vibration frequency and the distance between the vibration transducer and heat source. Enhancement of natural convection heat transfer by virtue of ultrasonic waves was reported by Fand [14], and Li and Parker [15], Wong and Chon [16], and Iida and Tsutsui [17], found that the natural convection heat transfer is enhanced more than pool boiling by ultrasonic vibration based on their investigation on the effects of ultrasonic vibration on pool boiling heat transfer as well

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as natural convection heat transfer. Park and Bergles [18], and Bonekamp and Bier [19], studied the influence of ultrasound on nucleate boiling heat transfer, and observed stronger enhancement at lower heat fluxes. Yamashiro *et al*, [20], showed enhanced quenching behaviour for a hot wire in water when ultrasonic vibration is imposed. A number of external conditions, such as ultrasonic wave power and frequency, dimension of heated wire, chamber dimension and liquid properties, also affect the heat transfer enhancement degree. Kim *et al*, [21]) reported the relationship between the flow behaviour induced by ultrasonic vibration and the consequent heat transfer enhancement in natural convection and pool boiling regimes. A high speed video imaging system was employed to observe the behavior of cavitation and thermal bubbles. It was concluded that, in the natural convection and subcooled boiling regimes, behaviour of cavitation bubbles strongly affects the degree of heat transfer enhancement. In saturated boiling, no cavitation occurs thus the reduced thermal bubble size at departure and acoustic streaming are major factors enhancing heat transfer rate. The highest enhancement ratio was obtained in natural convection regime where the effect of ultrasonic vibration is manifested through violent motion of cavitation bubbles.

Few works have been performed with surface vibration where boiling is involved. Saturated pool boiling of water using a steam-heated tubular test section was made by Carr [22]. Low-frequency, high-amplitude vibration increased the heat transfer rate at constant wall superheat by about 10% for both nucleate boiling and film boiling. Saturated pool boiling of water on a vibrating cylinder was reported by Kovalenko [23]. Improvement in heat transfer was noted only at very low heat flux; at higher heat flux the heat transfer was adversely affected; and when the boiling became fully developed, there appeared to be no effect. Nucleation in the region of less intense boiling was disrupted by vibration. Conclusion regarding the effect of vibration on nucleate boiling cannot be drawn from since the study was conducted at very low heat flux.

Chou *et al*, [24], studied the effects of the vibration and the reciprocating rotation of a cylindrical container on the heat transfer characteristics in detail for water as working fluid, and found that the boiling heat transfer can be raised by 20 to 65% without increasing the heat transfer area. The work was extended

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by Chou [25], to study the effects of the vibration and the reciprocating rotation on different grooved pattern. The boiling heat transfer reduced and converged to a constant as the frequency of reciprocating rotating disc increased. 15% increment in boiling heat transfer was obtained. The experiments of Zitko and Afgan [26], showed that the heat transfer coefficient is augmented by 15 to 63% during the boiling of ethyl alcohol, and the effect of vibration on heat transfer coefficient on a horizontal surface is smaller as compared with a vertical surface.

The effect of vibration on the heat transfer rate in the pool boiling of water was investigated using a horizontal 0.0315 cm diameter nickel-aluminum wire vibrated in a vertical plane by Calus and Rice [27]. The frequency of vibration was varied from 0-124 Hz, the amplitude from 0-0.2032 cm, and the heat flux from 0-7.25×10^5 W/m^2. The experimental data from both the stationary and the vibrating surfaces were correlated by a modification of the Rohsenow pool boiling equation. Chekanov and Kul’gina [28], studied the effect of harmonic oscillations (frequencies from 20 to100 Hz and amplitudes 0 to 0.4x10^{-4}m) on bubble detachment frequency and its dispersion. They observed decrease in bubble detachment frequency and its dispersion with vibration. Action by vibration fields on the internal characteristics of boiling process were investigated by Prisniakov and Prisniakov [29]. This research included an idealized determination of the influence of the vibration upon the internal boiling parameters (Hibiki and Ishii, [30]), as functions of amplitudes and frequencies: the overheating of surface, the steam bubble growth, the bubbles departure radius, the bubbling frequency, density of steam generation center. A minimum of overheating (f<100 Hz) was observed at very low values of heat flux corresponding to transition from convection to bubble boiling. A maximum of overheating (f=300 Hz) was observed at very high values of heat flux corresponding to transition from bubble boiling to film boiling. Rate of bubble growth on a vibrating heater increased, bubbles departure radius decreased with growth of amplitude. The frequency of departure of bubbles decreased (2 times) with increasing of amplitudes and frequency of vibrations. The influences of amplitude increased at lower frequencies of heater vibrations.

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Nangia and Chon [31], carried out an experimental investigation to determine the effects of vibration of the heat transfer surface in saturated pool boiling of water at atmospheric pressure. Wires of 0.01 in. diameter were heated electrically and vibrated electromagnetically at frequencies ranging from 20 to 115 cycles/sec. and amplitudes from 0.0118 to 0.0701 in. An increase in heat transfer up to a maximum of 200% at low wall superheat was observed for an increase in frequency and/or amplitude. At a heat flux of 105 B.t.u./(hr.)(sq. ft.) high-speed motion pictures were taken at 4,800 frames/sec. of the wire vibrating at 45 cycles/sec. with an amplitude of 0.0492 in. Comparison of these films with those taken at the same heat flux without vibration showed that the generating period and diameters at break-off for the pulsed wire follow normal distribution. The waiting period was much longer and more fluctuating in nature. A slight increase in bubble emission frequency was also observed for pulsating wire.

In spite of its significance, few studies have been conducted on the effect of oscillatory motion of heat transfer surface on boiling heat transfer, and most of them included heat transfer from a pulsating wire and a detailed study on effect of vibration on bubble dynamics is lacking. The major application of boiling heat transfer is in immersion cooling of electronic components where the real geometry is horizontal flat surface. So in the present study a circular horizontal copper surface is electrically heated and vertically vibrated. Effects of pulsation on bubble dynamics and heat transfer coefficients are studied.

2 EXPERIMENTAL SETUP

The experimental setup shown in Fig. 1 consists 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. There is provision for liquid charging, condenser cooling water inlet and outlet and pressure transducer in the top flange. Test section is inserted from the bottom flange. Drain valve is provided in the bottom flange. Two observation glasses are provided to record the boiling phenomena. The vapours produced during boiling are condensed and put back to the liquid pool by using a copper condenser coil. To maintain constant saturation temperature of the liquid during experimentation an auxiliary heater of 500W capacity is provided through the side wall. A cylindrical copper rod of 15mm diameter is

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used as heater rod. An electrical heating element of 500W capacity is inserted in to this rod to give heat input to the test surfaces as shown in Fig. 2. The heating element is connected to a wattmeter to read the power supplied to it. Copper heater rod is wrapped with high temperature nylon insulators to reduce the heat losses to the surrounding air by convection. The insulator-heater assembly thus formed is inserted into the vessel through the bottom lid with a portion of the assembly remaining outside the vessel. Gaskets are used to provide leak proof assembly. Replaceable Copper circular test piece of 19mm diameter and 7mm thickness are used. The bottom side of the test piece is provided with 15.7mm diameter central hole of 3mm depth so that it exactly fits on to the heater rod. To reduce the thermal contact resistance between the test surface and the heater rod, thermal grease is used. Fig. 2 shows the details of heater rod. Three K-type thermocouples are placed in the rod at a distance of 10mm each. Two thermocouples are provided in the liquid pool and one in the vapour region. A pressure transducer is used to measure the saturation pressure. The electrical output from all the sensors are collected and displayed digitally.

A Mechanical vibration exciter is used to vibrate the test surface vertically as shown in Fig. 3. Heater assembly is 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 is measured using a power oscillator. Amplitude is measured using an accelerometer

3 EXPERIMENTAL PROCEDURE

Known quantity of distilled water is charged in to the boiling vessel to maintain a fixed level in all the trials. Auxiliary heater and test heater are switched on. Prior to each test, water is boiled sufficiently to reduce the effects of any dissolved air in it. Required pressure is set in the pressure indicator. When the system pressure exceeds the set pressure, the PID controller activates the cooling water pump which delivers water from the tank through the condenser coil to cool the vapours to maintain the pressure constant. When the water reaches the saturation temperature, desired value of vibration is

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imposed to the system. The thermocouple readings and the frequency and amplitude of imposed vibration are noted down. Heat input is increased in steps. Experiments are done by varying the frequency and amplitude of vibration. The temperature gradient obtained from the thermocouples placed on the heater rod is used to calculate the test piece surface temperature by extrapolation. The local boiling heat transfer coefficient is calculated from (1) applying Newton's law of cooling.

$$h = \frac{q}{T_w - T_s} \qquad q = k\frac{dT}{dx} \qquad (1)$$

Where, T_s is the saturation temperature of the water at the corresponding pressure and T_w is the surface temperature of the test surface.

3.1. BOILING VISUALIZATION

The arrangement for pool boiling visualization is shown in Fig. 4. High speed camera (AOS Promon 501) is used for visualization of pool boiling on top of the test surface shown in Fig. 4. The camera is positioned in front of the sight glass. A concentrated light source is placed in front of another sight glass opposite to the camera to give uniform illumination of the test surface. A gigabyte Ethernet cable which acts as data logger connects the camera with PC for data transfer. Nikor lens 50mm FL, f1.4D was used. Promon studio viewer software interfaces camera with PC. This user interface software is used to control the triggering and recording the cine sequence, to set the shutter speed, pixel size, and frame rate of the cine sequences to be captured. The camera can record live cine sequence of boiling phenomenon on the test surface at a frame rate of 1000 fps (frame per second) with resolution of 320 × 240 pixel. These recorded cine sequence are played back and as per the requirement the cine length is marked frame by frame and converted into sequence of images which are processed in Matlab image processing tool to determine bubble diameter in pixel as a function of time. A reference object of known size is placed inside the boiling chamber and from the same focal distance its snapshot is taken and pixel size is measured from the image using a Matlab program. The ratio of actual size of the reference object to its image size is determined. The actual bubble diameter is then obtained by measuring its size from the image and scaling down to the ratio of reference object.

3.2 EXPERIMENTAL UNCERTAINTY

The thermocouples are calibrated against a precision mercury thermometer at ice point to

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an uncertainty of ±0.1°C. Uncertainty in distance measurement is ±0.1 mm. The Kline and McClintock [32], technique is used to estimate the uncertainty for the derived quantities. The resulting maximum uncertainty in the heat flux is 2.05%. The maximum uncertainty in the wall superheat values is 1.01%. The maximum uncertainty in the heat transfer coefficient is 2.2%. The maximum uncertainty in calculating the bubble size is ±0.05mm. The maximum uncertainty in calculating the bubble frequency is 6.25%.

3.3 VALIDATION OF EXPERIMENTAL SETUP

The boiling curve for the test surface when vibration is not imposed on it is compared with those predicted from three well known correlations, namely, Cooper [33], Foster-Zuber [34], and Rohsenow [35], as shown in Fig. 5. The trend of the experimental data matches well with that obtained from all the correlations. Cooper correlation with roughness value of 0.33μm predicts the present experimental data with an average error of 5.7%. Thus the reliability of the data and the accuracy of the experimental setup to carry out the experiments with induced vibration are proved

4 EXPERIMENTAL RESULTS

The purpose of this analysis is to study the effect of frequency and amplitude of vibration on boiling curves and heat transfer coefficient. In this analysis experimental data are obtained for two different scenarios: pool boiling without surface vibration and pool boiling with surface vibration. The results in Fig. 6 show the effect of vibration on wall superheat. It is clear that presence of vibration reduces the wall superheat. When the heat input is 120kW/m^2, the wall superheat reduces to as low as 8°C when vibration is induced to the test surface as compared to the wall superheat of 26°C without vibration. This trend continued throughout the heat flux interval up to the highest heat flux used in this investigation. The curves tend to converge at higher heat flux. The reduction in wall superheat when vibration was applied on the surface resulted in improvement in boiling heat transfer coefficient which is illustrated in Fig. 7. Highest improvement of 123% is observed with the highest amplitude and frequency of vibration. It can also be observed from Fig. 7 that improvement in heat transfer coefficient is higher when the test surface is vibrated with high amplitude and high frequency than at low amplitude but high frequency. This shows that amplitude of

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vibration has more significant effect on heat transfer than frequency. Increase in heat transfer coefficient is attributed to the effect of vibration on bubble departure cycle.

4.1 EFFECT OF FREQUENCY

Experiments were conducted at constant amplitude of 2.5mm. Frequency of vibration was varied from 2Hz to 10Hz. Wall superheat decreases significantly when the test piece is vibrated externally as depicted in Fig. 8. Increase in frequency of vibration has only marginal effect on wall superheat.

4.2 EFFECT OF AMPLITUDE

Experiments were conducted at constant frequency of 5Hz. Amplitude of vibration was varied from 1mm to 4.5mm. Wall superheat decreases significantly with increase in amplitude up to 2.5mm and further increase in amplitude does not improve the results, but the wall superheat is still lower than that without vibration as seen in Fig. 9.

It is established in literature that agitation of the liquid or any external agitation in the thermal boundary layer or any device to increase the bubble population or bubble emission frequency would enhance the heat transfer in boiling. Further, any mechanism to remove bubbles from the surface before they grow to their full size would increase the heat transfer. Results from the current work illustrate that boiling surface vibration creates agitation in the liquid pool which either disturbs the thermal boundary layer or removes the bubbles at their early growth stage. Visualisation is carried out to ascertain the exact cause for increase in heat transfer.

4.3 BUBBLE DYNAMICS

Inducing vibration to the test surface changes the bubble parameters which increases or deteriorates the boiling heat transfer rate. In general the bubble dynamics is complex, thus many researchers have carried out numerous experimental studies to understand the bubble dynamics. In the present work boiling visualization was carried out initially without surface vibration, then with vibration at constant amplitude of 2.5mm and at different frequencies of 2Hz, 5Hz and 10Hz. The bubble parameters such as bubble nucleation, bubble growth rate, bubble departure, bubble frequency and the influence of neighbour bubbles over the nucleated bubbles on the boiling surface are determined.

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The sequential images of nucleation, growth and departure of bubbles from the test surface when vibration is not induced to the test surface at wall super heat of 15.7°C shown in Fig. 10. Here most of the bubbles nucleated at an approximate time period of 0.001s and developed to a spherical shape. Frame (a) shows the bubble nucleation on the test surface, and grows in size which can be observed in frames taken after 10, 23, 36, 44 and 67 milliseconds respectively. In frame (e) the bubble reaches its departure diameter and departs from the surface. Frame (f) which was taken after 74 milliseconds shows the departed bubble. The bubble shape is spherical when it departs.

The frames in Fig. 11 demonstrate the bubble dynamics when the test surface was made to vibrate at 2Hz frequency and amplitude 2.5mm. The bubble nucleation, growth and departure pattern is almost same as that of the stationary test surface, however here it is much swifter. The bubble completes its life cycle in 65 milliseconds. The bubble diameter was rather small at the time of its departure. The external excitation causes the bubble to leave off the surface earlier. A small amount of coalescence occurs often, but it is not so remarkable.

The bubble dynamics on the test surface at 5Hz frequency, 2.5mm amplitude vibration is shown in Fig. 12. The Coalescence occurs horizontally along the surface, vapourization occurs more aggressively, which makes the adjacent bubbles to merge together. It can also be observed that the bubble diameter is higher in this case. Usually when coalescence occurs, initially the bubble adheres to the test surface, creating a strong surface tension force. This delays the nucleation of new bubble. When the waiting time is more, generally the growth time will also be more. Mushroom and oval shape can be observed at various stages of growth. The bubble dynamics on the test surface at vibration intensity of 10Hz frequency, 2.5mm amplitude is shown in Fig. 13.The bubble nucleates, grows and departs in 26ms from the surface. The departure diameter of the bubble is also small. Once the bubble departs it quickly rises towards the free surface of the liquid and sometimes it adheres to other departed bubble rising in the same direction, thus vertical coalescence occurs.

4.3.1. BUBBLE GROWTH RATE

The bubble generation process is intermittent and it is typically classified into three phases waiting phase, growth phase and an intake

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phase. The bubble growth rate is the total time elapsed for one bubble cycle commencing from its nucleation to departure. The growth rate of the bubble is given by (2).

$$\Delta t_w = f^{-1} - \Delta t_g \qquad (2)$$

The instantaneous bubble growth rate at constant amplitude 2.5mm and at different vibrational frequency is shown in Fig. 14. The bubble size varied from the same activation site and between different activation sites of the test surface. Hence a large sample size of 30 bubble life cycle (not coalesced) was considered to arrive at the mean size of the bubble. The mean value was then plotted as a function of the wall super heat. The bubble diameter increased with increase in time. The bubble diameter at the time of departure is 0.87mm and the time period for bubble growth is 0.007s for the stationary test surface. Similarly, the departure diameter of 0.54mm in the time period of 0.005s was observed for the test surface vibrated at frequency 10Hz. At vibrational frequencies of 2Hz and 5Hz the bubble growth time is 0.006s. It is observed that the bubble growth rate reduced with increase in vibrational frequency from 2Hz to 10Hz.

The bubble life cycle on the unexcited test surface represents in Fig. 15(a). Initial bubble nucleation size is 0.56mm. As the time progressed the bubble encompassed more vapour increasing its size linearly and departs at 0.007s measuring 0.87mm in diameter. The new bubble nucleates from the same active nucleation site and the waiting time for new bubble to nucleate is 0.001s. Fig.15 (b) shows sequel images of bubble growth rate at vibrational frequency 2Hz. The vapour bubble nucleates and departs in 0.006s measuring 0.76mm. Figure 15(c) shows the bubble life cycle at vibrational frequency 5Hz. The time taken for the bubble to nucleate and depart is 0.006s. Neck formation of the bubble can be clearly seen when the bubble is departing. The bubble departing size is 0.69mm. Bubble life cycle on excited test surface at vibrational frequency 10Hz is shown in Fig. 15(d). The isolated bubble nucleates and departs measuring 0.54mm in diameter in the time period of 0.005s.

4.3.2 BUBBLE DEPARTURE DIAMETER

Normalised bubble departure diameter as a function of frequency of induced vibration for different values of heat flux is shown in Fig.16. It is clear that bubble departure

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diameter decreases for oscillating surface which indicates the early departure of bubbles from the surface.

4.3.3 BUBBLE DEPARTURE FREQUENCY

The bubble frequency is the count of departing bubbles from the same activation site over a period time. Bubble frequency is the inverse of total time elapsed for one complete bubble life cycle plus waiting time for the next successive bubble to nucleate. Average bubble frequency is calculated considering a sample size of 30 bubble life cycle from same active nucleation site. The bubble frequency is normalised by dividing by the corresponding value for unexcited condition and the values are plotted as a function of frequency of induced vibration for different heat flux values as shown in Fig. 17. It may be seen that the bubble frequency is minimum at 5Hz. This is in contrast with the results of Chekanov and Kulg'ina who reported decrease in bubble departure frequency and its dispersion with increase in amplitude of oscillation. Change in bubble frequency was related to change in heater temperature and the pressure above the surface. Nangia and Chon have reported shorter growth period and longer waiting period for the vibrating wire compared to the stationary wire. The bubble departure frequency defined as the reciprocal of the sum of the waiting and growth period slightly increased for the vibrating wire. They attributed shorter growth period in the case of oscillating wire to the change in temperature distribution in the boundary layer and its thickness while longer waiting period to the delay in thermal boundary layer formation due to extra disturbance created by the pulsating wire.

5. CONCLUSION

To investigate the effects of external vibration on nucleate pool boiling heat transfer coefficient of water, experiments were conducted at atmospheric pressure. Boiling visualization was performed using high speed camera to study the bubble dynamics. The following conclusions were drawn from the studies.

- Experimental results illustrate that external excitation can enhance the boiling heat transfer coefficient. The effect of amplitude of vibration is significant on augmentation of boiling heat transfer.
- At low wall super heat the effect of vibration on bubble departure diameter is

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not significant. At high wall super heat increase in vibration intensity reduces the bubble departure diameter.

- Bubble growth time is shorter and diameter at departure is smaller for oscillating surface.
- Normalised bubble departure frequency is minimum at 5Hz frequency.
- The enhancement in heat transfer coefficient is attributed to the change in bubble dynamics due to induced vibration.

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7. NOMENCLATURE

a Amplitude of vibration (mm)

d Bubble departure diameter (mm)

f Frequency of vibration (Hz)

f_b Bubble departure frequency (Hz)

h Heat transfer coefficient (kW/m^2°C)

q Heat flux (kW/m^2) suffix

0 Parameter when vibration is not induced

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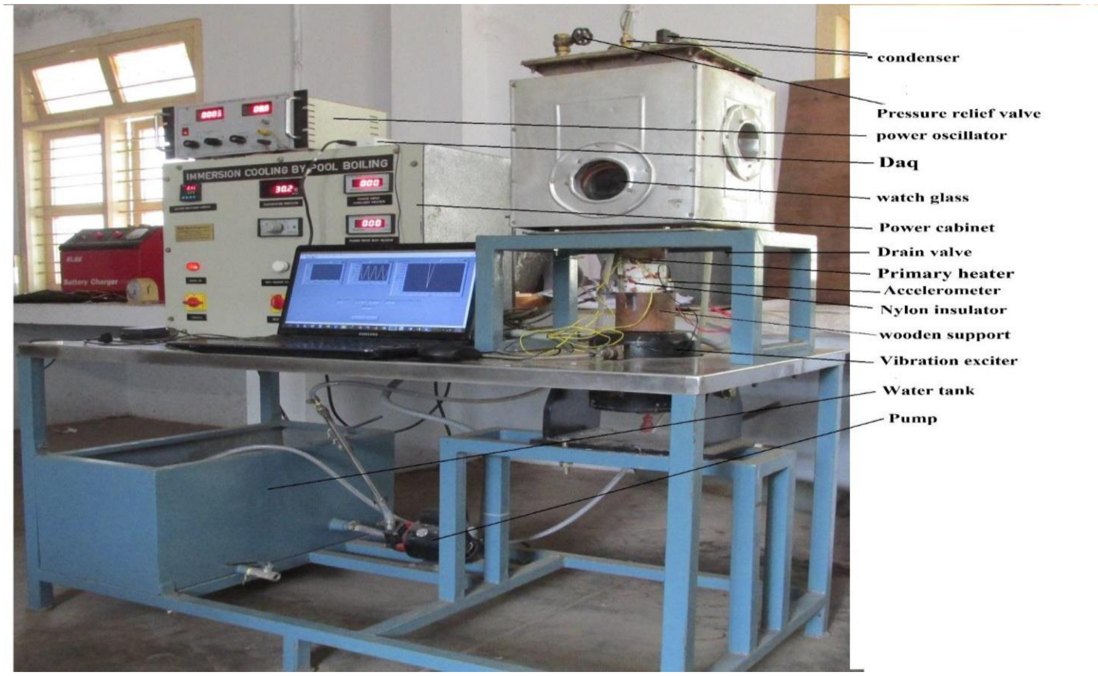
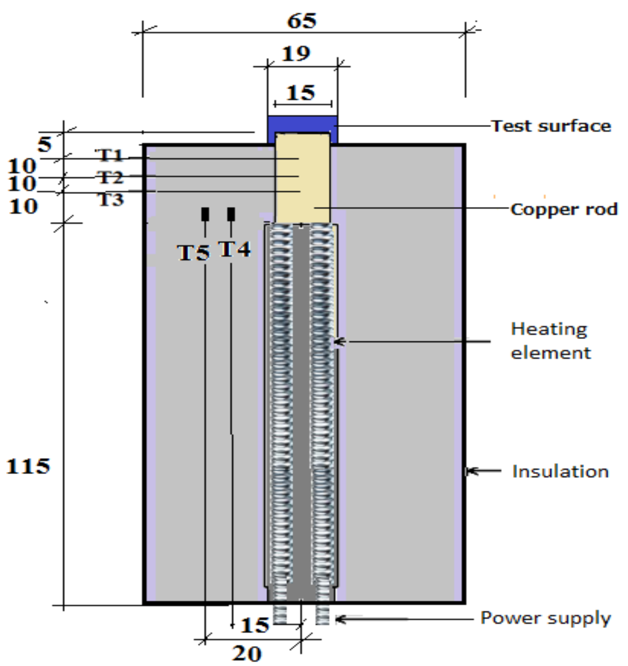


Fig. 1 Photograph of Experimental setup



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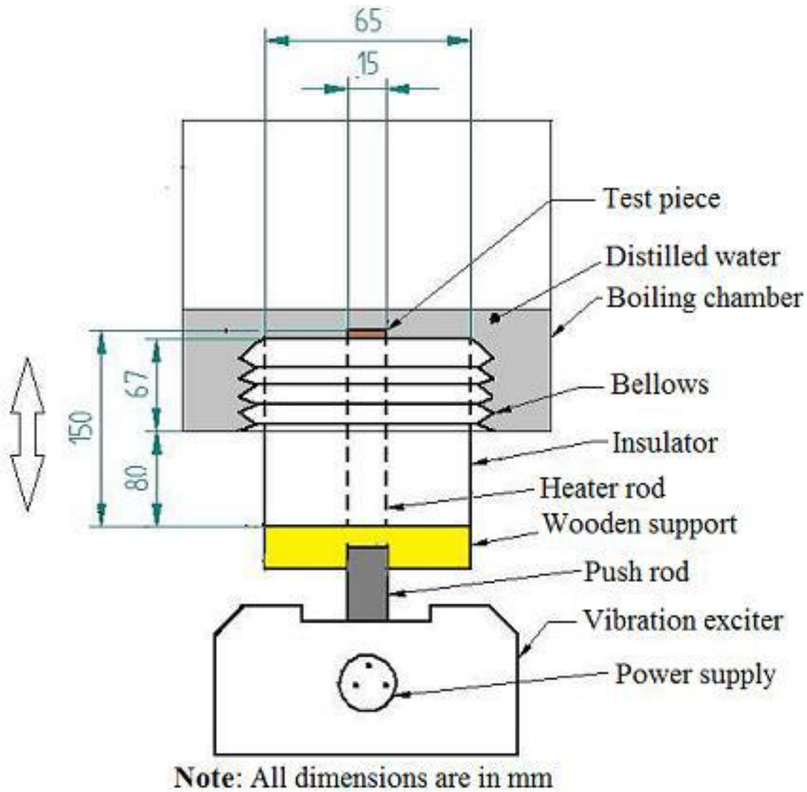
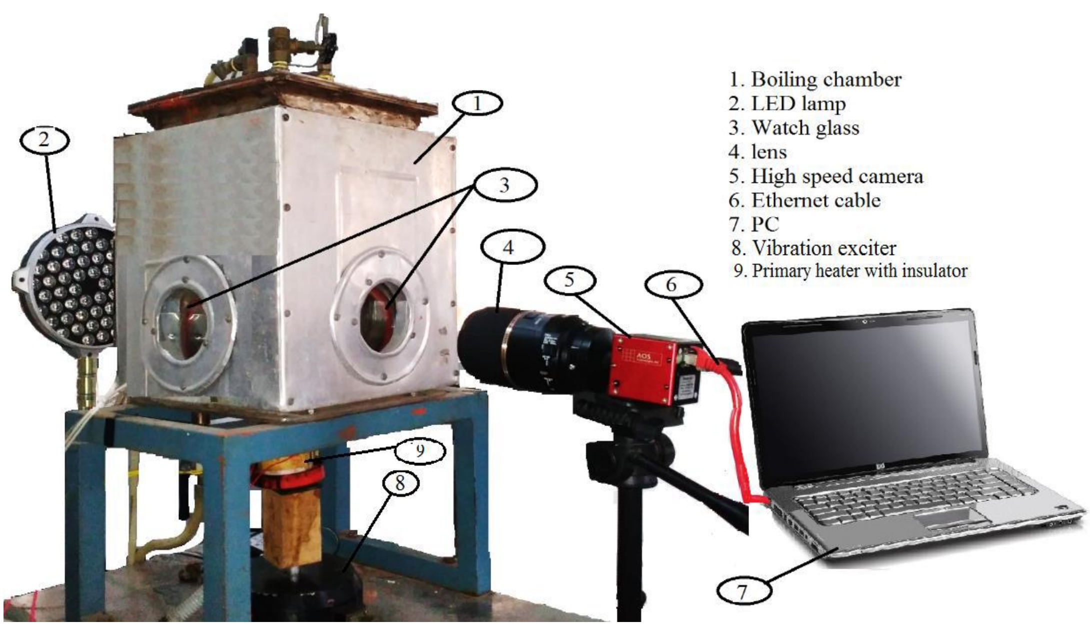


Fig. 3 Vibration arrangement



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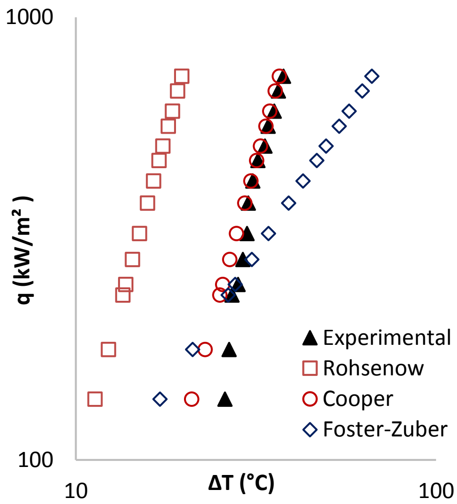

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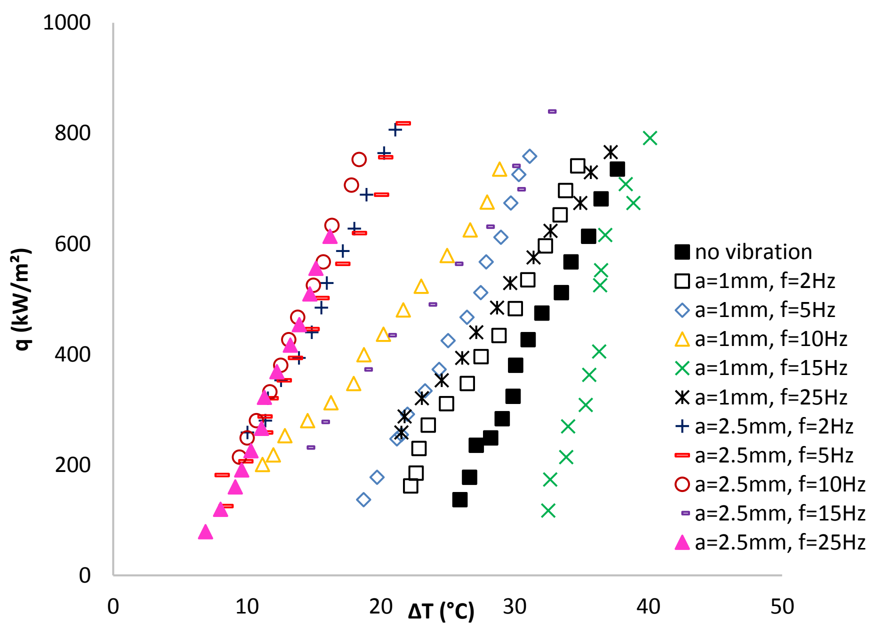

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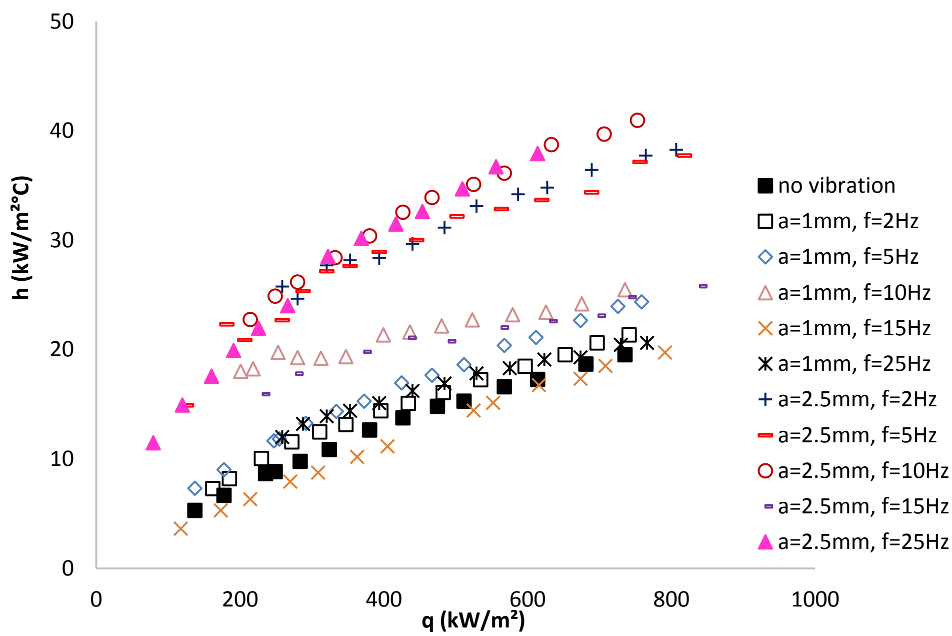

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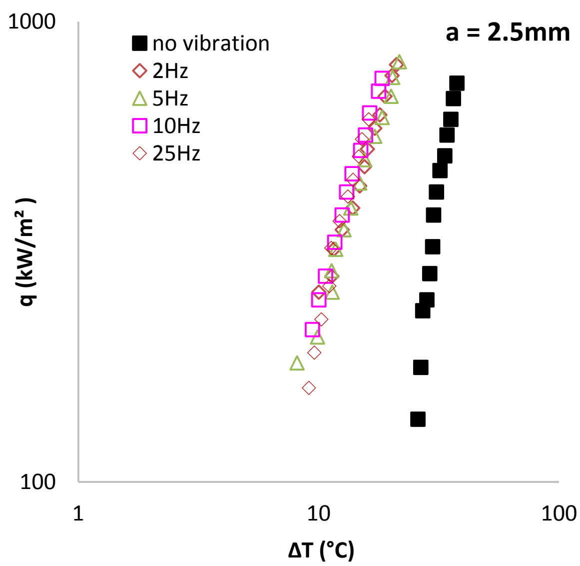

Fig. 8 Effect of frequency of vibration on boiling curves

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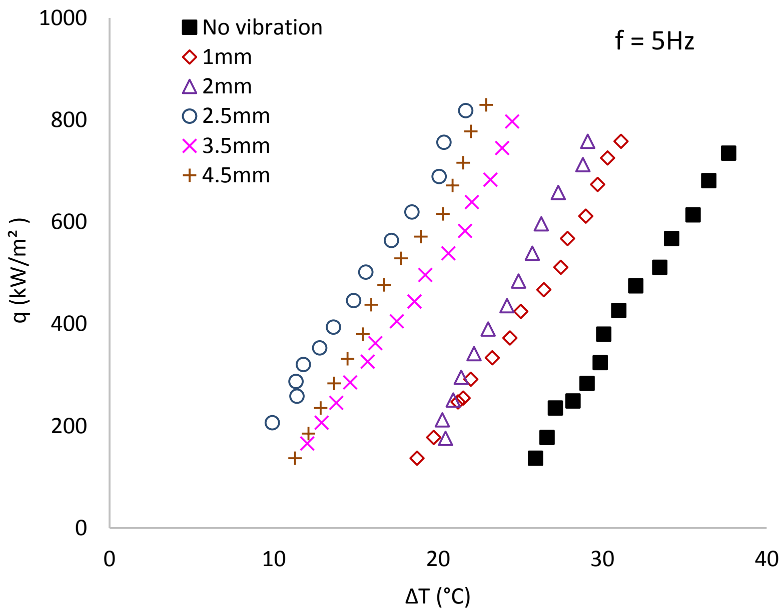

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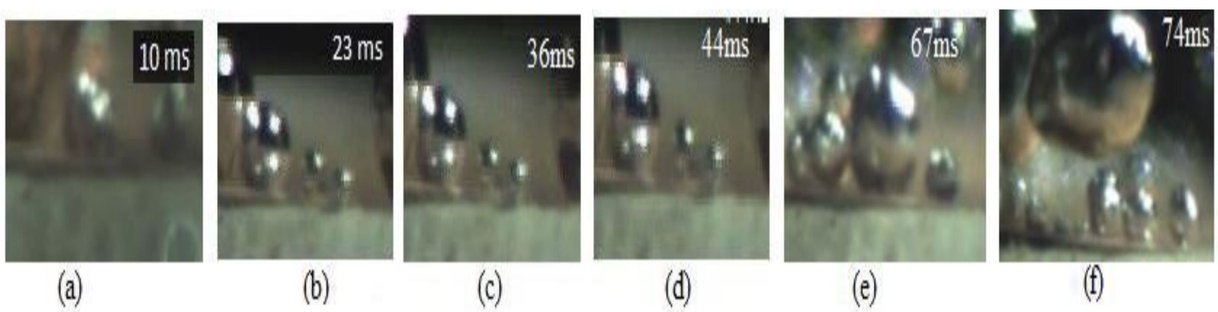

Fig. 10 Life cycle on stationary test surface Bubble at 15.7°C wall super heat

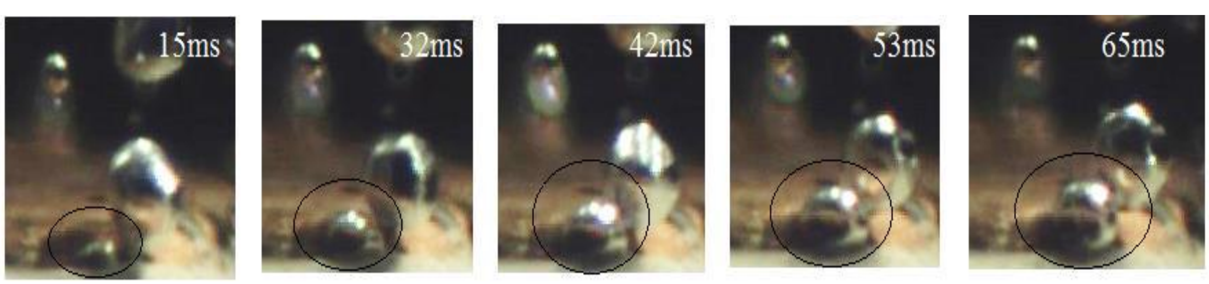

Fig. 11 Bubble life cycle at f=2Hz, a=2.5mm at wall super heat 14.8°C

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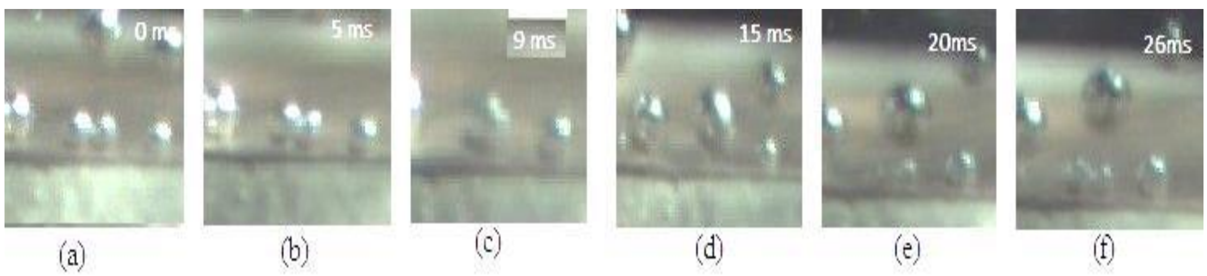
Fig. 12 Bubble life cycle at f=5Hz, a=2.5mm at wall super heat 13.2°C



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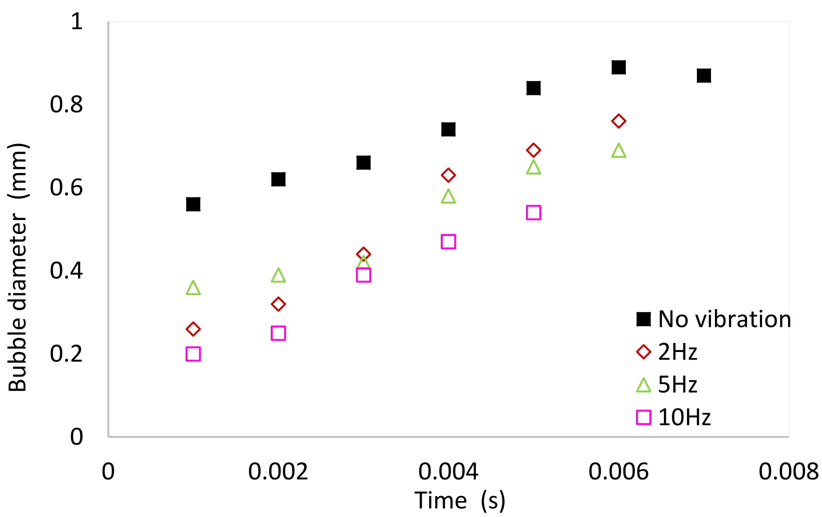

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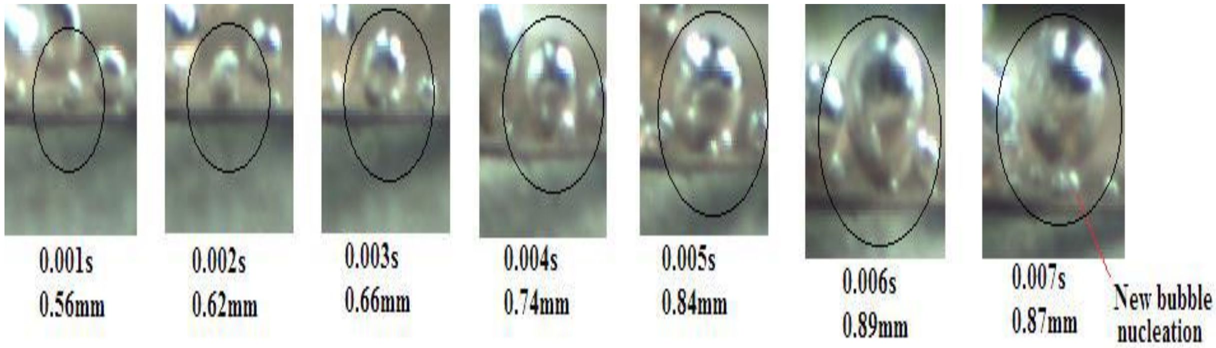
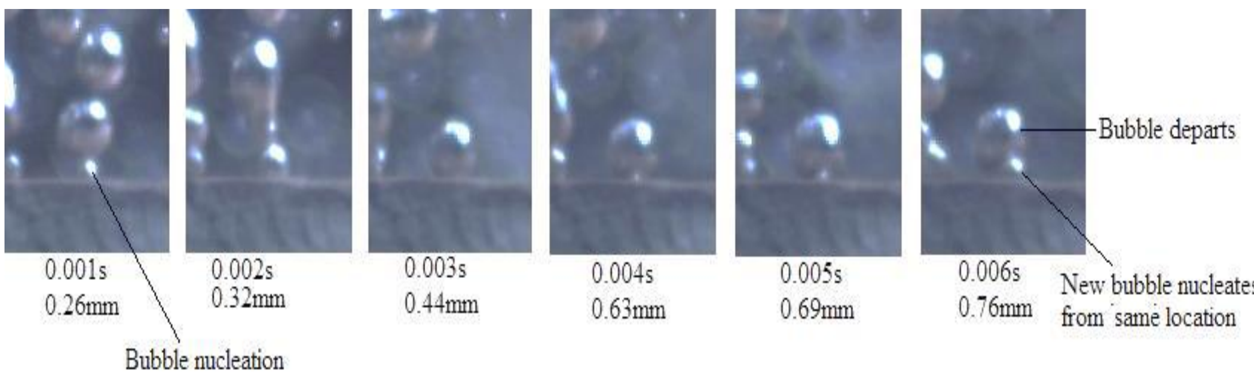
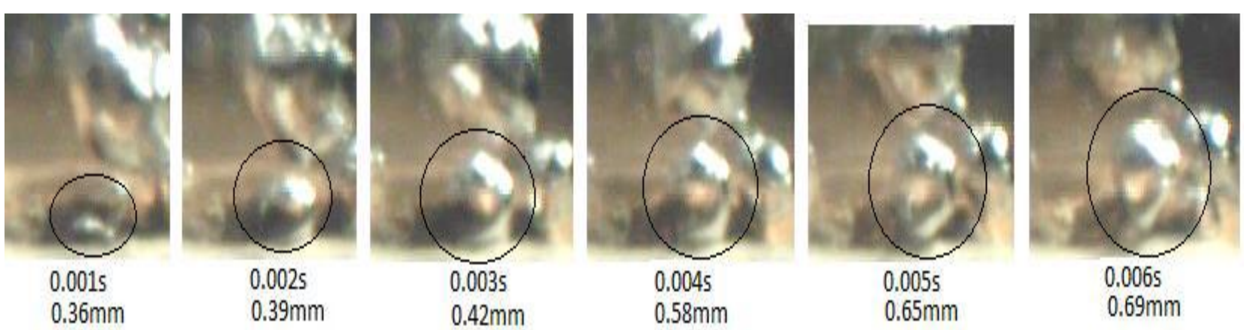


(a)



(b)



(c)

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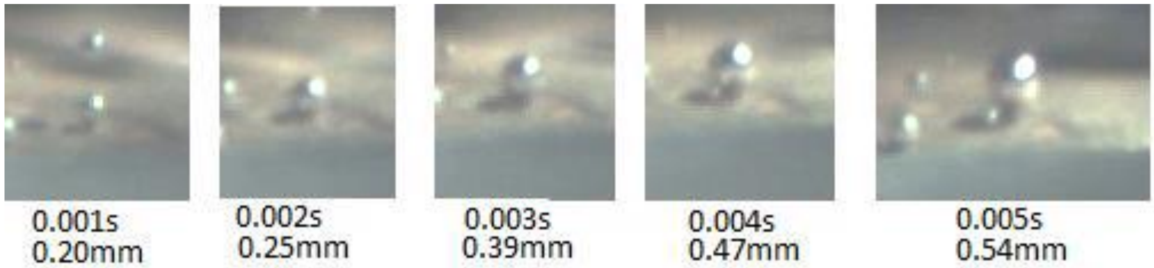

(d)

Fig. 15 Sample pictures of bubble growth rate: (a) without vibration, (b) with vibration, f = 2Hz, a = 2.5mm, (c) with vibration, f = 5Hz, a=2.5mm (d) with vibration, f =10Hz, a=2.5mm

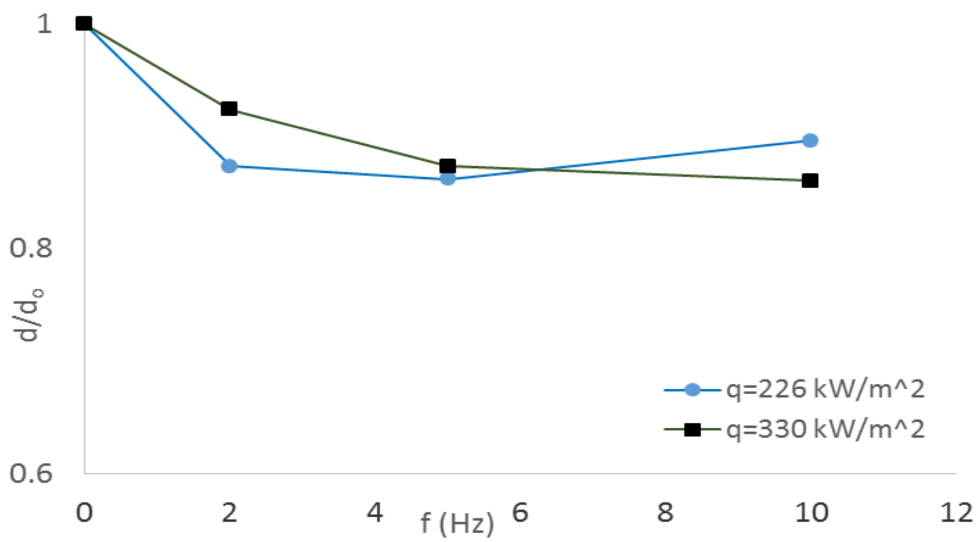

Fig. 16 Normalised bubble departure diameter v/s frequency of induced vibration

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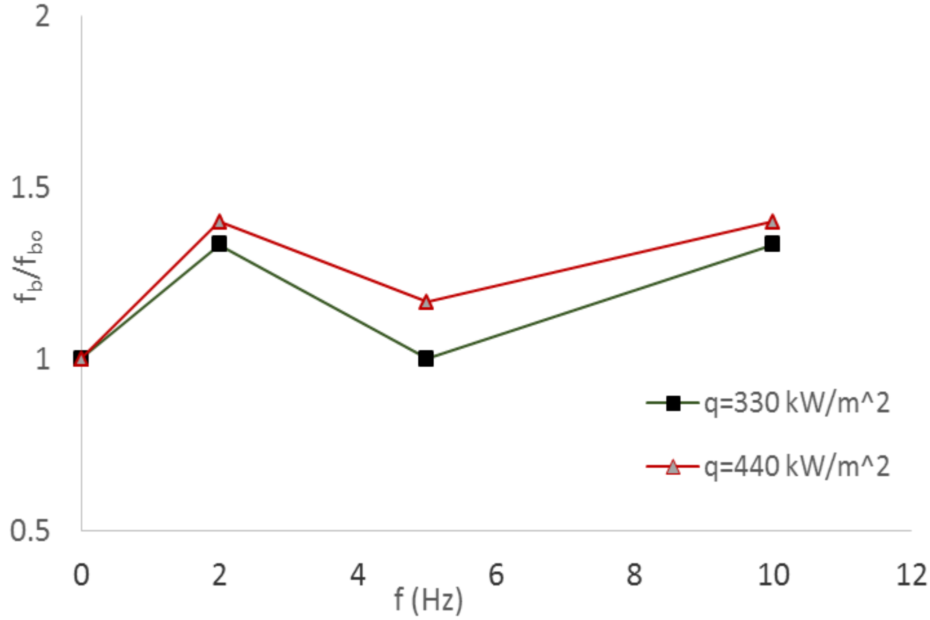

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