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Bubble Departure Phenomena of Pool Boiling on Enhanced Metallic Surface

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ABSTRACT

In present study, bubble departure phenomena on different modified surfaces for enhanced pool boiling of water are explored. Experiments were conducted for understanding bubble interaction with surfaces of different topography. Important parameters of pool boiling i.e. bubble departure diameter and bubble departure frequency were measured and analyzed to understand the mechanism of pool boiling and associated heat transfer. High speed video camera was employed to capture bubble phenomena on boiling surface. Three different surfaces have been used for experimentation as plain surface, pitted surface and finned surface. Copper is used as boiling surface and fin material. The setup was designed in such a way that the effect of surface topography can be precisely measured. It has been observed that a bubble departure phenomenon not only depends on the supplied heat flux, but also on the surface topography. Here it is revealed that with higher heat flux bubble departure diameter and bubble departure frequency generally increases along with heat transfer coefficient. But the increment is not linear as it seems. Although with the increase of heat flux, bubble departure diameter increases, there are other factors like surface tension, acting forces due to fluid motion, drag force and surface topography that affect the phenomena.

Keywords: *Boiling, Bubble departure, Enhanced heat transfer, Modified surfaces*

INTRODUCTION

Lord Rayleigh [1] pioneered the study of bubble dynamics. Since his work, a lot of studies have been conducted, yet, heat transfer enhancement in pool boiling is still not fully understood. To quantify the understanding of the phenomena various mathematical expressions have been proposed. Most of the correlations have limitations in terms of either being simple or too complex, which require iterative procedure to solve [2]. Fritz [3] model is consider as one of the most reliable model. Ruckenstein [4] measured the bubble departure diameter as a function of wall-superheat and proposed a correlation based on his findings. On the other hand Van Stralen and Zijl [5] also proposed an empirical correlation by considering bubble growth mechanism.

It is well known that different types of surfaces have different effects on pool boiling and heat transfer rate. Enhanced surfaces can greatly improve heat transfer rate. In this study pool boiling has been studied on different enhanced surfaces with different surface topography. Heterogeneous nucleation is the main focus for this study. The vapor bubble begins to form on the heated surface and starts to grow until it reaches a certain diameter and rise through the liquid. Also, higher heat transfer coefficient in nucleate pool boiling largely depends on heat transfer mechanism which is directly linked to bubble activity on the surface [6]. That's why almost all the correlation developed for modeling heat transfer phenomena contains a term related to bubble dynamics, especially bubble departure diameter. Beside bubble departure diameter, literature showed that bubble departure frequency plays an important role in heat transfer phenomena [7]. It should also be noted that theoretical models for prediction of the nucleate boiling heat transfer coefficient are still at the early stage of development [8].Predicting models are extremely helpful for various applications like cooling of nuclear reactor, refrigeration cycle, electronic component etc. Electronic devices are specially prone to heat damage. Thus, proper thermal management is extremely important in electronics components. The more and more compact devices are getting, the harder it’s getting to manage heat situation. In this present study, three different surfaces have been used and studied. The present study is an experimental investigation. The aim is to obtain a complete characteristics of bubble dynamics in pool boiling for different surface topography, to improve the visual understanding of bubble dynamics (bubble departure diameter, bubble departure frequency, bubble area density) in pool boiling, and to inquire relations between various parameters of boiling and bubble dynamics, i.e. heat flux, heat transfer coefficient, bubble departure diameter, bubble departure frequency, bubble area density etc

EXPERIMENTAL SETUP

In this experiment, the setup was designed in such a way that the boiling surface can be easily swapped out and replaced with different one with different topography so that the effect of surface topography is precisely reflected in the result. For better viewing and video recording at high speed the boiling vessel was chosen to be made of glass. It is difficult to acquire airtight setup when glass and metal are used together. The setup was properly sealed with enough silicon adhesive and rubber gasket. The whole setup was insulated for minimum heat loss. Figure 1 schematically demonstrates the experimental setup used in this study

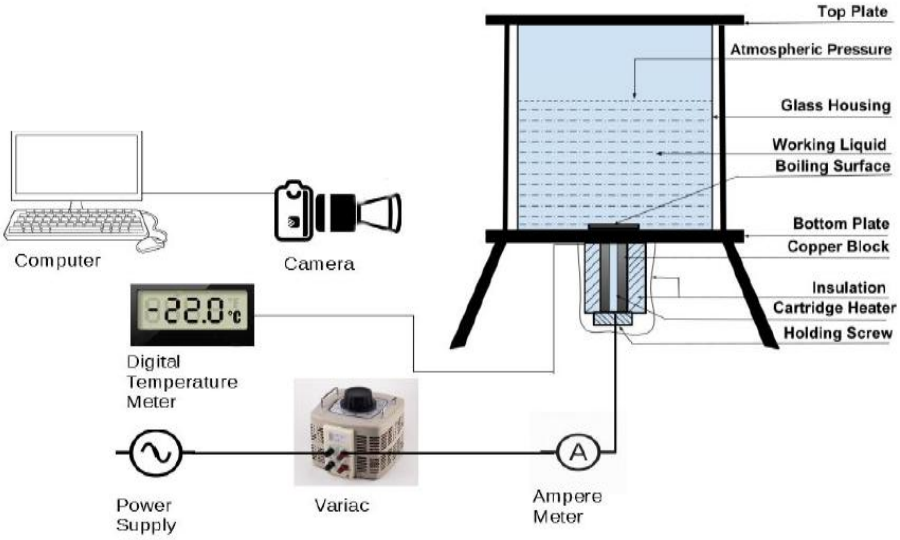


Fig1. *Schematic experimental setup for pool boiling*

A temperature-resistance glass container was used to contain the working liquids; the bottom surface of the container was replaced by the working surface (which is actually a copper block with various surface geometry). Glass container is 113 mm in length and 97 mm in diameter. A curtis heater was inserted inside the copper block through a fabricated hole, which acted as a source of heat. A variac was used to control the voltage of the heater thus controlling the power supply. The thermocouple was used to measure the temperature at different places.

A high-speed video camera (Phantom Miro EX4096MC, CMOS sensor, 8/12 bit color, 500-1260fps at full resolution (800x600 pixel), maximum 111,100fps at lowest resolution (32x16 pixel), ISO 4800(monochrome) and 1200(color)) was used to capture the departing bubble images during boiling.

Copper blocks were used as boiling surface. The blocks were 88 mm in height and 49 mm in diameter. The surface of the block which was treated as a plain surface when it is polished by zero grade emery paper and treated as a pitted surface when it is pitted 1 mm in depth and 1, 2 & 3 number of pits/cm² with custom-designed tool to ensure desired experimental conditions. For the finned surface, the fins were inserted on the copper block by press-fit. The fins were made of copper, approximately 5 mm in height and 2.5 mm in diameter and approximately 3 fins/cm^2 in density. During the experiment, the liquid level was such that the fins were always at submerged condition which is the mandatory criteria for pool boiling. When the heater was on, the pressure above the working fluid was at atmospheric. After achieving the desired experimental conditions, the temperature, video images and the power consumption were recorded for analysis.

Although it is said that the plain surface is smooth and was worked on with zero grade emery paper to make sure maximum polishness, it is possible that it contained microscopic level pits, grains, scratch etc from machining or polishing. These irregularities may allow gas to remain trapped. However given that the comparing pitted surface and finned surface has much larger irregularities, namely pits and fins, the microscopic pits and scratches can be ignored for comparison.

RESULTS & DISCUSSION

From Fig. 2 it is observed that the bubble departure diameter increases with the increase of wall superheat for all types of surfaces. Although the trend for bubble departure diameter increase is similar in all three surfaces, finned and pitted surface have higher bubble departure diameter than plain surface. It's true that with the increase of heat flux the bubble departure diameter increases, but it is not the sole reason. The surface roughness and fins have played a major role in the increase of bubble departure diameter. To put all these parameters in relation it can be postulated that with the increase of wall superheat the bubble diameter increase, to increase the wall superheat the heat flux is required to be increased. Meanwhile, the finned and pitted surfaces require much more heat flux than plain surface to achieve similar wall superheat. This heat is retained by the bubbles and they increase in diameter facilitating the carrying of the heat.

Like plain surface, no regular behavior is observed in pitted surface. Bubble embryos are hardly isolated at the beginning in pitted surface, which results in frequent merging of bubbles with neighboring bubbles increasing the departure diameter. Also the active site densities are higher in number easing the merging of bubbles, which all contribute to the higher bubble departure diameter compared to plain surface. It's difficult to predict the behavior of how often and how frequently it happens.

Finned surface shows a different pattern than plain and pitted surface. The bubble departure diameter at the beginning of boiling is larger than both plain and pitted surface. Which may be the result of initial higher heat transfer due to the fins and trapped gas. But later the bubble departure diameter falls below the average of pitted surface. This might be caused by the motion of fluid. At the very beginning, the fluid motion is quite steady and stable. The bubbles formed in this stage can absorb more heat without the force exerted by the fluid motion pushing on it, thus letting the bubble stay on the surface for longer time. Which in return let the bubbles grow? But as soon as the bubbles start to leave the surface in large number due to buoyancy with the increase of heat flux, the fluid motion increase as well. The process is more accelerated in finned surface compared to plain and pitted surface due to the fact that finned surface facilitated higher heat transfer rate.

In general, the initial rate of increase of bubble departure diameter is higher for all surfaces. This is because at the start of the boiling the bubble count is lower and the nucleation sites are few. Bubbles are more stable at this time. The less bubbles hardly disturbs the fluid resulting less fluid motion. Bubble also forms keeping considerable distance between them as well as between each nucleation site. As a result the acting forces on each bubble is much less which let the bubbles take up the heat from the surface for longer period without detaching.

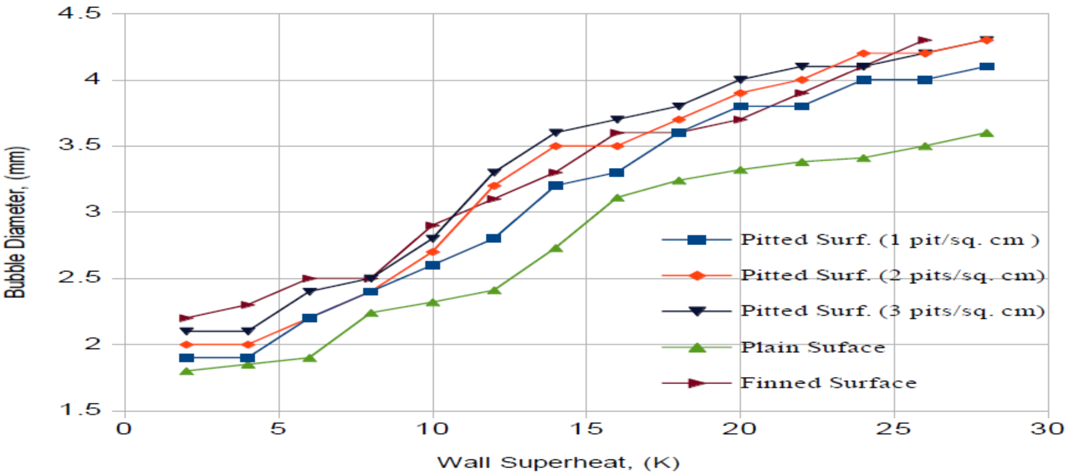


Fig2. *Comparison of different surfaces' bubble departure diameter with respect to wall superheat*

The prolonged heat absorption by the bubble while still attached to the surface let the bubble grow in relatively larger sizes as shown in Fig. 3. With the increase of heat flux, the nucleation sites start to increase as well as the bubble count. Hence it increases the bubble departure frequency as shown in Fig. 4. As soon as the bubble departure frequency increases, the fluid motion changes drastically. This changes the stability of bubbles and working fluid. The bubbles get comparatively less time to stick to the surface due to fluid motion. The increase in the number of bubble formation changes that scenario. The more the frequency increases the more the fluid motion is affected. On the other hand, often two or more bubbles tend to grow from the same site and their embryos remain attached to each other. The larger bubble slides away from the pairing exerting a sliding force on the smaller bubble in the direction of fluid flow which also contributes to the disturbance of fluid and average bubble departure diameter.

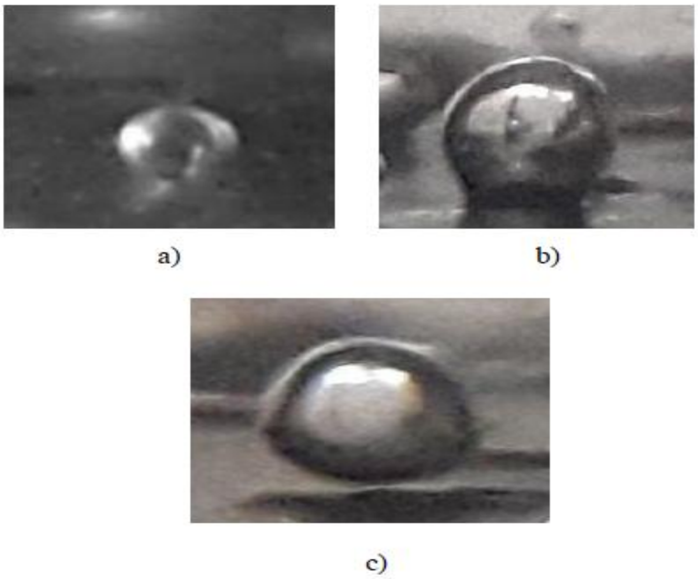

a)
b)
c)

Fig3. *a) Initialization of a bubble embryo [t=3ms] b) Prolonged heat absorption and growth [t=120ms] c) Detachment from the surface [t=130ms]*

Some bubbles merge with each other before leaving the surface originating from the same site. This also affects the average bubble departure diameter. At the wall surface, larger bubbles are often formed by merging two or more bubbles with each other. In lower heat flux, bubbles usually merge with the next bubble on the same site rather than with the bubbles from another site. This is because low fluid motion does not drag the bubbles horizontally. Sometime a second bubble forms as soon as the first bubble completes its growth. Two bubbles coincide at same site while one bubble is fully grown and the other is just halfway through the growth. In this case, two bubbles often merge in the vertical direction rather than horizontal. As a result, the lower portion of the merged bubble springs up due to the restoring action of the surface tension force. With the increase of heat flux nucleation sites also increases and bubbles merge with other bubbles of different nucleation site. Higher heat flux promotes higher bubble departure frequency which increases the fluid motion. It enables the bubbles to be dragged horizontally and merge. Bubble merging on the surface is shown in Fig. 5.

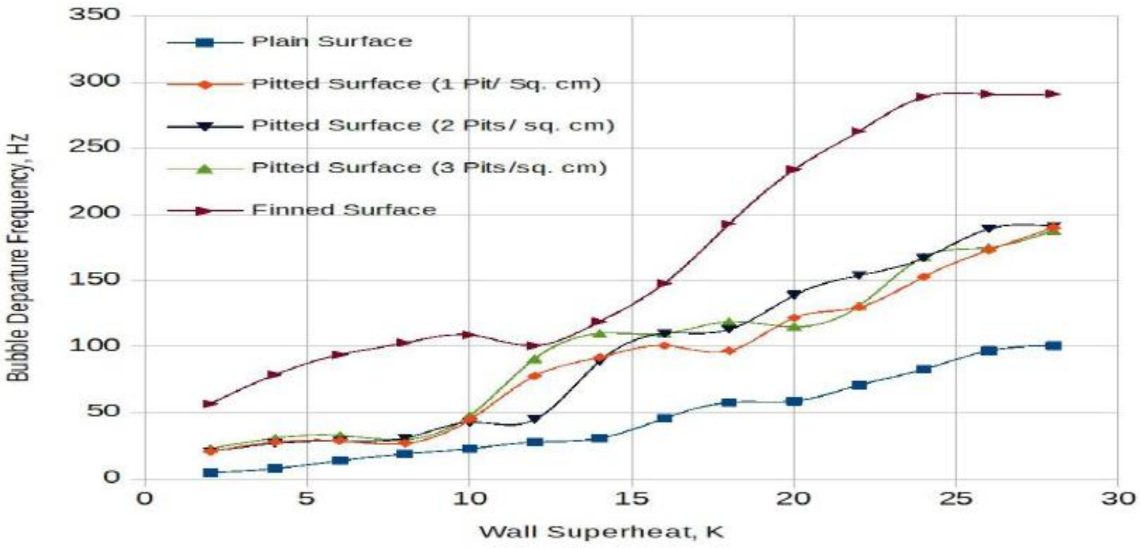


Fig4. *Bubble departure frequency at different heat flux for different surfaces*

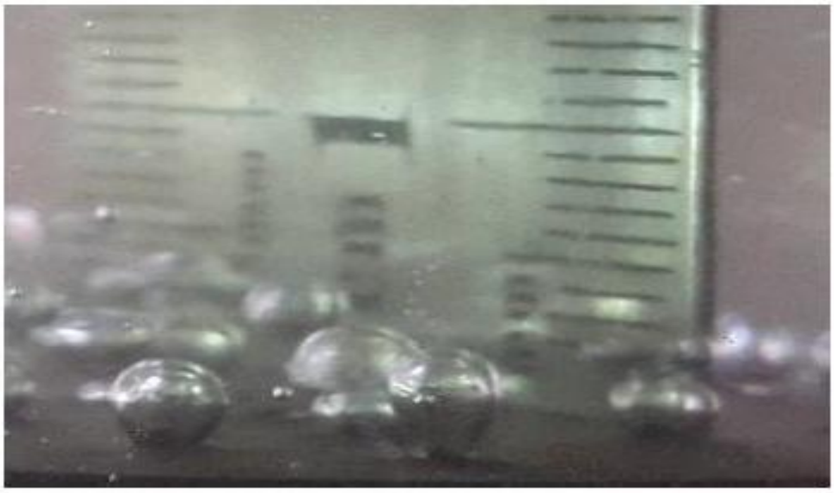


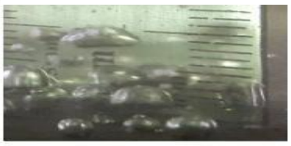
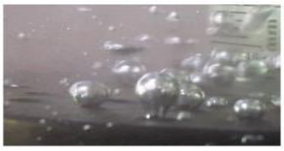
Fig5. *Merging of bubble embryos on plain surface*

Table 1 shows bubble departure phenomena at different heat flux. From the table it can be observed that for the plain surface, at lower heat flux up to 10 kW/m^2 the bubble forms a complete bubble embryo. The nucleation sites are fewer at this stage. But with the increase of heat flux, the bubble number increases as well as nucleation site densities. It is also observed that at higher heat flux the departed bubble's shape deforms and the bubble departure frequency increases.

For the pitted and finned surface, it is observed that the number of nucleation site is higher in lower heat flux than the plain surface. Both bubble departure diameter and bubble departure frequencies are higher at q = 60 kW/m^2 for pitted and finned surface. With pitted and finned surface, at q = 120 kW/m^2 bubbles frequently merges and forms larger bubbles than the plain surface.

For fluid motion in boiling, it is assumed that the bubble detaches if the combination of buoyancy and drag force is able to overcome the force due to surface tension [9]. It has been observed that at higher heat flux, most often the bubbles slide over the surface before it lifts off.

Table1. *Visuals of bubbles on different surfaces at different heat flux*

Surface Type\Heat Flux	$q = 10\ kW/m^2$	$q = 60\ kW/m^2$	$q = 120\ kW/m^2$
Plain Surface			
Pitted Surface			
Finned Surface			

In general, it is seen from the plot in Fig. 4 that with the rise of wall superheat the rate of bubble departure increased for all surfaces. However, bubble departure frequency is significantly higher for finned and pitted surface compared to the plain surface. When Fig. 4 is compared with Fig. 6, it is found that higher bubble departure frequency is linked to higher heat flux as well as wall superheat. It has been observed that higher heat flux increases nucleation sites. Nucleation sites are responsible for producing bubbles. As more nucleation sites are formed the more bubbles are formed and released from the surface. This is why higher wall superheat as well as higher heat flux tend to increase bubble departure frequency. When the bubble departure frequency increases, the bubbles scatter randomly due to fluid motion while ascending. This allows bubbles to collide with each other more often increasing the means of heat transfer.

Wall superheat and respective heat transfer coefficient is plotted in the Fig. 6. It is evident that surface topography has dramatic influence on the heat transfer process. Both finned and pitted surface has significantly higher heat transfer coefficient than plain surface. It is also observed that increasing cavities lead to an increase of heat transfer coefficient. In surfaces with 1 pit/cm^2, 2 pits/cm^2, and 3 pits/cm^2, they have slightly varied heat transfer coefficient as shown in Fig. 6.

The pitted surface promotes the heterogeneous nucleation and increases nucleation site. In finned surface, the heat transfer coefficient is even higher. From Fig. 6 it has also been observed that after a steeper increase in heat transfer coefficient the rate of increase of heat transfer coefficient drops. The steeper increase is associated with rapid bubble formation and higher bubble departure frequency. This phenomena is more noticeable in finned surface. When Fig. 6 is compared with Fig. 2 and Fig. 4, it can be observed that at this period both bubble departure frequency and bubble departure diameter dropped slightly which result in less steeper curve after the initial increase of heat transfer coefficient. Which might have caused the heat transfer coefficient to be less than desired?

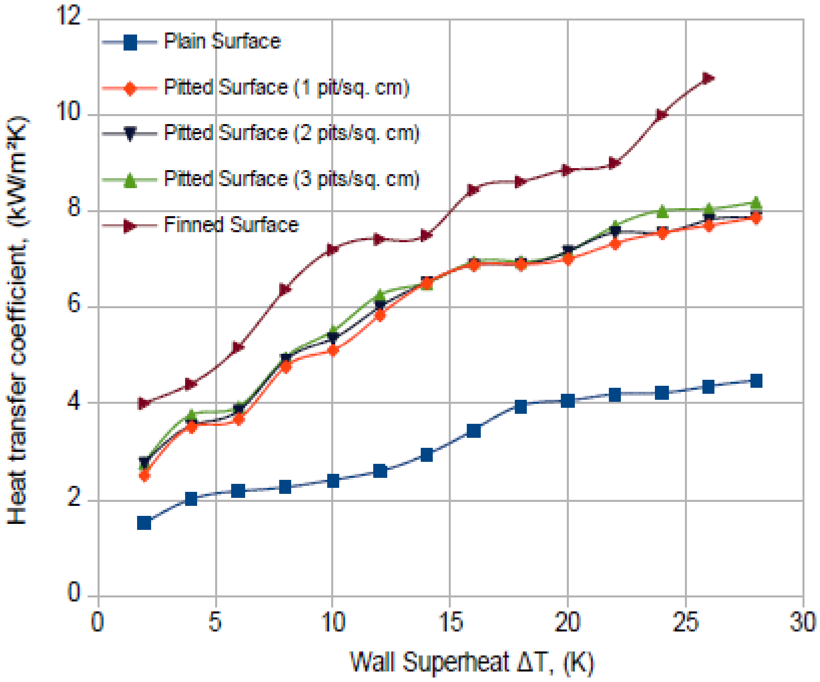


Fig6. *Heat transfer coefficient at different wall superheat for different surfaces*

CONCLUSIONS

In this study, the relation among the bubble departure diameter, bubble departure frequency and heat transfer in pool boiling on different surface topography has been studied. Conclusion is drawn based on the experimental findings. Summary of the conclusion is listed below:

- It has been observed that with the increase of heat flux the bubble departure diameter increases for all types of surfaces.
- Along with heat flux, surface roughness also plays an important role in bubble departure diameter. The bubble departure diameter on the pitted surface is significantly higher than plain surface as well as the bubble departure frequency.
- Bubble departure frequency is higher for the finned surface. It has been also observed that heat transfer coefficient is also higher for the finned surface which leads to the conclusion that bubble departure frequency has effects on heat transfer.
- Bubble merging in pool boiling has significant effect on crucial pool boiling parameters i.e. bubble diameter, bubble departure frequency and heat transfer coefficient.
- Heat transfer coefficient increases with the increase of heat flux for all surfaces.
- Heat transfer coefficient and bubble departure

frequency is significantly higher for finned and pitted surface compared to the plain surface.

- The experimental data from the present study has well agreed with literature.

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