Journal of Advances in Science and Technology
Vol. 13, Issue No. 1, (Special Issue) March-2017, ISSN 2230-9659

Review of Bubble Behaviour in Pool Boiling by Single Bubble Dynamics

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Abstract – Studies of bubble behaviour in pool boiling give different results at various operating conditions and parameters. To understand bubble behaviour, literature is reviewed in terms of heat flux, bubble growth, bubble release frequency, velocity, bubble departure dynamics, correlations, experimental and numerical studies at various conditions and parameters. After understanding the bubble behaviour in pool boiling this study may be beneficial for study of breaking of vapour bubble to improve the heat transfer rate by increasing critical heat flux (CHF). Breaking of bubble will be done with jet of steam or mechanistic approach to avoid blanket formation and thus enhancing critical heat flux.

Keywords— Bubble Departure Diameter, Bubble Releasing Frequency, Critical Heat Flux, Surfactants

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INTRODUCTION

There are number of applications of boiling in nuclear power plants and other many energy sources. Also boiling is having many domestic as well as industrial applications. Boiling is a very potential and methodical mode of heat transfer, which is encountered in ample engineering applications. Crucial field of application of boiling and evaporation is in power systems like nuclear power plants where large extent of heat is to be moved out through constraint space. Many researchers have extensively studied bubble dynamics during nucleate pool boiling heat transfer experimentally and numerically. A Few researches studied it on artificial nucleation sites. Researches also extensively investigated saturated pool boiling enhancement by using additives in water. Boiling is a phenomenon of vaporization in which liquid changes its phase to vapour when it is heated to its saturation point temperature. In boiling temperature of surface of the heating element is maintained greater than saturation temperature of the liquid, i.e., $T_s>T_{sat}$. The phase change allows heat to be transferred to and from the heater surface without affecting significantly the bulk fluid temperature, which can lead to higher heat transfer rates that correspond to less temperature differences. The latter also leads to large heat transfer coefficients as compared to typical single phase convection processes. Partially due to higher heat transfer coefficients, which allow for greater heat transfer, boiling is one of the best desirable heat transfer process to engineers.

Boiling is broadly classified as pool boiling or flow boiling depending on the presence of bulk fluid motion.

1. Pool Boiling**:** It is called pool boiling in the absence of bulk fluid flow.

2. Flow Boiling: It is called flow boiling or forced convection boiling in the presence of bulk fluid flow.

Pool and flow boiling are further classified as sub cooled and saturated boiling.

1. Sub cooled boiling: It is said to be sub cooled (or local) when the temperature of the main body of the liquid is lower than the saturation temperature T_{sat} (i.e. bulk of liquid is sub cooled).

2. Saturated boiling: It is said to be saturated (or bulk) when the temperature of the liquid is same as T_{sat} (i.e., bulk of liquid is saturated).

In pool boiling bulk fluid motion is absent. And the critical heat flux is the point upto which nucleate boiling occurs and beyond it film boiling is observed. In nucleate pool boiling the rapid formation of the vapour bubbles takes place at solid liquid interface. The bubble detaches from the surface when they reach a sufficient size and try to raise free surface of the liquid. Motivating factors for these studies include the partitioning of energy into liquid and vapour phases, the influence of bubble dynamics on the wall heat transfer, and the development of void profile during flow boiling.

BASICS OF POOL BOILING HEAT TRANSFER

In pool boiling the fluid is not forced to flow by a mover such as pump and due to the natural convection currents there is motion of the fluid and under the influence of buoyancy forces motion of bubbles occurs.

Depending upon the value of excess temperature (ΔT_{excess} = (T_w–T_{sat}), There are four different boiling regimes are named as Natural convection, Nucleate, Transition and Film boiling.

a) Natural Convection Boiling

In this region liquid is heated above the saturation temperature by few degrees. Therefore, liquid is slightly superheated and evaporates when it rises to the free surface. The fluid motion in this mode of boiling is occurs due to natural convection currents, and heat transfer from the heating surface to the fluid is by natural convection.

b) Nucleate Boiling

The nucleate boiling regime can be divided into two separate regions. In region A-B, isolated bubbles are nucleated at various preferential nucleation sites over the heating surface. But these bubbles are dispersed in the liquid shortly after their separation from the surface. And the space vacated by the rising bubbles is replaced by the liquid in the vicinity of the heater surface, and the process is repeated.

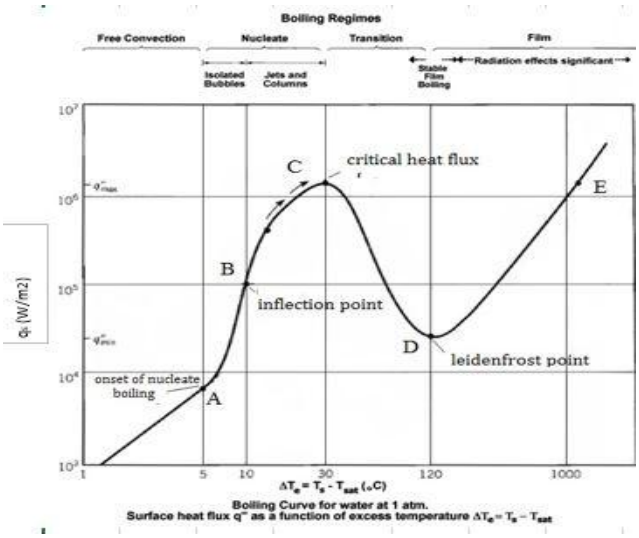

Fig 1 Boiling curve for water at 1 atmospheric pressure

In region B-C, the heater temperature is further increased, and bubbles form at such great rates at such a large number of nucleation sites that they form numerous continuous columns of vapour in the liquid. These bubbles move all the way up to the free surface, where they break up and release their vapour content. The large heat fluxes can be obtained in this region and are caused by the combined effect of liquid evaporation and entrainment.

At higher values of ΔT_{excess}, the evaporation rate at the heater surface reaches such high values that a maximum portion of the heater surface is covered by blanket of bubbles, making it difficult for the liquid to reach the heater surface and wet it. As a result, the heat flux increases at a lower rate with increasing ΔT_{excess} and reaches a maximum at point C. The heat flux at this point is called the critical (or maximum) heat flux, q_{max}.

c) Transition Boiling

As the heater temperature and thus the ΔT_{excess} is increased past point 30°C, the heat flux decreases, as in Figure 1.This is because vapour film covers a large fraction of heater surface, which acts as an insulation due to the low thermal conductivity of the vapour relative to that of the liquid. Both nucleate and film boiling partially occur in the transition boiling regime. Nucleate boiling at point C is completely replaced by film boiling at point D. Generally the phenomenon in the transition boiling regime, which is also called the unstable film boiling regime, is avoided in practice. Generally, transition boiling occurs over the excess temperature range from about 30°C to about 120°C for water.

d) Film Boiling

In this region, a completely stable vapour layer is covers the heater surface. Point D, where the heat flux reaches a minimum, is called the Leiden-frost point that liquid droplets on a very hot surface jump around and slowly boil away. The presence of a vapour film between the heater surface and the liquid is the major cause for the low heat transfer rates in the film boiling region.

OBJECTIVE

Here the objective is to understand the bubble behavior, its dependence on various operating conditions and various parameters. The main objective is to search best method to enhance the heat transfer rate by increasing critical heat flux.

PROPOSED WORK

It is proposed to review the literature of effect of different parameters on bubble behavior in pool boiling. The work is summarized as follows. Proposed work is to find out the different parameters which are affecting the behavior of the bubble. Then it will be beneficial for the breaking of the bubble for enhancement of heat transfer.

STUDY OF BUBBLE BEHAVIOR IN POOL BOILING

Nucleate pool boiling is the vast field of research the reason is a large amount of heat with a relatively small of temperature difference can be transferred. Nucleate pool boiling has applications in refrigeration and air conditioning systems, nuclear and thermal power plants, and other many energy conversion systems.

In recent years, many research have be done to enhance the heat transfer in pool boiling by bubble dynamics, and compiled literature has been reviewed as follows

1. Bubble Growth Rate

The heating surface of any commercial material contains cracks, roughness, pits which act as nucleation sites for nucleation of bubbles. Bubble gets nucleated due to different geometrical shapes and sizes of nucleation sites. The liquid in this cavity gets evaporated due to heat transfer and forms a bubble nucleus. The growth of bubble takes place in many stages and the bubble leaves the site of nucleation after the complete growth. Fig. 2 shows the solid surface temperature T_w is more than bulk temperature of liquid.

R_b - radius of bubble

R_c - cavity radius at its mouth

θ - angle made by bubble with the surface

δ - height of thermal boundary layer

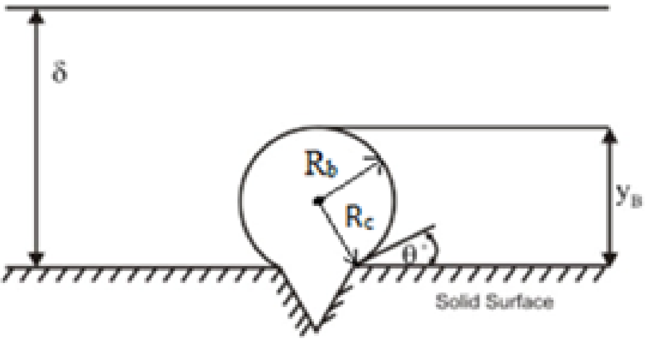

Fig 2. Bubble growth

Bubble growth is the important phenomenon in pool boiling which is to be studied as follows.

Yin Xiao Li [1] have studied the single bubble dynamics on superheated super hydrophobic surfaces and also corresponding heat transfer mechanism of pool boiling surfaces by coating a thin layer of polytetrafluoroethylene on top of silicon substrates with electro less etched silicon nanowires. When this hydrophobic surface immersed in water a vapor film is formed and when the superheat increased the bubble gets formed and then further escapes from the vapor film.

His results showed that growth rate of the bubble having little dependence on surface superheat and applied heat flux at large superheats due to the formation of vapour layer which limits the heat transfer from superheated super hydrophobic surfaces. There is a constant frequency of the bubbles departure at large superheats, which is a result of the constant departure velocity limit. The HTC (heat transfer coefficient) first increases and then slowly decreases as the superheat increases.

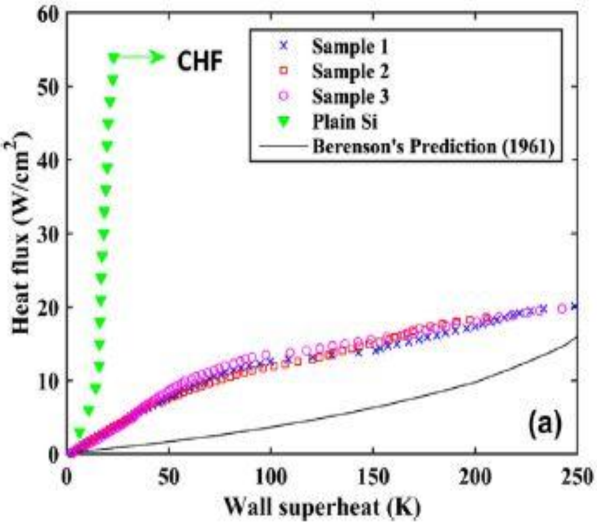

Fig.3 Heat flux as a function of wall superheat, compared with a plain silicon surface and Berenson's theoretical model for film boiling

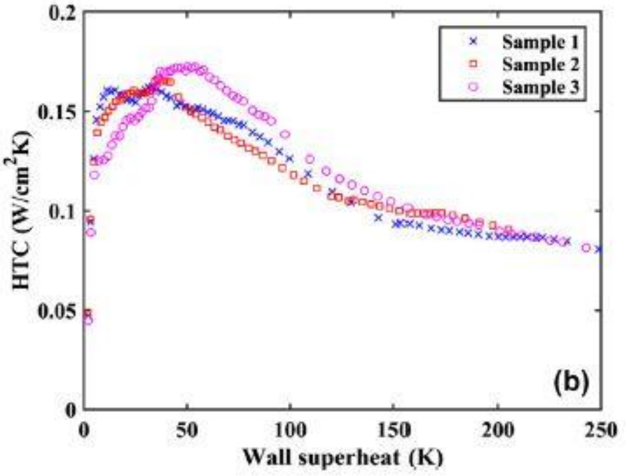

Fig. 4 Boiling curves for superhydrophobic surfaces. Heat transfer coefficient as a function of wall superheat

Youngsuk nam [2] have studied single bubble dynamics on a superhydrophillic surface with well defined nucleation sites. These superhydrophillic surfaces are prepared by forming CuO nanostructures on a silicon substrate with an isolated microcavity. Also he has studied wettability characters affecting on the nucleate boiling performance.

His results shows that the bubble departure diameter is observed to approximately 2.5 times smaller and the growth period almost four times shorter on the superhydrophillic surface than on the silicon surface. At higher superheat levels successive bubbles merge with each other before they depart from the surface. Also they stated that when bubble grows force of buoyancy having upward direction and surface tension having downward direction.

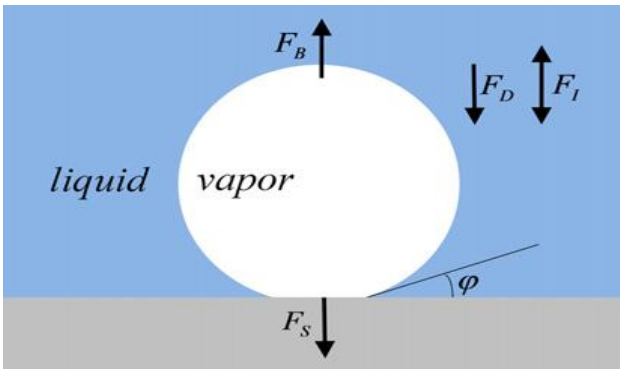

Figure 5 Schematic representation of forces acting on growing bubble on the wall

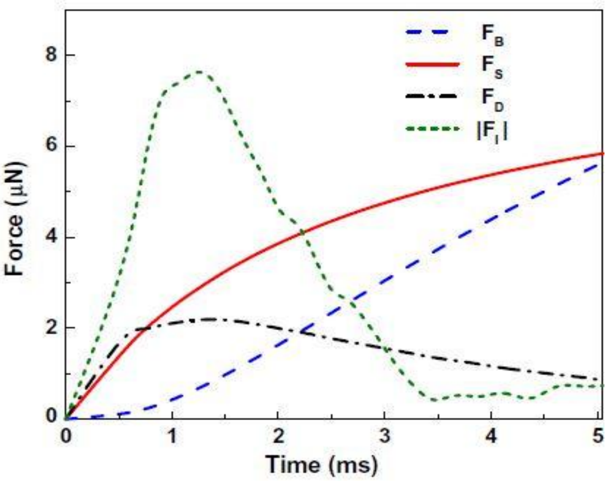

Fig. 6. Time evolution of forces acting on a simulated bubble in water during on

2. Active Nucleation Sites and Bubble Departure Diameter

Any commercial surface contains number of cracks, crevices at microscale level. These can be observed under high magnification ranges. Whenever liquid is pored over the surface some gases e.g., air are trapped in cavities these are called as nucleation sites.

The particular nucleation site activates at a particular temperature. i.e., all nucleation sites are not active at a time together. The number of nucleation sites increase as the heater surface temperature increases.

Bubble departure diameter is the diameter of the bubble at the time of detachment of vapour bubble from the heater surface after complete growth. It is the one of the important parameter which affects the heat transfer performance in pool boiling. As the bubble departure diameter increases the heat transfer rate decreases considerably. This is because as the bubble departure diameter increases it occupies more space over the heater surface and therefore there is very less contact of the liquid and heating surface. However as the bubble departure diameter decreases there is more contact of the liquid and the heater surface. As the bubble detaches from the surface liquid comes in contact of the heating element and therefore there is increase in the heat transfer.

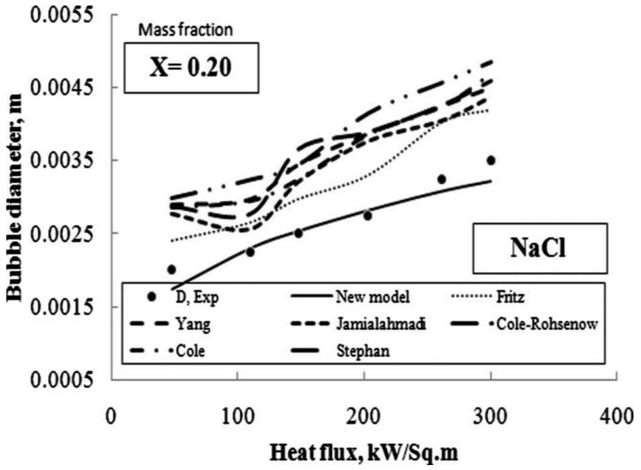

Fig.7 comparison of bubble diameter vs heat flux among existing models & experimental data

Seyed Ali Alavi Fazel [3] have presented the new experimental data for bubble departure diameter for various electrolyte aqueous solutions over a wide range of heat fluxes and concentrations. His results shows that bubble diameter increases either by increasing heat flux at any constant concentration or by increasing concentration at any constant heat flux.

Increasing electrolytic concentration could increase the bubble departure diameter and decrease the active nucleate site density.

Xiadan chen et.al [4] have studied the enhancement of heat transfer on thee hydrophilic-hydrophobic patterned surfaces in transparent mini chamber. Hydrophobic islands on hydrophilic networks were micro fabricated on $1mm^2$ indium tin oxide glass heater and hydrophobic islands were self-assembled monolayers (SAM). The results showed that CHF on wettability patterned surface was enhanced by 90° in comparison with a hydrophilic surface. Visualization results shows that heat transfer enhancement is due to increasing the active nucleation sites, decreasing the bubble departure diameter and activating more bubble interaction. These pattern increases the CHF by preventing formation of an insulating vapour layer.

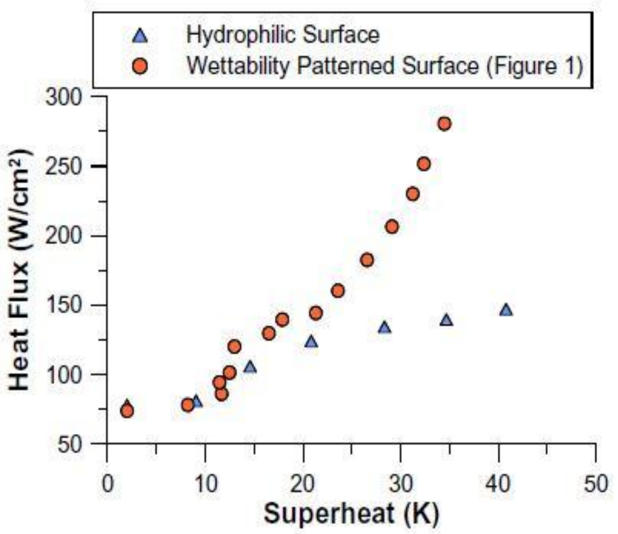

Fig. 8. Pool boiling curve with heat flux as a function of superheat on different heater surface.

3. Bubble Releasing Frequency and Heat Flux Removal Rate

Whenever the bubble leaves the heater surface the bulk fluid takes the space of the bubble. The heat is transferred from heater surface to the liquid and further phase change occurs and liquid gets transformed into vapor bubble. This vapor bubble contains lot of heat and which can be transferred to the liquid while upside movement of the bubble. Means that for better heat transfer the bubble should be fastly released detached from the heater surface and for that the frequency of bubble should be as high as possible. Hence it important to study the parameters which can increase the frequency and heat flux removal rate.

Seol Ha Kim et al. [5] have studied a heat flux partitioning analysis of nucleate pool boiling on micro structured surface through infrared visualization technique. In his studied he directly measured the parameters: bubble releasing frequency, bubble departure size, bubble growth time and nucleation site density through the infrared visualization technique, a nucleate boiling heat flux portioning analysis on pool boiling has been carried out. His experimental results indicate that sum of the three partitions of heat flux from the measured boiling parameters shows good agreement with the experimentally given total heat flux.

Attila markus et al. [6] have experimentally studied nucleate pool boiling at microscale level in two dimensions focusing on the influence of the cavity size and density on the growth and detachment of a single bubble. Also the interactions of the bubbles detaching from the two neighboring nucleation sites.

His results showed that bubble departure diameter is the function of cavity size and the constant heat flux. It is depend upon width of the cavity and weakly on the depth of the cavity. Also bubble departure diameter is the function of the cavity density.

Release period is the function of cavity size and cavity density. Release period increases as the width of the cavity increases. Also the release period decreases as the distance between the cavities decreases.

Xiangdong Li et al. [7]

His study reveals the effects of the nanoparticles deposition on the bubble behavior during the pool boiling. There is significant change in properties and microstructure of heater surface due to the deposition of nanoparticles, and hence alteration in the characteristics of bubble nucleation and departure of bubbles. Therefore he have used heat flux partitioning mode. In his study, new closure correlations were incorporated for the nucleate pool boiling parameters including the active site density the bubble departure diameter and frequency. His results demonstrated that HFP model achieved as satisfactory agreement with the experimental data available in the literature, and provided more feasible and mechanistic approach than the classic Rohsenow correlation for predicting nucleate pool boiling.

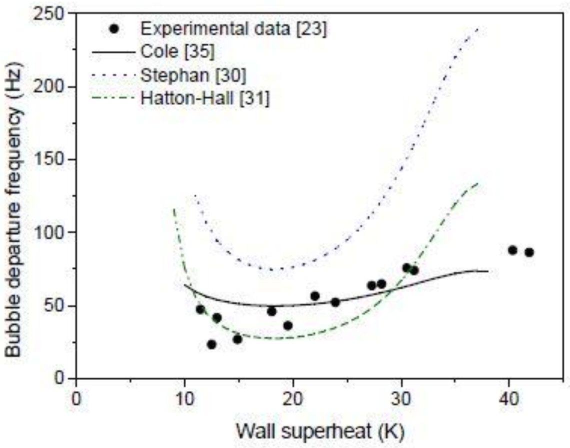

Fig. Comparison of bubble departure correlations against experimental data

Sina Shoghal et al. [8] have experimentally studied the comparison of boiling performance of nanofluids and mixtures of nanofluids with surfactants. They have investigated with different heat flux and concentrations of nanoparticles and surfactants. Thee nanofluids used are CuO and ZnO as waters based nanofluids and surfactants as SDS (Sodium Dodecyl Sulphate). His results showed that the addition of surfactant to nanofluid solution resulted in improvement of boiling performance. Also diameter of bubble gets decreased while no. of nucleation sites and frequency also increased by addition of SDS. The results also showed that frequency and nucleation sites increases with roughness.

Anil Acharya et al. [9]

They have reviewed the heat transfer enhancement in boiling under different conditions and configurations having different results. His study is useful to understand the effect of environment friendly surfactants. He have given different tables and tree diagrams showing boiling behavior and different affecting parameters on it. Also he reveals the experimental studies of pool boiling enhancement by additives.

Luke et al. [10] have focused his study on the activation of the bubbles and heater surface and cavities. For his study he used the high speed camera. But they have used some semi-automatic and automatic programs developed to track and observe the individual bubbles. His results shows that sliding of the bubbles upside the superheated tube surface grow at a similar rate as those staying on their nucleation site.

Hubner and Kunstler et al. [11] have investigated heat transfer in pool boiling from finned tubes with various shapes of the fins (T-shaped, Trapezoidal shaped, Y-shaped) to different hydrocarbons and partly fluorinated hydrocarbons. Whenever compared to corresponding measurements on plain tube, the heat transfer on traditionally finned tubes with trapezoid shaped fins is considerably improved and even better results are achieved with T-shaped and Y-shaped fins. Also the influences of microstructures (surface roughness) or macrostructures (fin geometry) on the heat transfer coefficient have been studied separately, in order to evaluate the enhancement of heat transfer by either influence.

Wen and wang et al. [12] carried out experiments for pool boiling of deionized water and acetone with different surfactants namely 95% sodium dodecyl sulfate (SDS), Triton S-100 and octadecylamine. They conducted these tests under atmospheric pressure to investigate the effect of surface wettability. They obtained boiling curves for different concentrations of surfactant solution on both smooth and roughened surfaces. This study shows that wettability is an important parameter in surfactant boiling and should be taken into consideration.

CONCLUSIONS

1. Addition of surfactant reduces the surface tension which is major cause of improvement of boiling performance.

2. Surface tension reduces negligible by nanoparticles but surface tension reduces considerably by addition of surfactant. i.e.

addition of surfactant to the nanofluid is beneficial for improving the boiling performance.

3. Interfacial, viscous and buoyancy forces are the major contributing parameters affecting on bubble behavior in pool boiling.

4. Bubble departure diameter and growth period both decreases by preparation of superhydrophillic surfaces.

5. Bubble departure diameter and release period both depend strongly on the width and weakly on depth of cavity. Increasing width of the cavity, both the bubble departure diameter and release period increase.

6. Surface roughness and wettability are major affecting parameters on bubble behavior in nucleate pool boiling.

7. Bubble formation in surfactant solutions are much smaller than the water and they covers the surface faster. The nucleation sites are activated faster due to the surfactant solutions for enhancement of heat transfer.

Hence further effort should be to investigate different parameters affecting on bubble behavior in pool boiling. Also further effort should be taken to find out better method to enhance the heat transfer rate in pool boiling. Based on this literature review new experimental setup for single bubble dynamics can be suggested which can be used for bubble braking to improve heat transfer.

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