Effect on bubble dynamics during pool boiling heat transfer in a novel aqueous binary mixture of surfactants

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Abstract Temperature near the heating region changes with the water boiling curve when the heat flux applied. In this study, experiments were carried out by maintaining a cylindrical subcutaneous hypodermic needle as a single active nucleation site. By controlling heat supplied to the site, a single bubble was formed in the saturated water. The boiling phenomenon was recorded. The surfactants used were sodium dodecyl sulfate (SDS) and centrimonium bromide (CTAB). Aqueous binary mixture SDS-CTAB was prepared on a volume percent basis. The effect was measured by studying a single bubble. The vapor bubble resulting from the nucleation site was observed. Bubble parameters, without and with a surfactant, were plotted in two heat fluxes concerning the excess temperature. It is found that, compared with saturated water, the average measurements of bubble detachment diameters and terminal velocities decreased, but the bubble departure frequency increased. On the other side of analysis, with increasing excess needle temperature of site, at 601 kW/m², the detachment diameter decreased, departure frequency increased, rising velocity was increased and at 950 kW/m², the detachment diameter increased, departure frequency increased, rising velocity decreased.

1. Introduction

Nuclear boiling heat transfer transfers a huge amount of heat, utilized in many applications such as rocket engines, boilers, and nuclear reactors. Single bubble formation is very important as it generates the slag and column for boiling enhancement. Therefore, to understand nuclear boiling, it is crucial to understand the dynamics of an isolated bubble.

Estimation of nucleate boiling parameters can be interpreted by the study of the single bubble dynamics by preparing artificial nucleation sites of different shapes. Shoji & Takagi [1] carried boiling experiments and produced an artificial cavity of three different shapes. Cylindrical cavities show continuous foaming from low heated wall temperatures. Cylindrical nucleation sites showed anticipated behaviour compared with concave and conical cavities. Qiu [2] formed cavities in polished wafers of silicon and found large forces of the surface tension and buoyancy. Lee [3] investigated uniform heat flux boundary conditions applied for forced convection boiling. Departure frequency increased, divergence size of the bubbles was nonaligned with the rising temperature of the wall. Siedel [4] investigated a single nucleation site, detachment diameter of bubble found nonaligned with the wall temperature. The frequency detachment of the bubble was proportional to the wall
temperature. Robinson and Judd [5] studied intercommunication of vapor-liquid for a bubble, suggested that initial bubble development is managed by the inside bubble surface tension.

1.1. Review on boiling including surfactant

Acceleration of studies on boiling with a surfactant solution began several years ago. Yang [6] suggested twelve measures in boiling acceleration with three surfactants. Gajghate [7] examined that the ultimate heat transfer level in water-based ammonium chloride at 2600 ppm concentration. King [8] investigated the reflex of surfactants on the development and detachment of the bubble, added surfactant lowered the detachment diameter of the bubble. Najim [9] calculated the dynamics of the bubble linked with changes in the nucleation sites diameter [10]. Also observed that the increase in the frequency of detachment at higher heat flux is greater than that in the lower heat flux [13]. Pawar [11], [12] and [25] conducted unsteady boiling experiments and used ammonium chloride as a surfactant to investigate the effect of the excess needle temperature, suggested that the detachment diameter was nonaligned with increasing excess needle temperature and departure frequency found increased in an aqueous surfactant solution. Acharya [17] studied a single bubble as an interest of the region. Hoang [15] investigated a model for the evaluation of the departure bubble diameter. Researchers [20] and [21] studied on natural heating surfaces, whereas [4,11,17,18] studied artificial heating surfaces. When compared to natural sites with the artificial, different behaviour for the detachment diameter of the bubble was observed. Their contradictions are tabulated in Table 1.

| Type of nucleation site | Author       | Detachment diameter | Departure frequency |
|-------------------------|--------------|---------------------|---------------------|
| Natural                 | [4] Siedel   | Increasing          |                     |
|                         | [18] Hutter  |                     | Increasing          |
|                         | [19] Gorenflo|                     | Decreasing          |
| Artificial              | [13] A. Najim|                     | Increasing          |
|                         | [20] Kutateladze|                   | Decreasing          |
|                         | [21] Cole    |                     | Independent         |
|                         | [25] Pawar   | Increasing at 601 kJ/m² | Decreasing at 950 kJ/m² | Increasing |

Table 1. shows that a minimum of two values of heat flux should be applied to heating surfaces during pool boiling. The experiment would be carried with the increase in the wall temperature in the heat flux. The bubble detachment diameter, the departure frequency, and the rising velocity were plotted. Bubble criterion measured in the solution with surfactant were correlated with those with the water. The effect of the addition of surfactants in water and the effect of heat flux are discussed.

2. Experimental Measurement

2.1. Experimental set-up

As shown in figure 1, a glass beaker of borosilicate material filled with 1800 ml of saturated water followed by an aqueous binary mixture of surfactant solution was used. A needle of DISPO VAN®, which acts as a bubble generation site, acts as the heat input surface. The needle of inner diameter 514 μm and length of 25 mm was placed perpendicular to the ground at the bottom of the middle of glass
containers. The needle top was cut precisely to allow flow through the needle and the bottom was closed to prevent flow it.

2.2. *The surface tension of aqueous binary mixture of surfactant solution*

The surface tension of aqueous binary systems was measured minimum five times and final average values were recorded. The percentage of the amount of primary SDS surfactant and the percentage of the amount of corresponding secondary CTAB surfactant in the same aqueous binary system shows the variation in surface tension. The surface tension of anionic-catanionic binary mixture of 25: 75 vol % SDS - CTAB was found least, those of 50: 50 vol % and 75: 25 vol % combinations of volume fractions were higher. Measurement shows per results of Ravikumar [26].

![Figure 1. Schematic diagram of the experimental set-up](image1)

![Figure 2. Procedure for Detachment diameter measurement using a high-speed camera](image2)

2.3. *Experimental procedure*

In the present study, a wide range of pool boiling experiments was carried out. A binary mixture of anionic - catanionic SDS-CTAB of 25: 75 vol % is used as a surfactant additive [26]. From the experimental measurement obtained, which are plotted for the bubble parameters versus excess needle temperature. The bubble generation has seen and accessed by a PCO AG 200 camera at 100 fps.

2.4. *Measurement of bubble parameters and Uncertainty of the measurements*

![Figure 3. Departure frequency measurement](image3)

![Figure 4. Rising velocity measurement](image4)
Bubble parameters were evaluated using ImageJ software. As shown in figure 2, a number of pixels on the bubble image counted and dimensions were measured. The detachment diameter of the bubble was measured at the center of gravity, which located about 75% height from the bottom point [15]. The bubble shape found balloon-shaped before departure.

Voltmeters, ammeters, camera, temperature indicators with least counts of 1 V, 1/100 amps, 0.01 sec, 1/100 °C. respectively. The maximum uncertainty of the heat flux was less than 0.02. The detachment diameter uncertainty measurement is ± 125 μm. The uncertainty in departure frequency is ±1/100 Hz. Boiling phenomena is very important for repeatability, to ensure it, all measurements were repeated at weekly intervals with these solutions. The data found within the aforementioned measurement tolerance and in good agreement.

The time marking function displayed at the top of the screen to determine the departure frequency, as shown in figure 3. The height traveled by the bubble is the average of the distances traveled until the next bubble seen, as shown in figure 4.

3. Results and Discussions

3.1. Detachment diameter (Dₙ)

The detachment diameter of the bubbles varies as tabulated in Table 2. The addition of a binary mixture of a surfactant solution reduces the downward force acting on the bubbles. Bubbles separate in smaller volumes than in saturated water, increasing the area of contact between the heated bubbles and saturated water, finally increasing the heat transfer rate from the needle to the water. The detachment diameter from the needle is reduced by 25% to 33% with the addition of surfactants and is shown in figure 5.

| Table 2. Experimental Results |
|--------------------------------|
|                                | 601 kW/m² | 950 kW/m² |
|                                | Water     | Binary mixture | Water     | Binary mixture |
| Dₙ, mm                         | 3.42±0.125 | 2.53±0.125 | 3.41±0.125 | 2.34±0.125 |
| f, Hz                          | 2.14±0.01  | 3.58±0.01  | 2.03±0.01  | 4.49±0.01  |
| Vₙ, m/s                        | 0.51±0.125 | 0.43±0.125 | 0.51±0.125 | 0.44±0.125 |

As the excess needle temperature increased, the detachment diameter decreased to 601 kW/m². The detachment diameter decreases due to excessive wall overheating [19], [20]. The detachment diameter increased at 950 kW/m² [18], [21] due to the capillary effect, which has been found to dominate the surfactant effect at higher heat fluxes [16]. It has been found a nearly constant behaviour of the detachment diameter at these conditions. The microlayer between the bubble and the heating surface is escaped not because of its vaporization but because of the capillary effect.

3.2. Bubble departure frequency (f)

The bubble departure frequency from the wall varies as tabulated in Table 2. This explains that the addition of a binary mixture of surfactant solutions increases the departure frequency considerably. The bubble departure frequency increases by 139% to 142% for heat fluxes of 601 kW/m² and 950 kW/m², when compared to saturated water.

The addition of the surfactant lowers the surface tension. Thus, the surface tension in the bubble also lowered. As the heat flux is uniform, vapor nucleation at this heat flux is uniform for both water and the surfactant solution. This lowered the downward surface tension force and the detachment diameter and increases the departure frequency.

Figure 6. shows that departure frequency is independent at higher heat flux. Siedel [4] previously concluded relation that parameter (Dₙ*f) is proportional to excel needle temperature. Here, it was seen
improving from 15°C to 22°C, $D_b$ found lowered at lower heat flux with excess needle temperature, positive value of the gradient of departure frequency is found higher as compared to that at lower heat flux. Also, $D_b$ found improved at higher heat flux, gradient of departure frequency at low heat flux is found less than higher heat flux. Finally, measurements of departure frequency were found by earlier observations by [14, 13,25].

![Graph 1](image1)

**Figure 5.** Detachment diameter vs excess needle temperature

![Graph 2](image2)

**Figure 6.** Departure frequency vs excess needle temperature

3.3. Rising velocity of bubbles ($V_b$)

The rising velocity of air bubbles changes is tabulated in table 2. This interprets that the binary mixture of surfactants solution reduces the rising velocity of the bubbles, which reduces 15% to 12% for heat fluxes of 601 kW/m² and 950 kW/m² as shown in figure 7. The addition of a binary mixture of surfactant solution reduces the detachment diameter, and the detached bubbles become less buoyant and take extra time to reach the liquid surface [7].

![Graph 3](image3)

**Figure 7.** Rising velocity vs excess needle temperature

It can be seen that the average rising velocity is nearly constant for water and surfactant solutions. $D_b$ is found to be nearly constant [23, 24]. Therefore Mchale relationship between $V_b$ and $D_b$, $V_b \alpha D_b^{1/2}$ is satisfied [14].
4. Conclusion
The addition of the surfactant lowered the detachment diameter by up to 33%, the departure frequency by up to 142% and the rising velocity by up to 12%.

Different behaviour was observed at the two heat fluxes, revealed some contradiction with the previous results. At 601 kW/m², the detachment diameter decreased (slope= -0.01), the departure frequency improved (slope = 0.27), and the rising velocity was increases (slope= 0.003) with addition of surfactant. At 950 kW/m², the detachment diameter increased (slope= 0.007), the departure frequency improved (slope = 0.08), and the rising velocity was nearly uniform (slope= 0.0006).

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