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"Review of Enhancement of Boiling Heat Transfer Rate by Addition of Surfactants"

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***Abstract*— The addition of additives to water is known to enhance boiling heat transfer. In the present investigation, boiling heat transfer coefficients are measured for Nichrome wire, immersed in saturated water with different surfactants. Experiments are carried out for nucleate boiling of over wide ranges of concentration and heat flux. Results are encouraging and show that a small amount of surface active additive makes the nucleate boiling heat transfer coefficient considerably higher, and that there is an optimum additive concentration for higher heat fluxes. Betel Nut enhancement of heat takes place at low excess temperature. Additive promotes activation of nucleation sites; the bubbles appeared in a cluster mode; the life-time of each bubble in the cluster is shorter than that of a single water bubble.**

The diameter of water bubble increases with increasing heat flux, whereas analysis of bubble growth in surfactant solution reveals the opposite effect: the detachment diameter of the bubble decreases with increasing heat flux. The kinetics of boiling (bubble nucleation, growth and departure) is investigated by high-speed video recording. Boiling curves for various concentrations show that the bubble behavior and the heat transfer mechanism for the surfactant solution are quite different from those of pure water.

***Index Terms*— Thermal Conductivity, Analysis, Simulation.**

I. INTRODUCTION

Boiling is a very effective and efficient mode of heat transfer, which is encountered in numerous engineering applications. Important field of application of boiling and evaporation are in desalination of seawater, in distillation process, in chemical industries & in refrigeration system which is becoming essential in some arid regions. Boiling with surfactant additives is generally an exceedingly complex process, and it is influenced by a larger set of variables than the phase-change process of pure water. Besides the wall heat flux (or wall excess temperature), heating surface geometry and bulk concentration of additives, the boiling behavior is also dependent upon interfacial properties, the nature of the additive, its chemistry, foaming etc. There has been extensive research and development in enhanced boiling heat transfer. Among the different enhancement techniques investigated, the use of surfactant additives in water has been found to change boiling phenomenon drastically. It is important to understand the effects of surfactants on boiling heat transfer and bubble dynamics. Surfactants are essentially low-molecular weight chemical compounds, with molecules that consist of a water-soluble (hydrophilic) and a water insoluble (hydrophobic) part. Depending upon the nature of the hydrophilic head group, surfactants are primarily classified as anionic, non-ionic, and cationic. Depending on the ionic character of the surfactant, the molecular weights and surface tension depression in aqueous solutions are generally greater in the order of non-ionic > anionic > cationic. Small concentrations of surfactant in water lower the solutions surface tension considerable, and the level of reduction depends on the amount and type of surfactant present in solution. In general, with increasing additive concentration the surface tension σ decreases appreciably. With increasing concentration, an asymptotic limit of σ is obtained at the critical micelle concentration (cmc) of surfactant, which is characterized by the formation of colloid-sized clusters or aggregates of monomers called micelles. The cmc is a direct measure of the effectiveness of a surfactant to reduce the solvent's surface tension, and it depends upon the surfactant's chemistry and ionic structure [1]. The surface tension of aqueous surfactant solutions has also been found to be temperature dependent. Elevated temperatures cause a decrease in surface tension.

The study of the saturated pool boiling of a surfactant solution shows a significant enhancement of heat transfer [29]. Pool boiling experiments can be carried out for a wide range of surfactant concentrations and heat fluxes. The results verify again that a small amount of surface-active additive makes the nucleate boiling heat transfer coefficient considerably higher. It was also found, that for some additives, the heat transfer increases at low concentration of surfactant, reaches a maximum and decreases with further increase in the concentration. Experimental data reported on the effect of surfactants on nucleate boiling heat transfer in water with nine different additives. Anionic, cationic, and non-ionic surfactants were studied at concentration up to 400 ppm [34]. The enhancement of heat transfer was related to the depression of the static surface tension. Boiling heat transfer coefficients were measured for an electrically heated platinum wire immersed in saturated water, and in water mixed with three different concentrations of sodium dodecyl sulphate (an anionic surfactant). Their results showed that addition of an anionic surfactant to water caused an increase in the convection component and a corresponding reduction in the latent heat component of the heat flux in the fully developed boiling region. The comprehensive reviews on the heat transfer in nucleate pool boiling of aqueous surfactants and polymeric solutions have been published. Experimental studied on nucleate pool boiling with Habon G surfactant additive. They obtained the boiling curves for various surfactant concentrations. Some of those boiling curves exhibit non-monotonous (S-shaped) behaviour with respect to wall superheat. They also found an optimum additive concentration to increase the heat fluxes, which was associated with the critical micelle concentration (cmc.). It was shown that surfactant additives at low concentrations could enhance the nucleate boiling heat transfer significantly.

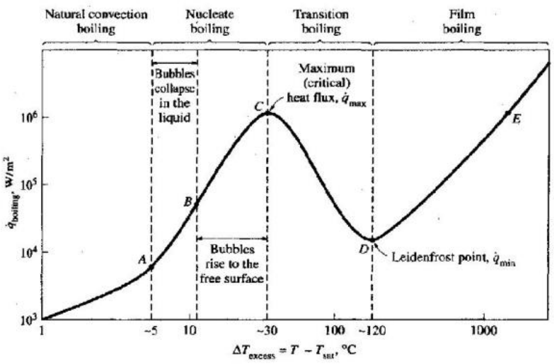

Fig. Typical boiling curve for water at 1 atmospheric pressure

After the extensive literature reviewed some of the questions are unattempted, like selection of the additive and its optimum quantity, whether surfactant mixes in solution or not. The mechanism of enhancement is not yet properly understood, but it is clearly understood that reduction in surface tension changes the boiling behaviour. Keeping this literature in view & energy crisis problems one can study to work on this “studies of effect of surfactants on CHF in pool boiling.” The main objective of the present investigation is to study the boiling heat transfer and bubble dynamics in the non-ionic & anionic surfactant solution at various concentrations of surfactant and different heat fluxes. A comparison of the results of this study with the ones reported for cationic and anionic surfactants provides information on the influence of an ionic nature of aqueous surfactant solutions on the pool boiling. Powdered Betel nut served as test surfactant and added in water with varying concentration in search to find optimum quantity [10]. The overall aim of this work is to understand the phenomenon of nucleate pool boiling of water with and without surfactants, as it is very complex in nature.

Objectives

The main objective of the present investigation is to study the boiling heat transfer and bubble dynamics in the anionic surfactant solution with negligible environmental impact at various concentrations of surfactant and different heat fluxes. A comparison of the results of this study with the ones reported for cationic and anionic surfactants provides information on the influence of an anionic nature of aqueous surfactant solutions on the pool boiling.

II. *LITERATURE SURVEY*

Pioro et al. [1] assessed the state-of-the-art of heat transfer in nucleate pool-boiling. They reviewed and examined the eff ects of major boiling surface parameters affecting nucleate-boiling heat transfer and examine the existing prediction methods to calculate the nucleate pool-boiling heat transfer coefficient (HTC). They pointed out that the major parameters affecting the HTC under nucleate pool-boiling conditions are heat flux, saturation pressure, and thermo-physical properties of a working fluid.

Bergles [2] reviewed many techniques that have been developed to enhance heat transfer in pool boiling. The passive technique does not require direct application of external power whereas the active technique requires an external activator / power supply to bring about the enhancement. Two or more of the above technique may be utilised simultaneously to produce an enhancement that is larger than the techniques operating separately. This is termed as compound enhancement.

Kim [3] reviewed nucleate pool boiling bubble heat transfer mechanisms. It includes enhanced convection, transient conduction, microlayer evaporation and contact line heat transfer. He also reviewed recent experimental, analytical, and numerical work into single bubble heat transfer to determine the contribution of each of the above mechanisms to the overall heat transfer. Transient conduction and micro-convection are found to be the dominant heat transfer mechanisms. Heat transfer through the microlayer and at the three-phase contact line does not contribute more than about 25% of the overall heat transfer.

Zuber [5] studied hydrodynamic aspects of boiling heat transfer. He concluded that, as wall superheat increases, superheated thermal boundary layer becomes thicker which results in increased departure diameters.

Mimik et al. [9] derived simple general relation for bubble growth rates in a uniformly superheated liquid under non-uniform temperature field around the bubble. The relation is valid in both regions: inertia controlled and heat diffusion controlled growth, respectively. The derived relation is compared with the existing experimental results for bubble growth in a uniformly superheated liquid with very good agreement. The results give an asymptotic growth rate of approximately.

Shoji & Takagi [11] studied bubbling features from a single artificial cavity. A single artificial cavity was manufactured on a thin Cu plate and was heated by a laser in a saturated water pool. Conical, cylindrical and re-entrant cavities were tested. Range of cavity depth is 30μm- 50μm. Range of cavity diameter is 50μm-100 μm. Conical cavities shows highly intermittent bubbling with large temperature fluctuations, requiring high superheat. Cylindrical cavities show continuous bubbling from low superheat with small temperature fluctuations. Re-entrant cavities show similar but slightly more complicated behavior than those cylindrical cavities.

Tiwari et al. [12] estimated the convective heat and mass transfer for pool boiling of sugarcane juice during preparation of jaggery. An indoor experiment was conducted to measure (i) the mass of evaporated water, (ii) the temperature of the sugarcane juice, (iii) the relative humidity above the sugarcane juice surface and (iv) The temperatures at the bottom and side of the pot etc. at intervals of 10 min for a given heat input. A regression analysis has been performed by using the experimental data in the correlation of Rohsenow for pool boiling. The results of the heat and mass transfer analysis predict that the boiling heat transfer rate per unit surface area ranges from 526 to 3452 W/m at a temperature of 10 0C above the saturation and the heat transfer coefficient varies from 50.65 to 345.20 W/m2 oC for heat input ranging from 160 to 340 W.

Abarjith et al. [13] studied experimentally and numerically, the growth and detachment of a single bubble on a heated surface during parabola flights of the KC-135 aircraft. An artificial cylindrical cavity was etched in the centre of a silicon wafer and it is heated on the back side under controlled superheat. It is observed that the bubble diameters and bubble growth periods are increased in reduced gravity condition. Small sub-cooling in the liquid caused significantly prolonged bubble growth periods and reduced bubble growth rates

Bothe et al. [14] simulated mass transfer from single bubbles and bubble chains rising in aqueous solutions using Volume of Fluid Method for two phase flow with high density ratio. They have taken account of mass transfer of a soluble component and its interfacial mass transfer. The Mathematical model and the numerical method allow for different solubility of the species in the respective fluid phases while volume changes due to mass transfer are neglected.

Li & Peterson [15] studied micro scale heterogeneous boiling on smooth surface from bubble nucleation to bubble dynamics. Boiling incipience and bubble dynamics are also studied on a carefully selected micro heater with a fabricated defect (i.e., a micro-cavity on the heater surface). Of industrial interest are the eff ects of dissolved gases on boiling incipience and bubble dynamics, which are also discussed in detail. Based upon this investigation, it is clear that explosive boiling can take place on a smooth surface no matter how slow the heating rate, and dissolved gases have a significant influence on the incipience temperature and bubble behaviour.

Chen and Groll [16] investigated numerically dynamics and shape of bubbles on heating surfaces. They solved the Young-Laplace Equation including a dynamic pressure. The results show that, (1) a growing bubble undergoes a series of shape changes, viz. spherical, hemispherical, oblate and elongated bubbles, until the detachment stops this evolution; (2) the dynamic force greatly influences the bubble shape even for a seemingly spherical bubble (except for micro spherical bubble); (3) a pattern (shape) map of bubbles can be developed by relating the aspect ratio to the ratio of dynamic and buoyancy forces; (4) for elongated bubbles, the point where the dynamic force changes from positive to negative can serve as a criterion for bubble departure; (5) the assumption of spherical bubbles or bubble segments could lead to big errors in force evaluations in engineering practice, especially for the liquid inertia force.

Mukharjee and Kandlikar [17] studied numerically, the single bubble with dynamics contact angle during nucleate pool boiling. They have been experimentally observed that the contact angle at the bubble base varies during the ebullition cycle. In the present numerical study, a static contact angle model and dynamic contact angle models based on the contact line velocity and the sign of the contact line velocity have been used at the base of a vapor bubble growing on a heated wall. The complete Navier–Stokes equations are solved and the liquid– vapor interface is captured using the level-set technique. The effect of dynamic contact angle on bubble dynamics and vapor volume growth rate is compared with results obtained with the static contact angle model.

Kenning et al. [18] studied experimentally and numerically the Confined growth of a vapour bubble in a capillary tube at initially uniform superheat. The diameter of capillary tube is 800 μm and depth is 120mm. Bubble growth was triggered in a capillary tube closed at one end and vented to the atmosphere at the other and initially filled with uniformly superheated water. They observed that, the growth of a bubble created a pressure pulse that reached a maximum value and then gradually declined as the bubble approached the end of the tube. The decrease in superheat available to drive bubble growth was a large fraction of the initial superheat.

Luo et al. [19] did numerical modelling for Multiphase Incompressible Flow with phase change. A general formula for the second-order projection method combined with the level set method is developed to simulate unsteady, incompressible multifluid flow with phase change. A subcell conception is introduced in a modified mass transfer model to accurately calculate the mass transfer across the interface. The third-order essentially non-oscillatory (ENO) scheme and second-order semi-implicit Crank-Nicholson scheme is employed to update the convective and diffusion terms, respectively. The projection method has second-order temporal accuracy for variable-density unsteady incompressible flows as well. The level set approach is employed to implicitly capture the interface for multiphase flows. A continuum surface force (CSF) tension model is used in the present cases. Phase change and dynamics associated with single bubble and multi-bubbles in two and three dimensions during nucleate boiling are studied numerically via the present modelling. The numerical results show that this method can handle complex deformation of the interface and account for the effect of liquid–vapor phase change.

Dhir et al. [20] studied bubble dynamics and heat transfer during pool boiling and flow boiling diameter. In this paper, the results of an alternate approach based on a complete numerical simulation of the process are given. Single and multiple bubbles are considered for both pool and flow boiling. The simulations are based on the solution of the conservation equations of mass, momentum, and energy for both phases. Interface shape is captured through a level set function. A comparison of bubble shape during evolution, bubble diameter at departure, and bubble growth period is made with data from well-controlled experiments. Among other variables, the effect of magnitude of gravity and contact angle is explicitly investigated. They identified that the merger process is highly non-linear. A lift force is leading to the premature departure of bubbles from the heating surface. The pressure difference across the bubble lifts the bubble off from the surface for the vertical up flow boiling process.

Siedel et al. [21] investigated experimentally the bubble growth, departure and interactions during pool boiling on artificial nucleation sites. They used conical shaped cavities as artificial nucleation sites to study interactions between cavities. Bubble growth is studied under various wall superheat conditions. The diameter of cavity is 180 µm and depth is 500 µm. Bubble growth appears very reproducible, the volumes at detachment being independent of the wall superheat, whereas the growth time is dependent on the superheat. Oscillations were observed during growth, showing the interaction of one bubble with the preceding bubble released from the same nucleation site.

Kunkelmann and Stephan [22] did CFD simulation of boiling flows using the Volume-of-Fluid method within Open FOAM which is open source software. He put emphasis on implementation of the contact line evaporation, which can typically not be resolved by the numerical grid, and on the conjugate heat transfer between solid and fluid. The results showed good agreement with analytical solutions.

Wu and Dhir [23] investigated dynamics and heat transfer associated with a single bubble in sub cooled Pool boiling. The applied numerical procedure coupling level set function with moving mesh method has been validated by comparing the results of bubble growth history including bubbled departure diameter with data from experiment. The prediction of bubble dynamics and heat transfer for various sub-cooling's as well as different levels are presented.

Nam et al. [24] studied experimentally, the single bubble dynamics on a superhydrophillic surface with artificial nucleation sites. The superhydrophillic surfaces are prepared by forming CuO nanostructures on a silicon substrate with an isolated micro-cavity. The bubble departure diameter in water is observed to be 2.5 times smaller and the growth period 4 times shorter on the superhydrophillic surface than on a silicon substrate. He performed the calculation for forces acting on the single bubble.

Lee et al. [25] studied experimentally Height effect on nucleation-site activity and size-dependent bubble dynamics in micro-channel convective boiling. Nucleation sites were shaped as an inverted pyramid with a square base. Bubble nucleation activity is found to depend on the channel height. The variation height is 5 µm - 500 µm. The critical size, above which nucleation sites are active, increases with the channel height. Hence, smaller nucleation sites are active in smaller height micro-channels. The bubbles, practically two-dimensional, assume a balloon-like shape elongated in the stream wise direction. The bubbles grow in volume essentially at a constant rate, which increases with increasing input power. The bubble departure size, independent of the input power, decreases exponentially with increasing Reynolds number (flow rate).

Lesage [26] analysed quasi-static bubble size and shape characteristics at detachment, experimentally and numerically. He uses four needles of diameter 0.394mm, 0.543mm, 0.838mm and 1.185 mm with depths 77.96mm, 42mm, 64.24mm & 62mm respectively. It shows that bubble detachment shape and normalize size characteristics are dependent on the Bond number with characteristics length equal to cavity radius. This effectively means that two sets of different working conditions- such as fluid characteristics, gravitational field strength and cavity size yielding the same bond number will generate detachment bubbles of the same shape yet of different size.

III. *Experimental procedure*

1. Fill Stalagmometer up to the top mark with DM water. Release water to the weighing bottle and count how many drops it takes to decrease the water level in Stalagmometer down to water mark. Write number of drops
2. Empty and dry the weighing bottle and Stalagmometer and prepare them for next measurement.
3. Repeat the step 1 and step 2 for liquid with unknown surface tension.

IV. *Experimental set up*

The apparatus for experimental studies on pool boiling is shown in Figure 4.1. It consists of cylindrical glass container housing, the test heater and the heating coil for the initial heating of the water. The heater coil is directly connected to the mains and the test heater is connected also to mains via a dimmerstat. An ammeter is connected in series while the voltmeter across it to read the current and voltage. Voltage selector switch is used to select the voltage range. These controls are placed inside the control panel. K-type thermocouple is used to measure the temperature of Nichrome wire which connected to Digital temperature indictor.

To study the kinetics of vapour bubble in pool boiling phenomena for pure water with and without surfactant a camera is fixed near to apparatus in such a way that boiling phenomenon can be recorded by camera to make observations in terms of bubble nucleation, growth and its departure. Electronic balance was used for the measurement of the mass of surfactants has least count of 1mg.

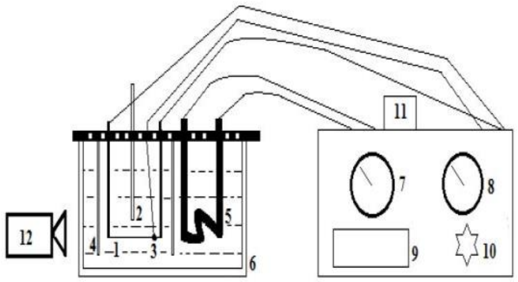

Figure 4.1 Schematic Figure of Experimental Setup

1. Nichrome wire 2.Thermometer 3.Thermocouple 4.Acrylic fence 5.Auxiliary heater 6.Glass vessel 7.Voltmeter 8.Ammeter 9.Digital temperature indicator 10.Dimmerstat 11.Power supply switch 12.Camera

V. *Test procedure*

The glass container was filled with 2 litres of pure water and it kept on a stand, which is fixed on a wooden platform. The temperature of bulk water i.e. saturation temperature of water was measured using mercury thermometer with least count of 0.1°C. A (Cr-Al) k-type thermocouple is connected to Nichrome wire to measure the temperature of wire using digital temperature scanner having least count 10°C. The heating surface was cleaned routinely before and after each test with a sequence of operations involving application of constantan cleaner and washing with hot tap water and deionized water. During a test, the glass jar was loaded with 2000 ml of liquid to bring the surface to a level 30–40 mm above the heater. Steady state boiling was achieved in 15-20min after the supplementary heater was turned on. This was determined by monitoring the temperature of the solution. Surfactant solutions were replaced with fresh samples after single test. This precaution was taken in order to minimize changes in solution properties, which might have occurred at high temperature due to evaporation over long periods of time. The kinetics of boiling (bubble nucleation, growth and departure) i.e. bubble behaviour with and without surfactants in water was recorded by Nikon camera (36X) video recording. Experiments were carried with and without surfactant in pure water (i.e. deionised water) by varying heat flux. Concentration of different surfactant was varied from 100- 600 ppm in pure water. Each experiment was repeated two times to maintain the repeatability.

VI. Scope for Future Work

Heat transfer enhancement using surfactant solution is the active technique. One can study the compound technique i.e. surfactant solution with structured wall surface, extended surfaces, fins etc. or compounding of surfactants for heat transfer enhancement. Pool boiling heat transfer phenomenon includes heat transfer due to conduction, convection and evaporation, by using the parameters related to these phases one can model new equations. In this study considered the only effects of surface tension on the heat transfer enhancement. The results showed that up to certain concentration heat transfer coefficient increases and further increase in concentration heat transfer coefficient slightly decreases, this is due Marangoni effect. One can study effects of parameters in Marangoni number and study the effects of viscosity on heat transfer.

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