Pool Boiling Heat Transfer in Aqueous Solutions of Triton X-100 Surfactant

Paresh M. Wadekar
[1]Mechanical Engineering Department,
Annasaheb Dange College of Engineering and Technology,
Ashta Shivaji University Kolhapur, India,

Prasad V. Kengar
Automobile Engineering Department,
Annasaheb Dange College of Engineering and Technology,
Ashta Shivaji University Kolhapur, India

Vinayak T. Kumbhar
Mechanical Engineering Department,
Annasaheb Dange College of Engineering and Technology,
Ashta Shivaji University Kolhapur, India,

***Abstract*— The main objective of the current study is to investigate the effect of adding different amount of Triton X-100 surfactants. The heat transfer performance in distilled water with Triton X-100 is investigated by using nichrome wire heater. The experiment is carried out for different concentration from 100 to 700 ppm. Heat transfer enhancement is observed due to the change in the thermophysical properties of the aqueous solution. The experimentation shows that the surface tension is reduced due to addition of Triton X-100 in distilled water. The experiment is carried out to observe the behaviour of boiling at different heat flux. From the observation, the experiment is carried out up to critical heat flux with different concentration. The effects of surfactant concentration and the excess temperature ΔT on heat transfer performance are also studied.**

Keywords*— Surfactant, Boiling, Enhancement, Heat Transfer, Surface Tension.

I. INTRODUCTION

Boiling is a very effective and efficient mode of heat transfer, which is encountered in several engineering applications. Boiling and evaporation playing a important role in desalination of seawater, in distillation process, in chemical industries & in refrigeration system which is becoming necessary in some arid regions. Boiling with surfactant additives is generally an extremely 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 wide research and development in enhanced boiling heat transfer. Among the different improvement techniques investigated, the use of surfactant additives in water has been found to change boiling phenomenon significantly. 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 character 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 significant, 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 considerably. 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 decrease 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 reduction in surface tension.

The study of the saturated pool boiling of a surfactant solution shows a significant enhancement of heat transfer. It showed that the surface tension of the surfactant solution had significant influence on the heat transfer coefficient in boiling of dilute sodium lauryl benzene sulfonate and sodium lauryl sulfate solution. Pool boiling experiments were 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 significantly 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 Triton X-100 additives. 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 sulfate (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 [2]. 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) behavior 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 (c.m.c.). It was shown that surfactant additives at low concentrations could enhance the nucleate boiling heat transfer extensively.

With its ability to transfer large amounts of heat with relatively small temperature differences, pool boiling has attracted considerable research attention. This mode of heat transfer is encountered in many different applications ranging from energy refrigeration and air-conditioning to conversion systems also chemical thermal processing that employ both Newtonian and non-Newtonian liquids. In recent years, wide effort has been taken by many researchers to enhance boiling heat transfer, and an exhaustive compilation of the associated literature has been reviewed as follows:-

Tzan and Yang [3] carried out nucleate boiling of aqueous solutions of sodium lauryl sulfate (SLS) over relatively large ranges of concentration and heat flux in pool boiling apparatus. After conducting the experiment result shows that by adding small amount of surfactant in water, the heat transfer coefficient changes significantly higher, and heat flux is also maximum for optimum amount of surfactant concentration. The h value will get lower by adding surfactant concentration beyond optimum value. Using same pool boiling apparatus, heat transfer rate for nucleate pool boiling of n-propanol-water binary mixtures with various amounts of sodium lauryl sulfate also measured. The importance of the mass diffusion effect, caused by preferential evaporation of the more volatile component at the vapor-liquid interface on the boiling of the binary mixture, has been confirmed. Finally experiments conclude that the effect exerted by the addition of surfactant dominates over the mass diffusion effect in dilute binary mixtures.

Hetsroni et al. [4] investigated experimentally saturated and subcooled pool boiling of environmentally acceptable surfactant solutions, on a horizontal tube. By using High-speed video recording camera the kinetics of boiling like bubble nucleation, growth and departure was investigated. Using experimental result boiling curves for various concentrations was prepared and compare. The bubble behavior and heat transfer mechanism for additive solution are quite different from DM water. Specific features of boiling of nonionic surfactant solutions were revealed.

Auracher and Buchholz [5] develop an experiments technique for precise and systematic measurements of entire boiling curves under steady-state and transient conditions. Pool boiling experiments for well wetting fluids and fluids with a larger contact angle (FC-72, isopropanol, water) yield single and reproducible boiling curves if the system is clean. Heating and cooling transient yield different curves on clean surfaces. Measurements with micro sensors give an insight in the two-phase dynamics above the heating surface and the temperature field dynamics above and beneath the surface. For these studies they have used Micro thermocouples embedded in the heater, a micro optical probe and a micro thermocouple probe, both movables above the heater surface. Localized and rapid temperature drops are observed indicating high heat fluxes at the bottom of the bubbles. The hot spots are occurred before reaching the CHF, which increases towards the Leidenfrost point. Boiling regime wetting events are observed in entire transition, but no ones in film boiling. Very small vapor superheats exist in the bubbles and strong superheats in the surrounding liquid occur in low heat flux nucleate boiling. In film boiling the bubbles leaving the vapor film can reach superheats of 30 K or more near the surface (e.g. for isopropanol). An interfacial-area-density model enables the prediction of entire boiling curves. To predict CHF the concept of a reaction-diffusion model is presented. The triggering of CHF is due to instability of dry spots on the heating surface.

Hetsroni et al. [6] in saturated nucleate pool boiling of water, with constant wall heat flux q = 10 and 50 kW/m^2. The captured images showed that the bubble shape is close to axially-symmetric and vertically non-symmetric. The life-time and the volume of bubble growth-rate in surfactant solution did not differ significantly from those of water for heat flux of q = 10 kW/m^2. The time behavior of the contact angle of bubble growing in surfactant solution is qualitatively similar to that of water. At a heat flux of q = 50 kW/m^2, boiling in surfactant solution was observed to be more vigorous than the pure water. Surfactant 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. By increasing the heat flux the detachment diameter of water bubble increases, whereas analysis of bubble growth in surfactant solution reveals the opposite effect.

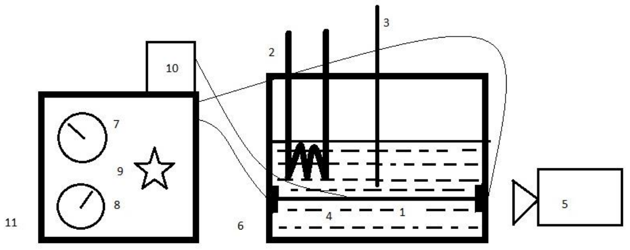
Jones et al. [7] experimentally explored pool boiling at atmospheric pressure from surfaces with a wide range of surface roughness in two fluids with differing wetting characteristics. The test surfaces ranged from a polished surface (R_a between 0.027 µm and 0.038 µm) to electrical discharge machined (EDM) surfaces with a roughness (R_a) ranging from 1.08µm to 10.0 µm. For same set of surfaces, different trends were observed in the heat transfer coefficient with respect to the surface roughness for two fluids. The heat transfer coefficient was found to continually increase with increasing roughness for FC-77. For water, EDM surfaces of intermediate roughness displayed similar heat transfer coefficients that were higher than for the polished surface, the highest heat transfer coefficients is shown by roughest surface. The heat transfer coefficients were more strongly influenced by surface roughness with FC-77 than with water. For FC-77, the roughest surface produced 210% higher heat transfer coefficients than the polished surface while for water, a more modest 100% enhancement was measured between the same set of surfaces. Although the results show the inadequacy of characterizing nucleate pool boiling data using R_a, the obtain effect of roughness was correlated using h proportional to R_a^m as has been done in several prior studies. With predictions from several widely used nucleate boiling correlations the experimental results were compared.

Chan et al. [8] investigate the boiling heat transfer from longitudinal rectangular-finned surfaces immersed in saturated water at low vapor pressures, finned surfaces with assorted fin spacing, fin thicknesses, and fin heights on a copper based surface. All the finned surfaces were found to increase both boiling heat transfer coefficients and critical heat fluxes. Heat transfer coefficients have been obtained at the pressures and optimal fin thickness was found for a design. Factors affecting the boiling characteristics have been identified and the optimal enhancement requires a balance of the active nucleation sites, bubble flow resistance, natural convection, thin film evaporation, liquid superheating, heat transfer area, bubble coalescence, and liquid reflux resistance. High speed visualization of vapor plug and vapor film generation on the boiling surfaces has revealed significant insights into the Boiling mechanisms at low saturation pressures.

Paresh Wadekar et al. [9] conducted and experiments on sodium dodecyl sulphate (SDS). Addition of different amount of SDS surfactant in water it reduces the surface tension significantly. The heat transfer enhancement with SDS is increase up to 600 ppm concentration later on it will be steady or reduce. This happened due to CMC of SDS is 600 ppm. Results shows that addition of small amount of surfactant changes the heat transfer behavior drastically.

Raj et al. [10] carried out an experimental investigation for different gravity conditions to validate the performance of phase change system, using scaling parameter to obtain heat transfer at varying gravity levels. Pool boiling heat flux data over a continuous range of gravity levels (0–1.7 g) was unavailable until recently. The results of a variable gravity is used by the author, subscooled pool boiling experiment to develop a gravity scaling parameter for n-perfluorohexane/FC-72 in the buoyancy-dominated boiling regime ($L_h/L_c > 2.1$). The heat flux prediction was then validated using heat flux data at different subcoolings and dissolved gas concentrations. The scaling parameter can be used as a tool to predict boiling heat flux at any gravity level in the buoyancy dominated regime.

Inoue et al. [11] measured the surface tension of ethanol/water mixtures over the whole fraction range with and without the surface active agent. The boiling heat transfer coefficient, at the beginning of boiling and the critical heat flux were measured for water and ethanol/water mixtures, with and without surfactant, over a horizontal fine heated wire which is kept at a pressure of 0.1 MPa. The experimentation was carried out in the whole range of the ethanol fraction and in a surfactant concentration varying from 0-5000 ppm. It was also found that enhancement due to surfactant disappears over 1000 ppm. Finally they concluded that reduction in surface tension due to surfactant remarkably enhances the heat transfer coefficients in the nucleate pool boiling.



1- Nichrom Wire, 2- Water Heater, 3-Thermometer, 4- Thermocouple, 5-High Speed Camera, 6-Glass Pool, 7-Voltmeter, 8-Ammeter, 9- Dimmer Switch, 10-Wire Temp. Indicator, 11-Power Supply

Figure 1: Schematic diagram of Experimental Setup

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The apparatus for experimental studies on pool boiling is shown in Figure 1. It consists of a clear cylindrical glass container. One auxiliary water heater is provided in container to heat the water up to saturation temperature i.e 95^0C. One thermometer is used to measure the water temperature.

Nichrome wire is used as superheated surface to transfer the heat to water. This Nichrome wire is connected to the mains via Dimmerstat. An ammeter is connected in series while the voltmeter connected across it to read the current and voltage. These controls are placed inside the control panel.

The glass container is kept on a stand. The glass container is filled with 2 Litter water and surfactant mixture. One K-type thermocouples are used to measure the temperature bulk water i.e. saturation temperature of water and temperature of main heater using digital temperature.

In experimental procedure the water and surfactant mixture is added in to the glass container. Triton X-100 surfactant with various concentrations will be taken for the experimental purpose. Auxiliary heater is connected to mains, when switch is ON electricity is supplied to the heater. This heater is used to heat the mixture upto the saturation temperature. When thermometer shows the saturation temperature the auxiliary heater will turn OFF.

Experimental work is concentrated on bubble formation on Nichrome wire for that purpose; electricity is supplied to the main heater surface through Dimmerstat. The required amount of heat flow will be maintained by Dimmerstat through an ammeter and voltmeter. As the temperature of the Nichrome wire will increase above saturation temperature, the mixture surrounded to Nichrome wire will start changing the phase from liquid to vapour as temperature of surface is superheated and bubble will form. The temperature of the Nichrome wire is indicated by the temperature indicator which is connected to the thermocouple which is in contact with Nichrome wire.

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.

Initially, 2 L of demineralised water is taken in the borosil glass pool and is heated to the saturation temperature by a secondary heater. As the temperature reaches about 95^0C, the auxiliary heater is switched off and the Nichrome wire heater is switched on. The electric supply to the Nichrome wire is gradually increased, and the current and voltage are measured at each step by constantly recording the temperature of the water and wire. The phenomenon is recorded on camera for further analysis. As the boiling heat transfer rate is very sensitive to the state of the heating surface, boiling of pure water was carried out until the reproducibility of the boiling curve became very good before beginning of each set of experiments with the addition of various amounts of surfactant. This state of the heating surface must be ensured for the Nichrome wire used for heating purposes, because for some runs, the wire breaks at critical heat flux (CHF) and is replaced by a new piece of wire. Thus, for complete experimentation, a long single Nichrome wire is cut into 0.10-m-long pieces.

Various researcher have investigated a number of surfactant for heat transfer enhancement Triton X-100 is used for this investigation. It come under nonionic surfactant that has a hydrophilic polyethylene oxide chain and an aromatic hydrocarbon lipophilic or hydrophobic group. Triton X-100 is soluble at 25 °C in water, ethylene glycol, ethyl ether, ethyl alcohol. This surface active agent is used for the detergent. It is environment friendly surfactant. For this studies different concentration of Triton X-100, viz., 100, 200, 300, 400, 500, 600, 700 ppm is added in demineralised water to determined the effect of different concentration.

The procedure from the beginning is repeated by emptying the pool of distilled water and filling it with aqueous surfactant solutions of different concentrations. The Nichrome wire is changed every time and thermocouple reattached.

III. RESULT AND DISCUSSION

Surface tension data for different concentrations of Triton-X-100 is measured by Drop weight method. It **Error! Reference source not found.**shows an increase in surfactant concentration up to 700 ppm leads to significant decrease in surface tension, whereas the changes in surface tension are very small of concentrations in the range 400-700 ppm during all temperature. But in all cases an increase in a liquid temperature leads to a decrease in the surface tension.

Figure 3 shows a set of boiling curves for water containing Triton X-100. Triton X-100 presents a violent incipient boiling in which, generating larger and less distributed bubbles. Furthermore, the Triton X-100 requires a higher superheat to reach the incipient boiling region, as depicted in fig. 3. The figure shown optimum quantity of Triton X-100 can be select for the boiling process in base fluid. At 400ppm the result was better for boiling process at low excess temperature with comparing water.

However, once h_{fg} is overcome, an “explosive boiling” occurs. This non-uniform boiling behaviour seems to deteriorate the efficiency of the pool boiling heat transfer for Triton X-100. The power required to reach the critical heat flux is low as compared to other surfactant solutions means heat required to reach the maximum heat flux is low at 400 ppm beyond this concentration heat flux increases with increasing excess temperature. Heat transfer co-efficient increases with increase of Heat flux at low excess temperature for varying concentration observed in the fig. 4(a, b) as compared to water.

The influence of heat flux and additive concentration on the nucleate boiling heat transfer rate of Triton X-100 solutions is more evident if the experimental data in Figure 3 are expressed as a plot of heat transfer coefficient versus heat flux, as shown in Figure 4. The heat transfer coefficient is increased as the heat flux and concentration are increased, except when the heat flux level is higher and the concentration of solutions is higher than 500 ppm.

To understand the boiling behavior of aqueous surfactant solutions qualitatively, the boiling history for pure water and Triton X-100 solutions was photographed using a charged coupled device (CCD) camera. These images for *q* of 18 to 1.4 MW/m2 are shown in Figure 5. Boiling in surfactant solutions, in comparison with that of pure water, is observed to be more vigorous with clusters of smaller-sized and more regularly shaped bubbles. In both surfactant solution and pure water, the bubbles mostly originate from the underside of the wire heater and then slide along the heater surface before departure.

These sliding bubbles tend to knock off the bubbles growing on the top surface of the heater, causing their early departure, and this tendency was observed to increase with increasing bubble departure frequency. With surfactant solutions, the lowering of surface tension promotes nucleation of smaller-sized bubbles and activation of nucleation sites in a clustered fashion, especially at lower heat fluxes. The bubbles depart at much higher frequencies, and the coalescence between two neighboring bubbles or sliding bubbles along the heater surface is minimal. The departing bubbles were seen to reach the pool free surface. At high heat fluxes, due to the vigorous bubbling motion, the liquid free surface in the pool oscillated mildly. This was also observed with the boiling of pure water. Furthermore, with increasing Triton X-100 concentration beyond a certain amount, no significant differences were observed in the boiling evolution in surfactant solutions having concentrations more than 500 ppm.

IV. CONCLUSION

Saturated nucleate boiling is carried on Nichrome wire by using pure water with Triton X-100 surfactant. Experiment is carried out for relatively wide range of concentration viz., 100 to 700 ppm with different heat flux. The result shows that by adding small amount of surfactant into the water, heat transfer rate is changes significantly. It was also found that there is critical missile concentration (cmc) for heat flux. The heat transfer coefficient is again lower if concentration is increase. From the study it is found that heat transfer rate is increase upto 500 ppm. Above 500 ppm insignificant enhancement is found.

V. REFERENCES

[1] J. Rosen and M. J, Surfactants and Interfacial Phenomena, 2nd Edition ed., John Wiley & sons, 1989.
[2] C. N. Ammerman and S. M. You, “Determination of the boiling enhancement mechanism caused by surfactant addition to water,” Journal of Heat Transfer, vol. 188, p. 429–435, 1996.
[3] Y. L. Tzan and Y. M. Yang, “Experimental study of surfactant effects on pool boiling heat transfer,” Journal of Heat Transfer , vol. 112, p. 207–212, 1990.
[4] G. Hetsroni, M. Gurevich, A. Mosyak and R. Rozenb, “16. G. Hetsroni, M. Gurevich, A. MosBoiling Enhancement with Environmentally Acceptable Surfactants,” International Journal of Heat and Fluid Flow, pp. 841-848, 2004.
[5] H. Auracher and M. Buchholz, “Experiments on the Fundamental Mechanisms of Boiling Heat Transfer,” ABCM Journal of the Brazilian

Society of Mechanical Science & Engineering, vol. XXVII, January-March 2005.

[6] G. Hetsroni, E. Pogrebnyak, I. Sher and A. Mosy, “Bubble growth in saturated pool boiling in water and surfactant solution,” International Journal of Multiphase Flow 32, p. 159–182, October 2005.

[7] B. J. Jones, J. P. McHale and S. V. Garimella, “The Influence of Surface Roughness on Nucleate Pool Boiling Heat Transfer,” ASME journal of heat transfer, vol. 131/121009, December 2009.

[8] M. A. Chan, C. R. Yap and K. C. Ng, “Pool Boiling Heat Transfer of Water on Finned Surfaces at Near Vacuum Pressures,” ASME journal of heat transfer, vol. 132 / 031501, March 2010.

[9] P. M. Wadekar, R. Bajaj and K. D. Devade, “Enhancement of Pool Boiling Heat Transfer In Water With Sodium Dodecyl Sulphate Surfactant,” IJSART, vol. 1, no. 6 JUNE 2015, pp. 197-204, 2016.

[10] R. Raj, J. Kim and J. McQuillen, “Gravity Scaling Parameter for Pool Boiling Heat Transfer,” ASME journal of heat transfer, vol. 132 / 091502, September 2010.

[11] T. Inoue, Y. Teruya and M. Monde, “Enhancement of Pool Boiling Heat Transfer in Water and Ethanol/Water Mixtures with Surface Active Agent,” International Journal of Heat and Mass Transfer 4, pp. 5555-5563, 2004.

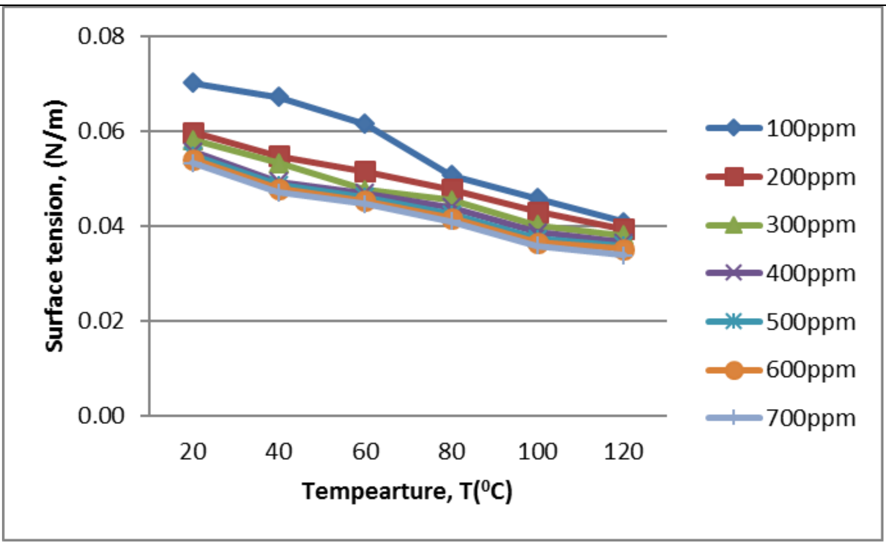


Figure 2 : Surface tension variation of aqueous surfactant solution of Triton X-100

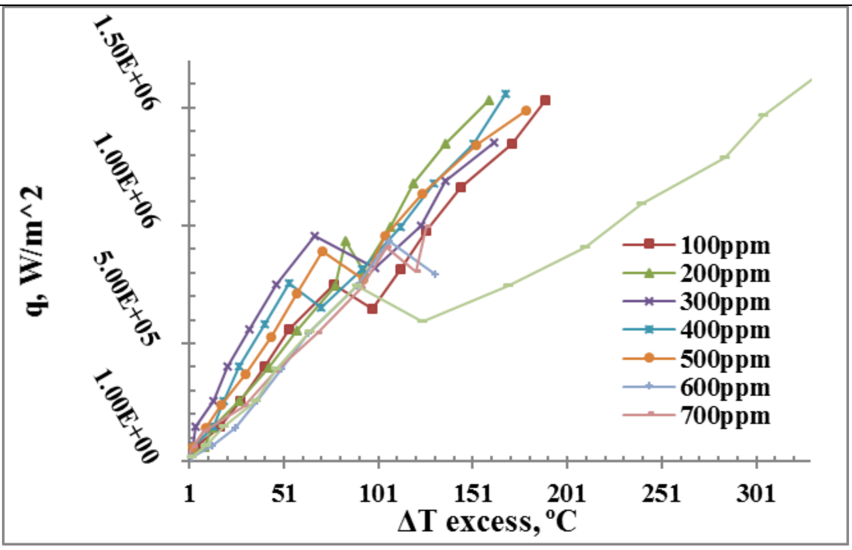
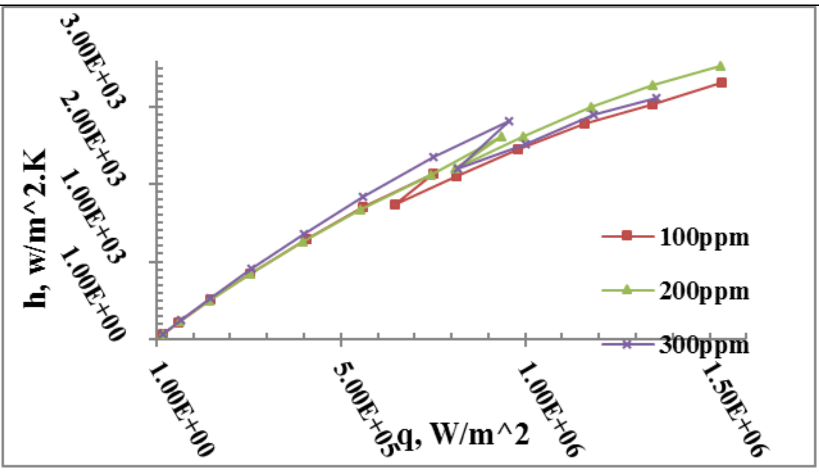
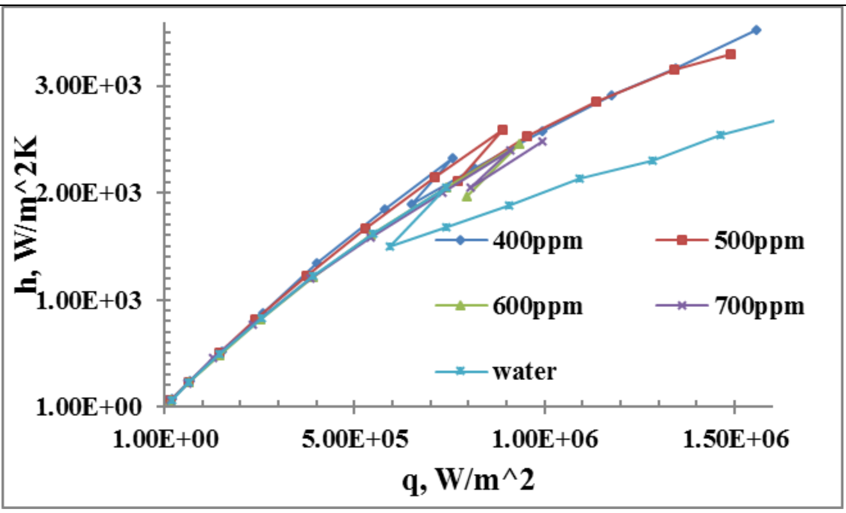


Figure 3 Heat flux vs. heater excess temperature for various concentrations of Triton X-100 in pure water

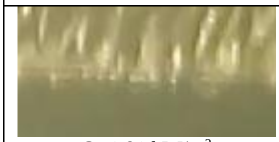
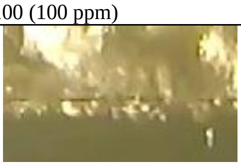
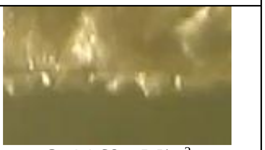
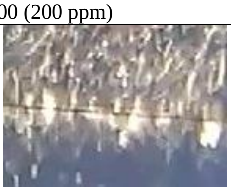


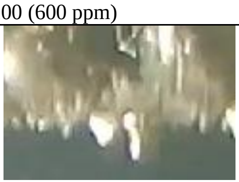
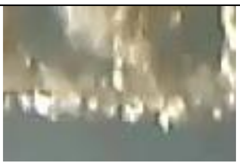
a)



b)

Figure 4 (a, b) Heat transfer coefficient vs. heat flux for various concentrations of Triton X-100 in water

Pure Water			
 Q=1.68 kW/m^2	 Q=6.72 kW/m^2	 Q=4.8 mW/m^2	 Q=23.95 mW/m^2
Water with Triton X-100 (100 ppm)			
 Q=1.91 kW/m^2	 Q=10.68 kW/m^2	 Q=4.68 mW/m^2	 Q=24.68 mW/m^2
Water with Triton X-100 (200 ppm)			
 Q=1.68 kW/m^2	 Q=1.68 kW/m^2	 Q=1.68 kW/m^2	 Q=1.68 kW/m^2
Water with Triton X-100 (300 ppm)			

<table>
<tr><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td></tr>
<tr><td colspan="4">Water with Triton X-100 (400 ppm)</td></tr>
<tr><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td></tr>
<tr><td colspan="4">Water with Triton X-100 (500 ppm)</td></tr>
<tr><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td></tr>
<tr><td colspan="4">Water with Triton X-100 (600 ppm)</td></tr>
<tr><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td></tr>
<tr><td colspan="4">Water with Triton X-100 (700 ppm)</td></tr>
<tr><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td><td>
Q=1.68 kW/m^2</td></tr>
</table>