

# International Engineering Research Journal

## Performance Evaluation of Critical Heat Flux by using the Surfactants

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**Abstract**—For many key industrial applications such as the refrigeration, petrochemical processing, pharmaceutical, hygiene and personal care, refining, and food processing, among others Boiling with surfactant is important. Moreover, surfactants in trace amounts are present in boilers of conventional power plants and have also shown promise to augment the nucleate boiling performance of water. The experimental set up for the present investigation includes electric heating element submerged in water and mounted vertically. Two thermocouples and a digital indicator measured the temperature of the heater surface and solution temperature. The actual heat transfer rate is obtained by multiplying the voltmeter and ammeter readings. The vapor produced by the heat input condenses by a water cooled coil and the liquid formed which returns to the cylinder for re-evaporation. Several different surfactants were employed: [SDS (Sodium Dodecyl Sulfate), [SLES (Sodium Lauryl Ether Sulfate) (anionic)] and [Triton X-100 (Octylphenol Ethoxylate) (nonionic)], they have different molecular weights, ionic nature and number of ethylene oxide EO groups attached to its polar head. Pool boiling experiments were carried out a relatively wide range of surfactant concentrations: SDS ( 300 - 10000) ppm; SLES ( 250 - 4000) ppm; Triton X-100 (100 - 800) ppm and heat fluxes (38.10 - 101.60) kW/m<sup>2</sup>. The boiling results show that with the addition of small amounts of surfactants, the saturated nucleate pool boiling critical heat flux of water is found to be altered due to reduction in the surface tension and this enhances the heat transfer. The enhancement in nucleate pool boiling depends upon wall heat flux (or temperature difference), concentration of surfactant, ionic nature, molecular weight and number of (EO) group.

With the concentration enhancement achieved and for enhanced solutions it is observed  $C < CMC$ . The optimum enhancement is at or near the CMC of surfactants. However, the maximum heat transfer enhancement is in the order of SDS > SLES > Triton X-100, this is also, in the reverse order of their molecular weights and number of (EO) groups.

**Keywords:** Pool boiling, Surface tension, Surfactant, Critical Heat Flux, Surfactant Concentration and Wire Diameter

### 1 INTRODUCTION

#### 1.1 Boiling Heat Transfer

The mode of heat transfer, where phase change is occurs from liquid to vapor is known as boiling heat transfer.

There are two basic types of boiling

1) Pool boiling: where heated surface is submerged below a free surface of liquid.

2) Flow boiling: where the liquid flows on a heated surface. Pool and Flow boiling are mostly used in power and process industries.

#### 1.2 Pool Boiling

At a superheated wall that is small compared to the dimensions of the pool of nominally stagnant liquid in which it is immersed vapor is generated in pool boiling.

The motion of the liquid is induced by the boiling process itself (analogous to single-phase natural convection at a heated wall in an unbounded fluid) and the velocities are assumed to be low. The conditions such as the basic division into nucleate, transition and film boiling and studies of bubble nucleation and motion are convenient for small-scale laboratory experiments and much of the understanding of boiling. However, pool boiling is unusual in industrial equipment.

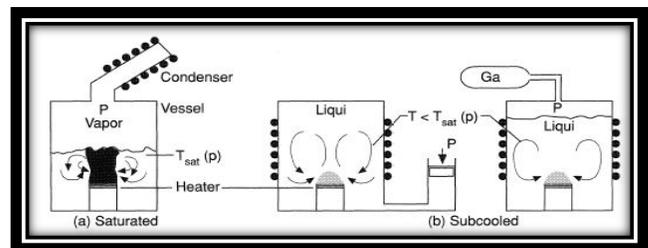


Figure 1.1 Boiling mechanisms

Even though there is no natural flow of liquid past over the hot wall, custody of the liquid and close spacing of multiple heaters, as in kettle reboilers, means that conditions are closer to Forced Convective Boiling. By a thin metal wall the boiling liquid is separated from the heat source is often a hot fluid, whereas in pool boiling experiments electrical resistance heating is often used. Consequently it is important to appreciate the special conditions of pool boiling experiments and to exercise caution in transferring the information they provide to large-scale industrial systems in which flow effects are generally significant. The techniques that are used in pool boiling experiment that are review with this article. Pool boiling behavior is described in more detail in the articles

on Boiling, Nucleate Boiling, and Burnout(Pool Boiling).

Pool boiling curve:

-Different boiling regimes:

Four boiling regimes are observed in the boiling curve.

These are

-Natural convection regime.

-Nucleate regime.

-Transition regime and.

-Film boiling regime.

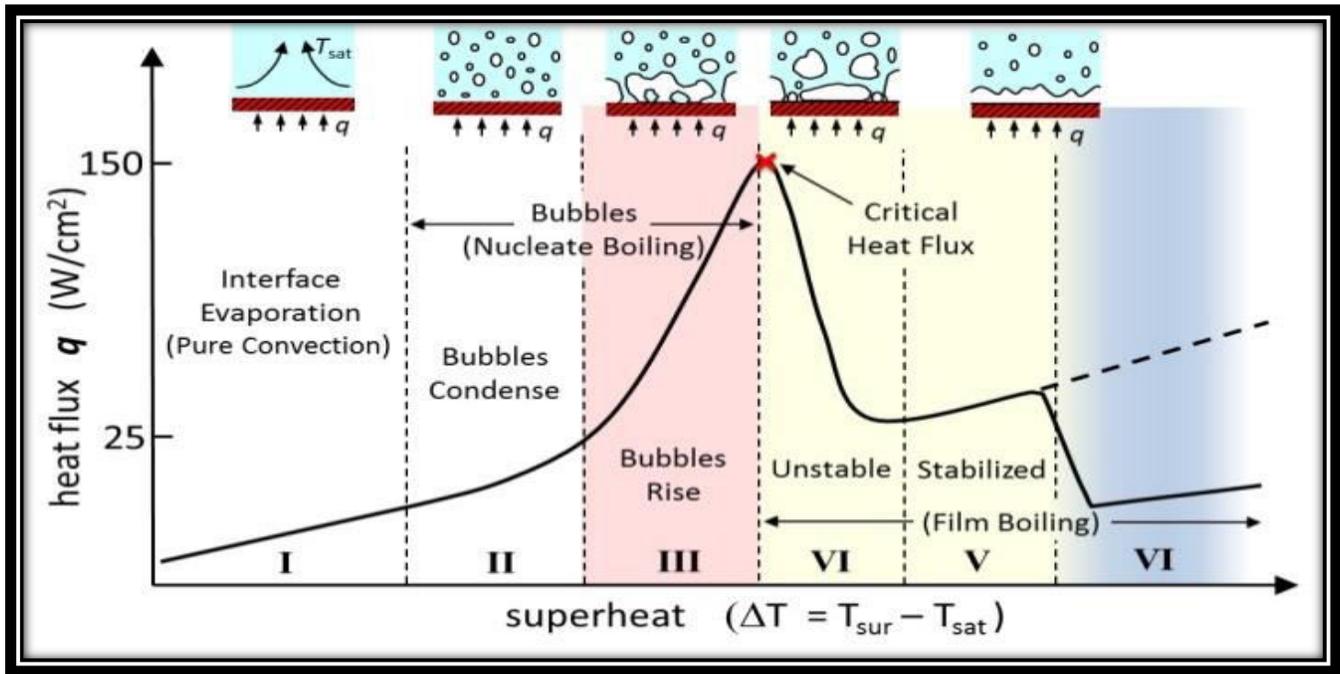


Figure 1.2 - Pool boiling curve

1- Natural convection regime:

As fluid reaches to its saturation temperature boiling starts. But actually it needs some more temperature start the boiling. For water this temperature is about 2 to 6 degrees. At that condition bubble forming observed. Bubble formation is observed in natural convection boiling. Bubbles are an indispensable part of boiling. Not required to tell that all the heat transfer is only due to natural convection currents in this region. This stage happens when the fluid is slightly superheated.

2- Nucleate boiling regime:

Nucleate boiling regime is the most desirable regime of boiling heat transfer. In this regime at different nucleation sites bubbles start to form. The bubbles those are formed in the first region, when they leave the heater surface, they are most likely to collapse. These are isolated bubbles. There is a significant increase in the rate of bubble formation. When bubbles leave the surface they collapse and the space vacated is filled by the surrounding liquid and thus heat transfer is accelerated.

After taking a lot of heat, bubbles are big enough and they rise to the top surface of liquid. These bubbles are energy movers. Thus with the excess temperature, a significant increase in the boiling curve is observed. In this region they form continuous columns of bubbles. At that point the highest heat flux or critical heat flux or the burning heat flux is found. This point is known as the burning point or critical heat flux.

3- Transition regime:

It is a most unstable and undesired part of boiling. Huge drop in heat flux is observed at this stage, due to the formation of vapor blanket over the heater surface. So transfer the heat from heater surface to surrounding liquid become quite difficult. That's why significant drop in heat flux is observed.

4- Film boiling regime:

This is the interesting part of boiling. At this regime heat transfer increases. After critical heat flux heater surface absorbs heat in the transition boiling. After sometime it leaves the heat into the liquid as the heat is very massive radiation heat transfer comes in process and increase in the heat flux is observed. At the first part of this region minimum heat flux is observed, known as Leiden frost point or the minimum heat flux point. In this part the burnout phenomenon can occur very frequent.

1.3 Flow Boiling

Flow boiling occurs when all the phases are in bulk flow together in a channel. For example, vapor and liquid flow in a pipe together. The multiphase flow may be classified as adiabatic or diabatic, i.e., without or with heat addition at the channel wall. An oil/gas flow in a pipeline, or air/water flow are example of adiabatic flow. In these cases the flow patterns would change as the inlet mass flow rates of the gas or liquid are altered or as the velocity and void distributions develop along the channel. Boiling will not take place and phase change will only occur if in a one component multiphase flow (e.g., steam-water) the

pressure decreases and flashing occurs.

Examples of adiabatic flow are to be found in the riser tubes of steam generators and boiler tubes in power plants or in the coolant channels between nuclear fuel elements in a boiling water reactor. Boiling starts on the walls of the channels and due to vapor production the flow patterns change as one observes the flow downstream in the

channel due to the production of vapor. This is an important difference between pool boiling and flow boiling; i.e., that the forced flow of the multiphase system causes flow pattern transitions at a given wall heat flux (or temperature) as fluid flows along the channel, the integral power deposited in the fluid increases.

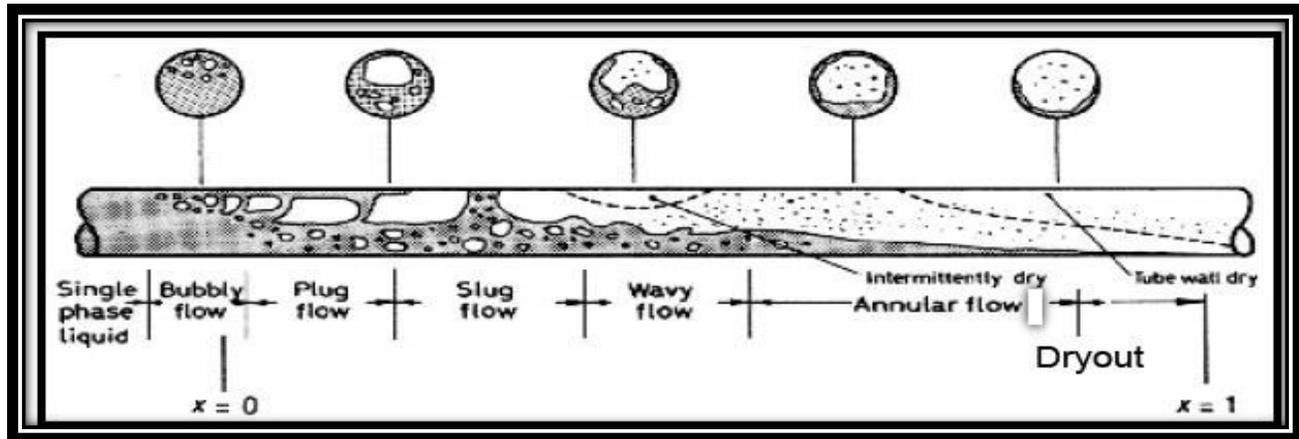


Figure 1.3 - Flow boiling

#### 1.4 Surfactant

Surfactants are essentially low-molecular weight chemical compounds, with molecules consisting of a combination of a water-soluble (hydrophilic) and a water insoluble (hydrophobic) part.

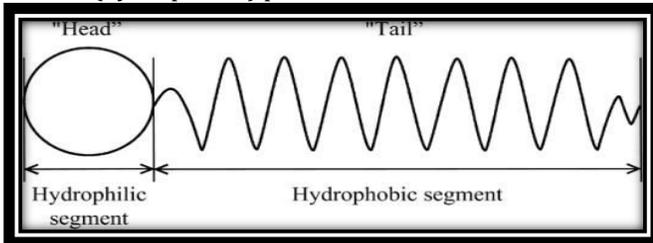


Figure 1.4 - Molecular structure of surfactant

Surfactants or surface active agents are a special class of all round amphiphilic compounds that possess spatially distinct polar (hydrophilic head) and non-polar (hydrophobic tail) group. In solution they show interesting phenomena by the interfacial and bulk-solvent properties modification. The unusual characteristic properties of surfactants in solution especially at the interfaces owe it to the presence of distinct hydrophilic as well as hydrophobic domains in the same molecule. In view of its amphiphilic nature and special ability of minimizing the interfacial tension, surfactant finds applications in all aspects of our daily life directly otherwise in household detergents, personal care products and in industrial process as in pharmaceuticals, food processing, oil recovery and in nanotechnologies, etc. Detergents, a term often used interchangeably with surfactants especially the anionic ones, refer to a combination of synthetic surfactants with other substances - organic or inorganic - formulated to enhance functional performance specially as cleaning

agents. Colloids and surface science have emerged as a versatile interdisciplinary subject, which have made inroads, inter alia, into the study of mimetic chemistry that play a vital role in understanding a diversity of functions in the living cells and also the complex life processes.

## 2 LITERATURE SURVEY

### 2.1 Reviewed Papers

1) Critical heat flux during pool boiling on a vertical heater of wire or plate has been measured employing water and R113. The experiment was made for a wire of 0.5 to 2 mm in diameter and for a plate of 5, 7 and 30 mm in width and from 20 to 300 mm in height. The pressure was 1 and 2 bar for water and 1, 2, 3 and 4 bar for R113. The experiment shows that for the case of both wire and plate of 5, 7 mm, a large coalesced bubble entirely surrounds the vertical heater and rises surrounding it, while for the case of  $w = 30$  mm, a large bubble rises along its surface as it cannot surround. The characteristic of CHF can be divided into two regimes depending on the flow condition when CHF takes place. Correlations are proposed for the CHF of the wire and the plate of  $w = 5$ , and 7 mm, yielding good accuracy. The CHF for the plate of  $w = 30$  mm has a similar tendency to that in one side headed surface and can be predicted reasonably by existing correlation for one side heated surface. (M. Monde, T. Inoue, Y. Mitsutake (1997)).

2) While certain surfactant additives are well known to significantly enhance boiling heat transfer, the enhancement mechanism is still not so clear for the present. In order that more conclusive information of fundamental boiling phenomena in surfactant solutions can be collected, surfactant effects on interfacial properties at gas/liquid interface, nucleate boiling heat transfer,

boiling incipience, and single vapor bubble growth dynamics for three additives - including 99% SDS, 95% SLES, and Triton X-100 were experimentally studied in this work. The nucleate boiling heat transfer coefficients were tried to correlate with the equilibrium and dynamic surface tension of the aqueous surfactant solutions. The results reveal that neither equilibrium nor dynamic surface tension can successfully explain the boiling phenomena. (Wuu-Tsann Wu, Yu-Min Yang, Jer-Ru Maa(1998)).

3) Boiling heat transfer from horizontal stainless steel tubes, submerged in sub-cooled surfactant solutions of various concentrations, was studied experimentally. The kinetic of boiling (bubble nucleation, growth and departure) was investigated by high-speed video recording in combination with Infrared Thermography. The specific features of boiling of surfactant solutions were revealed. It was found that the sub-cooled nucleate boiling of surfactant could not be described by a single curve, in contrast to water. A boiling hysteresis was found for degraded solutions. This phenomenon may be related to formation of a surfactant monolayer, which results in damping of an interfacial motion. (G. Hetsroni, M. Gurevich, A. Mosyak, R. Rozenblit, L.P. Yarin(2000)).

4) During nucleate pool boiling of pure water and water with cationic surfactant, the motion of bubbles and the temperature of the heated surface were recorded by a high-speed video camera and an infrared radiometer. All experiments were performed at saturated boiling conditions. The boiling curves for various concentrations were obtained and compared. The results show that the bubble behavior and the heat transfer mechanism for the surfactant solution are quite different from those of pure water. The heat transfer dependence on the relative changes of both the surface tension and the kinematic viscosity was discussed. (G. Hetsroni, J.L. Zakinb, Z. Linb, A. Mosyaka, E.A. Panchalob, R. Rozenblita (2001)).

5) Dynamic and equilibrium surface tension data for aqueous solutions of four surfactants and two polymers are experimentally obtained using the maximum bubble pressure method. The additives employed are SDS, SLES, Triton X-100, Triton X-305, HEC QP-300, and Carbopol 934. Measurements are obtained at a surface age of 50 ms, which represents the dynamic conditions for bubble frequencies that are typically observed during nucleate boiling of water. To understand the additive adsorption/desorption kinetics during boiling, dynamic surface tension measurements at 80°C are also obtained. The results indicate significant differences between the dynamic and equilibrium values, as well as between those measured at room and elevated temperatures. Adsorption isotherms with surface tension and concentration normalized by the respective values at critical micelle concentration are shown to represent the generalized behavior of surfactants. (Raj M. Manglik, Vivek M. Wasekar, Juntao Zhang(2001)).

6) By testing against collected data from twelve surfactant additives, criteria for a given surfactant as a

competent additive in enhancing nucleate boiling heat transfer of water is proposed in this work. As a result of the criteria, high solubility, high equilibrium tension depression, and low equilibrium contact angle depression are required. A surfactant is incapable of enhancing boiling of water, in which it dissolves sparsely. For a highly soluble surfactant, boiling heat transfer enhancement by its addition is enhanced by the depression of equilibrium surface tension but suppressed by the depression of equilibrium contact angle. Due to the counterbalancing with each other by these two effects different degrees of boiling enhancement will be achieved. Surfactant additives can be categorized accordingly. (Y. M. YANG and J. R. MAA(2001)).

7) Saturated and subcooled pool boiling of environmentally acceptable surfactant solutions, on a horizontal tube, was investigated experimentally. The kinetics of boiling (bubble nucleation, growth and departure) was investigated by high-speed video recording. Boiling curves for various concentrations were obtained and compared. It was observed that the bubble behavior and the heat transfer mechanism for the surfactant solution are quite different as compared to pure water. Specific features of boiling of nonionic surfactant solutions were revealed. (G. Hetsroni, M. Gurevich, A. Mosyak, R. Rozenblit, Z. Segal(2003)).

8) The presence of surfactant additives in water was found to enhance the boiling heat transfer significantly. The objective of the present investigation is to compare the bubble growth in water to that of a surfactant solution with negligible environmental impact. The study was conducted at two values of heat fluxes to clarify the effect of the heat flux on the dynamics of bubble nucleation. The bubble growth under condition of pool boiling in water and non-ionic surfactant solution was studied using high speed video technique. The bubble generation was studied on a horizontal flat surface; and the natural roughness of the surface was used to produce the bubbles. (G. Hetsroni, A. Mosyak, E. Pogrebnyak, I. Sher, Z. Segal(2005)).

9) This paper presents a state-of-the-art review with respect to studies of boiling phenomena of aqueous surfactant and polymeric additive solutions in the literature. Both nucleate pool boiling and flow boiling are concerned. First, the effect of surfactants and polymeric additives on the physical properties of aqueous surfactant and polymeric additive solutions is discussed. The experimental results of surface tensions and viscosities of aqueous surfactant and polymeric additive solutions by the authors and other researchers are presented to show the variation of the physical properties and interfacial phenomena affected by the concentrations and/or temperatures of surfactant and polymeric additive solutions. Then, a generic review of boiling phenomena for both nucleate pool boiling and flow boiling with surfactants and polymeric additives is presented. (Lixin Cheng, Dieter Mewes, Andrea Luke(2006)).

10) In this paper, bubble dynamics in pool boiling heat transfer using saturated water and aqueous

Ammonium Chloride (anionic surfactant) solution has been studied experimentally. The concentration of surfactant was taken 2600 ppm (Parts per Million). Single bubble is generated using right angle needle tip of a hypodermic needle as a nucleation site. The bubble dynamics was studied using SONY Cyber-shot DSC-H100 camera operating at 30 frames per second at atmospheric pressure. Bubble growth in saturated water is compared surfactant solution. The result shows that, at low heat flux ( $q = 235 \text{ KW/m}^2$ ), the bubble diameter, bubble height and bubble volume in surfactant solution approximately similar to that of water. At high heat flux ( $q = 738 \text{ kW/m}^2$ ), the departure diameter of water bubbles was approximately same. But, in surfactant solution, with increase in heat flux the departure diameter decreases and thereby pool boiling heat transfer coefficient enhances. The enhancement is observed due to surface tension of the aqueous solution. The effect of surfactant on bubble release frequency is also discussed. (A. Najim, A. R. Acharya, A. T. Pise, S. S. Gajghate(2014)).

11) Boiling heat transfer is used in variety of industrial processes and applications, such as refrigeration, vapor cycle power generation, heat exchangers, petroleum refining, and chemical manufacturing. Enhancements in boiling heat transfer processes are critical for making these applications more energy efficient. The objective of this paper is to exhibit the water pool boiling phenomena under the effect of environmentally friendly surfactant additives. The test setup used in this study has multiple benefits. First, the test setup enhances teaching in variety of classes through in-class demonstrations and student experiments. An experiment is explained to help the students to visualize and understand different modes of boiling heat transfer. In addition, the test setup provides a platform for research in boiling enhancement. Using surfactant additives in boiling causes increased number of nucleation sites and decreased level of wall superheat. (Dikici, B., Eno, E. & Compere, M. J Therm(2014)).

12) As so many applications are related to Pool Boiling. The Pool Boiling is mostly useful in arid areas to produce drinking water from impure water like sea water by distillation process. To distill the pure water is very difficult as it has having high surface tension. The surface tension is important factor to affect heat transfer enhancement in pool boiling. We can increase the heat transfer rate by reducing the surface tension in pool boiling. From so many years we are using surfactants domestically. It is proven previously by experiments that the addition of little amount of surfactant reduces the surface tension and increase the rate of heat transfer. There are different groups of surfactants. From those conducting experimentation with anionic surfactant Ammonium Dodecyl Sulfate (ADS), which is most human friendly and three times best soluble than Sodium Dodecyl Sulfate, to test the heat transfer enhancement. (Mr. P. Atcha Rao, Mr. V. V. Ramakrishna(2015)).

13) The experiments on pool boiling have conducted

to study the nucleate pool boiling of pure water with and without surfactants. The motive behind this study is to find the effects of optimum concentration of different surfactants on the heat transfer rate of pure water without any abnormalities. With the help of video camera kinetics of boiling (bubble nucleation, growth and departure) was recorded. The boiling curves ( $q$  Vs  $(T_w - T_{sat})$ ) for different concentrations of surfactants in pure water were obtained. Also from the current data, the heat transfer coefficient for pure water with and without surfactants were calculated and compared. The results showed that the addition of surfactant can enhance the water boiling heat transfer, and the enhancement is more obvious for SLS solution as compared to other surfactants. Also the bubble behavior and the heat transfer mechanism for the surfactant solution are quite different from those of pure water. The heat transfer depends on the comparative changes of the properties of solution such as surface tension, density and the viscosity was discussed. (R. B. Gurav, J. D. Patil, Irani Behram Fardoon).

## 2.2 Summary of review papers

### 2.3.1 Pool Boiling Without Surfactant

With its ability to transfer large amounts of heat in relatively small temperature differences, nucleate boiling has attracted considerable research attention. As entrapped gas or vapor expands at small cavities on the surface, bubbles are created in nucleate boiling. The bubbles grow to a certain size, depending on the surface tension at the liquid – vapor interface and the temperature and pressure. Depending on the temperature difference, the bubbles may collapse on the surface, may expand and detach from the surface to be dissipated in the body of the liquid, or at sufficiently high temperatures may rise to the surface of the liquid before being dissipated.

### 2.3.2 Effect Of Surfactant On Pool Boiling

Surfactants tend to appreciably change in the boiling curve of water by essentially modifying nucleation and the associated bubble dynamics. The enhancement in nucleate boiling heat transfer has generally been observed to increase with the concentration of surfactants in aqueous solutions. In study on aqueous solutions of neutralized alkyl glyceryl sulfonate (AGS), a sharp degradation in the boiling heat transfer coefficient at high heat fluxes and large surfactant concentrations has been reported Manglik (1998). The reduction in  $h$  is even more pronounced and occurs at much lower wall heat flux with higher surfactant concentrations in AGS aqueous solution,  $h$  decreases dramatically. For the saturated boiling of aqueous Habon G solutions Hetsroni (2001), depending upon the Habon G concentration, the heat transfer coefficient is found to increase by as much as 120% over that for pure water. In addition, there appears to be a critical concentration level, beyond which there is a reduction in the extent of heat transfer enhancement at high heat fluxes.

Wasekar (2001) investigated saturated, nucleate pool boiling in aqueous surfactant solutions experimentally; aqueous solutions of SDS, SLES (ionic surfactants) and

Triton X-100, Triton X-305 (nonionic surfactants) were used in investigation. The optimum heat transfer enhancement was observed to be at or around CMC of the surfactant and tended to follow reverse order to their respective molecular weights and EO groups. It shows maximum enhancement of 65% for (2500 ppm) queues SDS solution.

Saturated, nucleate pool boiling in aqueous surfactant and polymer solutions was experimentally investigated by Zhang (2004). The surfactant additive enhances the heat transfer by significantly altering the nucleate boiling in water. The enhancement increases with concentration, with an optimum obtained in solutions at or near the critical micelle concentration CMC of the surfactant. The performance is seen to be dependent upon the wall heat flux (or temperature difference), concentration, surfactant molecular weight and EO group. Sethuraghavan (2005), studied the bubble dynamics characterized by its departure diameter and bubble surface is presented in a wide range of concentrations for the following surfactants: SDS and SLES (anionic), CTAB, Ethoquad O12/PG and thoquad 18/25 (cationic), and Triton X-100 and Triton X-305 (non-ionic). The surface tension effects of the aqueous surfactants on the rapidly growing and departing liquid-vapor interface are found to be a function of the surfactant molecular weight, ionic nature, and number of ethylene oxide (EO) group attached to its polar head. Bigger departure-diameter bubbles with longer bubble surface age as compared to their lighter counterparts are produced by the higher molecular weight surfactants. Also much smaller departure diameters are obtained with increasing concentration. The addition of small amounts of surfactants to water has been found to enhance the critical heat flux in pool boiling significantly.

Because of their low concentration, the presence of surfactants in water causes no significant change in the solvent physical properties except for surface tension.

Boiling with surfactants is generally a very complex process, and it is influenced by a larger set of variables in comparison to the phase-change process of pure water. Besides the wall heat flux or (temperature difference), heating surface geometry, and bulk concentration of surfactants, the nucleate boiling behavior is also dependent upon, among others, the role played by surface tension, interfacial stresses, the nucleation process. Furthermore, it appears that the boiling mechanism itself is influenced by the nature of surfactant and its chemistry in the solution.

### 2.3 Surfactant Effects on the Thermo-physical Properties

Surface tension and viscosity of aqueous solution are perhaps the primary thermo-physical properties that are influenced by the presence of small amounts of surfactant. The extent of surface tension reduction of the solution depends upon the chemistry and concentration of the surfactant as well as the temperature of the solution. Several studies have reported the effects of surfactant type and concentration on the solution's surface

tension. Typical measurements of  $\sigma$  reported by Wu et al. (1995) for aqueous solutions of sodium lauryl sulfate (SLS, an anionic surfactant), polyoxyethylene sorbitan monooleate (Tween-80, a nonionic surfactant), and dodecyl trimethyl ammonium chloride (DTMAC, a cationic surfactant) at 298 K (25°C) are presented

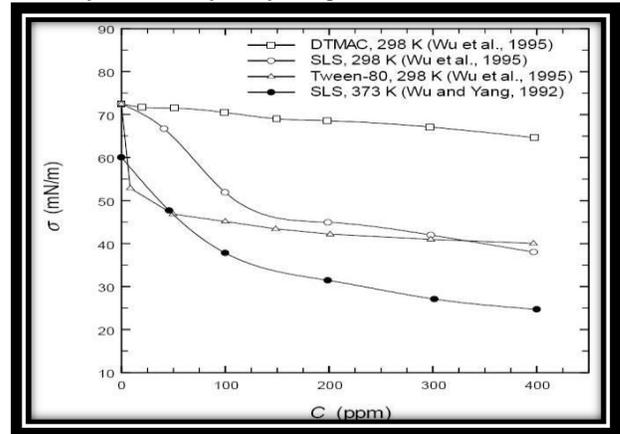


Figure 2.1- Surface tension variation with concentration of aqueous surfactant solutions.

Figure 2.1. It is seen that with increasing surfactant concentration the surface tension decreases appreciably. It should be noted that the molecular weights of these surfactants considered in the above study also vary in the same order, which suggests that higher molecular weight surfactants affect a higher surface-tension depression in aqueous solutions. Also, the surface tension is seen to decrease asymptotically with increasing concentration. This asymptotic limit is referred to as the critical micelle concentration CMC of the surfactant.

The CMC is a direct measure of the effectiveness of a surfactant to reduce the solvent's surface tension. At low concentration, surfactant molecules arrange themselves at the interface in the form of monomers with their hydrophilic part inside water and the hydrophobic part away from the interface. This results in an appreciable reduction in the surface tension at the interface. This process continues with increasing concentrations until CMC is reached, at which point no more molecules can be arranged at the interface. The surfactant molecules then cluster together inside water to form micelles. It should be emphasized here that CMC of each surfactant depends upon its chemistry and ionic structure.

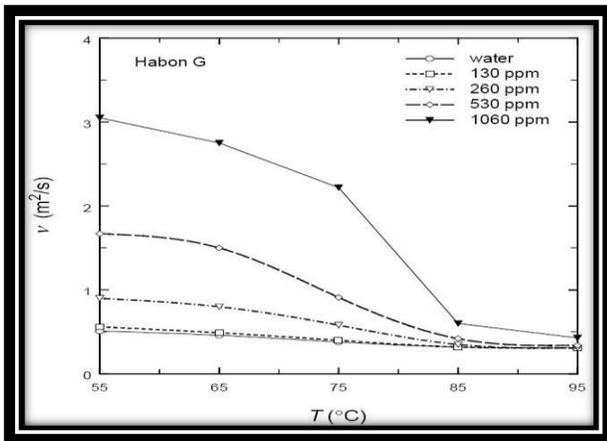


Figure 2.2- Temperature effect on the kinematic viscosity of aqueous Habon G solutions

The measured viscosities for both SLS and Tween-80 aqueous solutions at room temperature were found to be constant and independent of shear rates i.e., they display a Newtonian behavior over a wide concentration range of (125 to 500) ppm.

Post-micellar solutions, however, may show appreciable increases in dynamic viscosity and tend to be viscoelastic. The viscoelastic nature is brought about by the long cylindrical micelles behaving like polymers.

Hetsroni et al., (2001), studied the effect of temperature on the dynamic shear viscosity of a cationic surfactant (Habon G) over a temperature range of 298 K – 333 K (25°C -60°C). The concentration of Habon G was around its CMC for a given shear rate, the viscosity was found to decrease with an increase in solution temperature. Moreover, the change in shear viscosity at 333 K over the shear rate range of (1 – 1000 s-P1)P was negligible. They also measured the kinematic viscosities for various concentrations of Habon G over a temperature range of 328 K – 368 K (55°C – 95°C), the results of which are shown in Figure 2.2. It is clearly seen that near boiling temperatures the kinematic viscosity approaches that of pure water for both pre-micellar and micellar solutions.

## 2.4 Selected surfactants

After surveying all the research papers and on basis of study material, decided to study three different surfactants, those are 1. Sodium Lauryl Ether Sulfate (SLES), 2. Triton X-100 (Octylphenol ethoxylate)

### 2.5.1 Sodium Dodecyl Sulfate (SDS)

Sodium dodecyl sulfate (SDS or NaDS)  $[\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}]$  (M 288.38 g/gmol), also known as sodium lauryl sulfate (SLS).

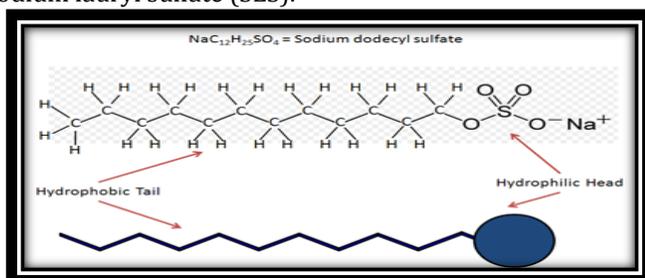


Figure 2.3 - Molecular structure of Sodium Dodecyl Sulfate (SDS)

It is anionic surfactant that is used in household products such as toothpastes, shampoos, shaving foams and bubble baths for its thickening effect and its ability to create lather. The molecule of sulfate group having 12 carbon atoms attached to a tail, giving the molecule the amphiphilic properties required for a detergent. It is prepared by sulphation of 1-dodecanol (lauryl alcohol,  $\text{CH}_3(\text{CH}_2)_{10}\text{CH}_2\text{OH}$ ) followed by neutralization with sodium carbonate.

### 2.5.2 Sodium Lauryl Ether Sulfate (SLES)

In the many personal care products (soaps, shampoos, toothpaste, detergent etc.), SLES is found as surfactant. It is an inexpensive and very effective foamer. It is a white gel material with a molecular weight higher than (422 g/gmol). Its chemical formula is  $[\text{CH}_3(\text{CH}_2)_{10}\text{CH}_2(\text{OCH}_2\text{CH}_2)_n\text{OSO}_3\text{Na}]$ . The product of commerce is heterogeneous, both in the length of the alkyl chain (12 being the mode of the number of carbon atoms), and  $n=3$  (number of ethoxyl groups).

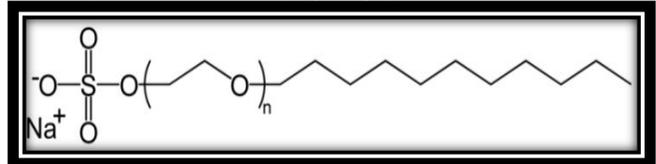


Figure 2.4 - Molecular structure of Sodium Lauryl Ether Sulfate (SLES)

### 2.5.3 Triton X-100 (Octylphenol ethoxylate)

$(\text{C}_{14}\text{H}_{22}\text{O}(\text{C}_2\text{H}_4\text{O})_n)$  is a nonionic surfactant which has a hydrophilic polyethylene oxide group (on average it has 9.5 ethylene oxide units) and hydrophobic group (M= 624 g/gmol). Also known as Octylphenol ethoxylate.

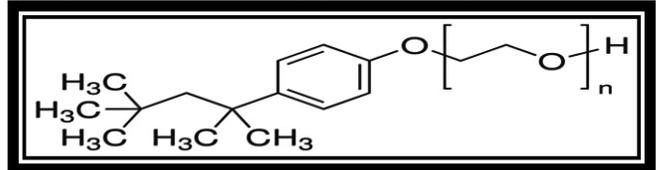


Figure 2.5 - Molecular structure of Triton X-100 (Octylphenol ethoxylate)

The part formed from ethylene oxide is more hydrophilic than the part from propylene oxide. It is very viscous at room temperature and is thus easiest to use after being gently warmed, Soluble in water. It is applications detergent & wetting agent for hard surface cleaners, metal cleaners, paper production, and textile processing emulsifier & process aid for metalworking fluids, and oilfield applications.

## 2.5 Physio-chemical properties of various surfactants

Table 2.1 - Properties of various surfactants

Surfactant (Chemical Name)	SDS (Sodium dodecyl sulfate)	SLES (Sodium lauryl ether sulfate)	Triton X-100 (Octylphenol ethoxylate)

Chemical Formula	$\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}$	$\text{CH}_3(\text{CH}_2)_{10}\text{C}_2\text{H}_4(\text{OCH}_2\text{CH}_2)_n\text{OSO}_3\text{Na}$	$\text{C}_{14}\text{H}_{22}\text{O}(\text{C}_2\text{H}_4\text{O})_n$
Ionic Nature	Anionic	Anionic	Non-ionic
(EO group)a	(0)	(3)	(9-10)
Appearance	White Powder	Slightly yellow viscous liquid	Clear liquid
Molecular weight	288.3 g / mole	422 g / mole	624 g / mole (average)
Manufacturer	Fisher	Henkel	Union Carbide
Melting point	>206°C	5°C	6°C
Boiling point	-	> 100°C	270°C
Specific gravity	0.4 g/cm <sup>3</sup>	1.03 g/cm <sup>3</sup>	1.065 g/cm <sup>3</sup>

### 3 OBJECTIVE AND SCOPE OF THE PROJECT

#### 3.1 Objective

To study the effect of different surfactants on critical heat flux

To study the effect of surfactant concentration on critical heat flux

To study the effect of wire diameter on critical heat flux with surfactant

To study the effect of sub-cooled temperature on critical heat flux with surfactant

#### 3.2 Scope Of The Project

The present study focuses on the boiling performance of aqueous anionic SDS, SLES and nonionic (Triton X-100) surfactant solutions in sub-cooled nucleate pool boiling covering for each surfactant, a wide range of pre-micellar to post-micellar concentrations. The aims of this study are summarized in the following points

1-Experimental determination of the critical heat flux with and without the addition of surfactants to pure water.

2-Quantify the effects of surfactant concentration, ionic nature, its ethoxylation, and molecular weight on the nucleate boiling performance of water on horizontal cylindrical heater.

3-Comparison obtained results with available correlations and data in literature.

4-Noticing any probable alteration in performance of bubble dynamics to record the difference caused due to the addition of surfactants to pure water.

### 4 METHOD OF IMPLEMENTATION

Selection of different surfactants, study the properties of different surfactant, identify the suitable surfactant which gives desired effect on critical heat flux, check the effect of selected surfactant on critical heat flux.

### 5 EXPERIMENTAL WORK

The experimental system was carried out to study the effect of surfactant additives on critical heat flux for water in nucleate pool boiling. The experimental techniques, the details of apparatus and the measuring devices are viewed in this chapter for aqueous anionic SDS, SLES and nonionic (Triton X-100) surfactant solutions. Pool boiling experiments were carried out a relatively wide range of surfactant concentrations.

#### 5.1 Experimental Apparatus

The apparatus consists of cylindrical glass container housing and the test heater (Nichrome wire). Test heater is connected also to mains via a dimmer. An ammeter is connected in series while a voltmeter across it to read the current and voltage. The glass container is kept on a stand, which is fixed on a metallic platform.

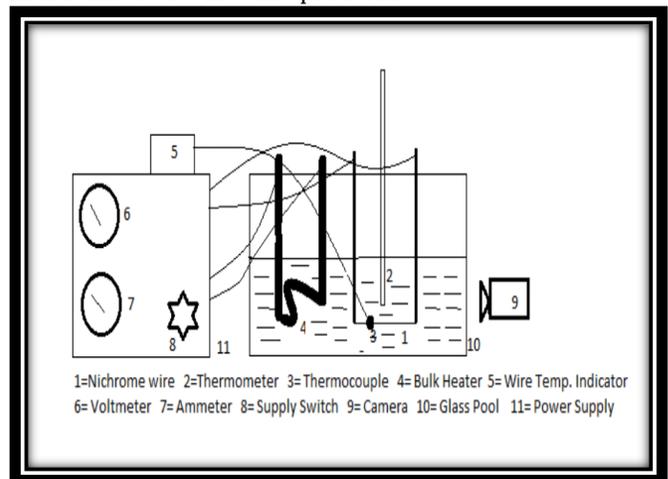


Figure 5.1 - Experimental set-up ( line diagram )



Figure 5.2 - Experimental set-up ( Instrument )

#### 5.2 Specifications:

- Glass container : Dia.186.5 mm.& Height 97mm
- Dimmer stat : 10 Amp, 230 volts.
- Power indicator : 400 W
- Thermometer : 0 to 1000 C
- Nichrome wire size : 0.12 to 0.29 mm

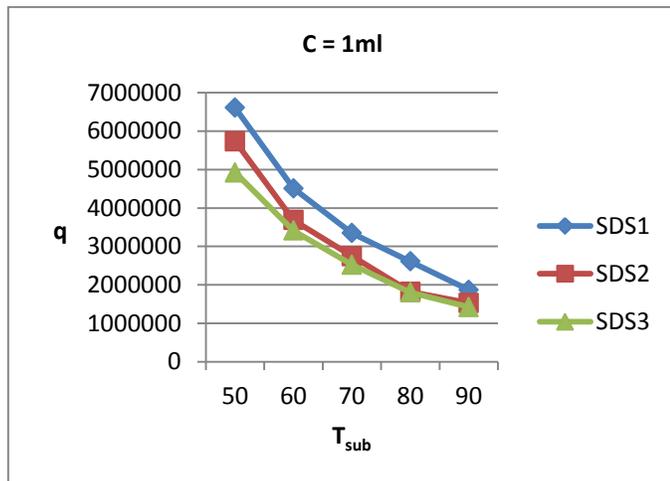
- Nichrome wire resistance : 6.4 ohms.
- Length of wire (L) : 80 mm

### 5.3 Procedure

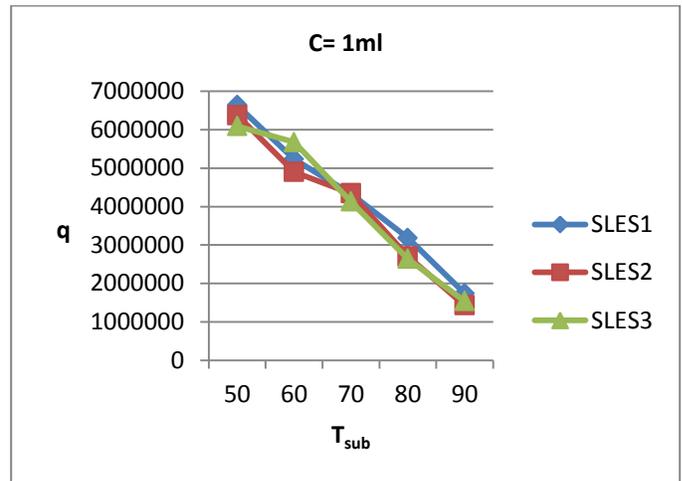
Close the valve V, Fill the water bath with water up to 3/4<sup>th</sup> of its capacity. Connect the test heater wire. Connect electric supply to the set up. Switch ON the heater and wait till desired temperature achieved. Switch-ON the test heater. Very gradually increase the voltage across it by slowly changing the variac from one position to the other and stop a while at each position to observe the boiling phenomena on wire. Go on increasing the voltage till wire breaks and carefully note down the voltage and current at this point. Bring the variac to zero voltage. Repeat the experiment for different water bath temperature.

Now remove all the water, add fresh water add any one surfactant (fixed concentration) and repeat the whole process. Repeat the experiment for different surfactants, for different concentration of surfactant with different diameters of the wire.

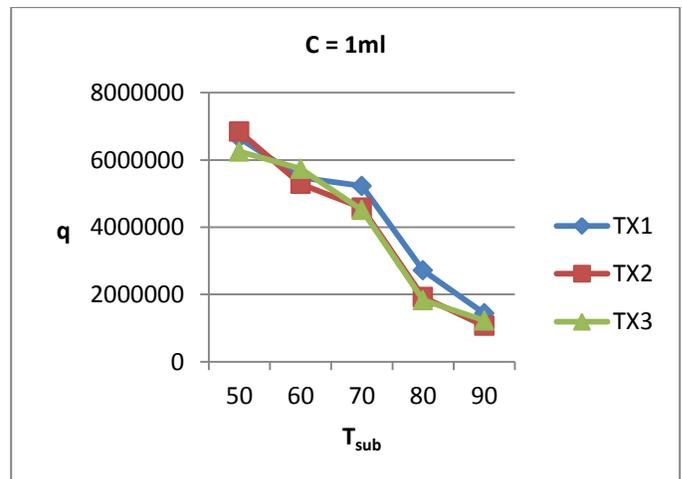
### 6 OBSERVATIONS AND RESULTS



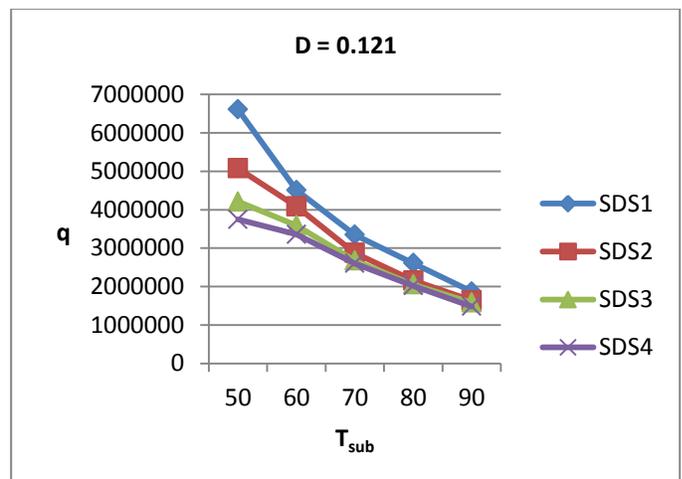
Graph 6.1 Critical heat flux Vs Sub-cooled Temp. for constant concentration of SDS at different wire diameter



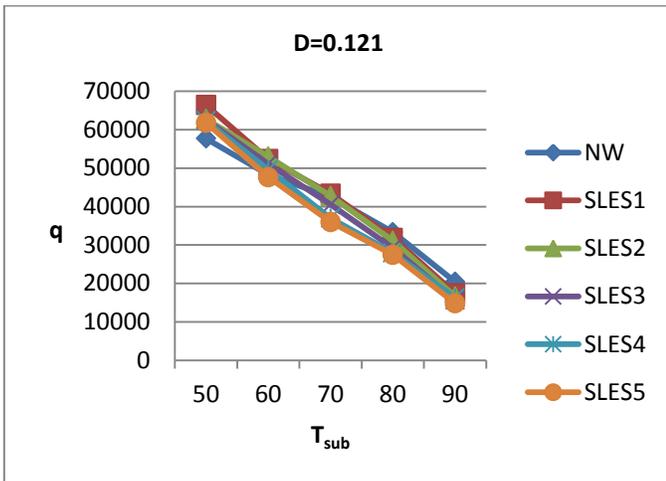
Graph 6.2 Critical heat flux Vs Sub-cooled Temp. for constant concentration of SLES at different wire diameter



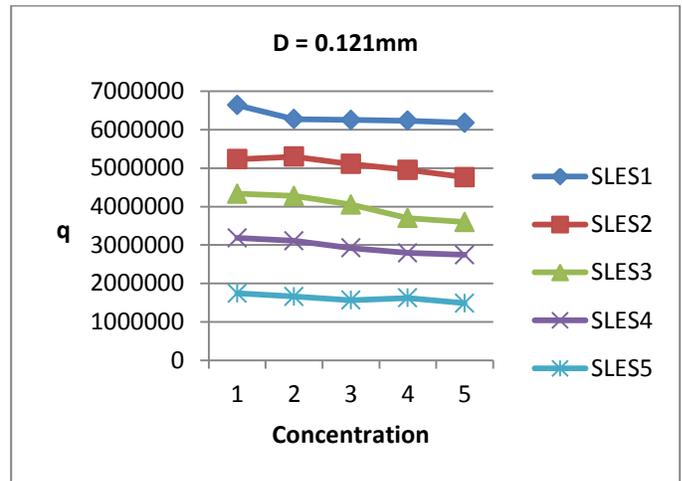
Graph 6.3 Critical heat flux Vs Sub-cooled Temp. for constant concentration of Triton X-100 at different wire diameter



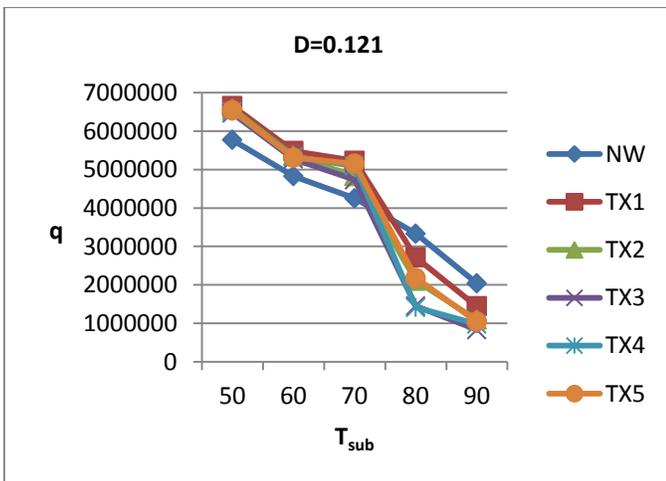
Graph 6.4 Critical heat flux Vs Sub-cooled Temp. for constant wire diameter at different concentration of SDS



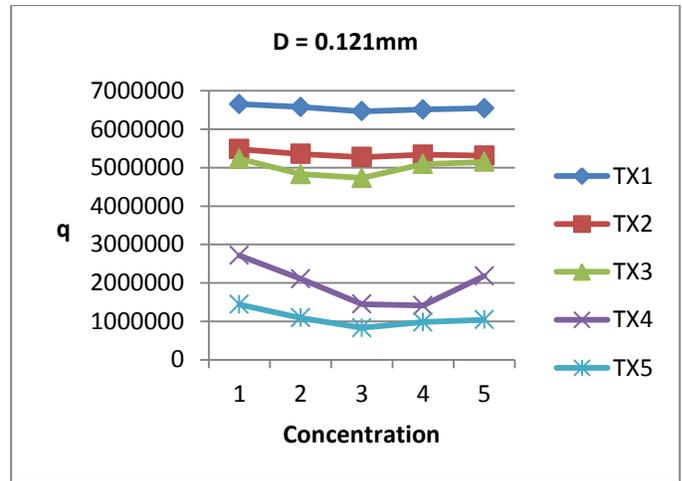
Graph 6.5 Critical heat flux Vs Sub-cooled Temp. for constant wire diameter at different concentration of SLES



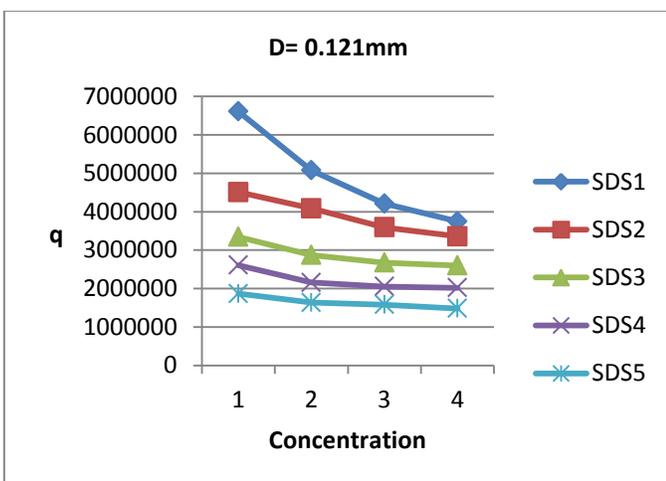
Graph 6.8 Critical heat flux Vs Concentration of SDS for constant wire diameter at different temp.



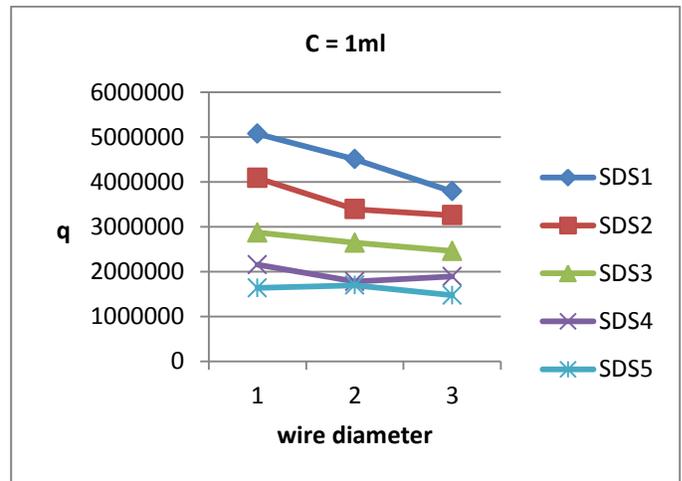
Graph 6.6 Critical heat flux Vs Sub-cooled Temp. for constant wire diameter at different concentration of SLES



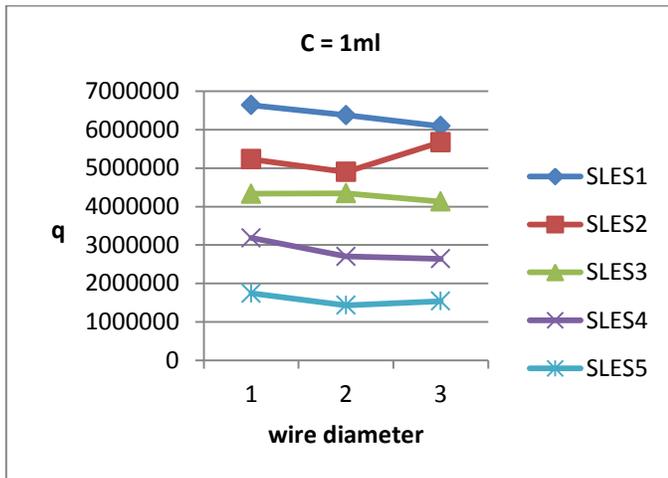
Graph 6.9 Critical heat flux Vs Concentration of SDS for constant wire diameter at different temp.



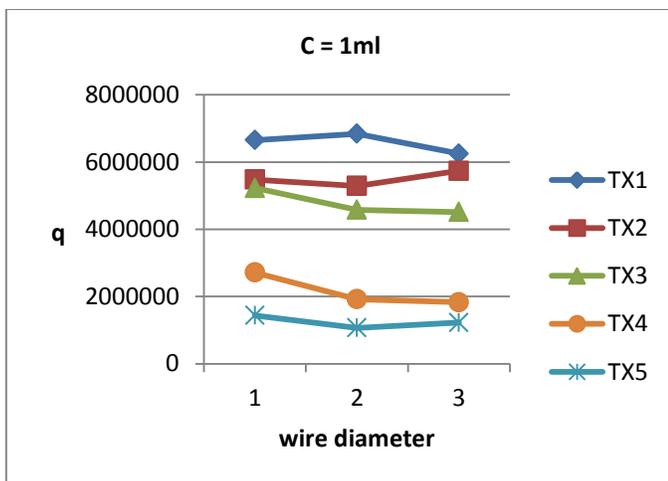
Graph 6.7 Critical heat flux Vs Concentration of SDS for constant wire diameter at different temp.



Graph 6.10 Critical heat flux Vs wire diameter for constant temp at different Concentration of SDS.



Graph 6.11 Critical heat flux Vs wire diameter for constant temp at different Concentration of SDS



Graph 6.12 Critical heat flux Vs wire diameter for constant temp at different Concentration of SDS

## 7 CONCLUSION

From all the gathered data from experimentation it is observed that, up to certain concentration (3 ml/lit) critical heat flux increases for different surfactant and after this concentration it decreases.

As we increases the diameter of wire critical heat flux get decreases.

As sub-cooled temperature is increased critical heat flux start to decrease.

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