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## Using Surfactant to Enhance the Nucleate Pool Boiling Heat Transfer

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**Abstract** In the present work, a controllable test rig is implemented to investigate experimentally the nucleate pool boiling heat transfer from a heated tube to an aqueous solution of surfactant. *Three* tubes are made of brass, aluminum, and stainless steel with almost the same surface roughness. Each one of these tubes is tested with *three* aqueous solutions of surfactant; the anionic sodium dodecyl sulfate (SDS), the anionic sodium lauryl ether sulfate (SLES) and the nonionic octylphenol ethoxylate with 9-10 moles of ethylene oxide (Triton X-100). Each one of the three aqueous solutions is investigated at concentrations of 0, 200, 500, 1000 and 1500 ppm. The experimental investigations showed that, for all studied cases, the heat transfer coefficient increased with the increase of heat flux. For all cases of SLES and SDS, the heat transfer coefficient increased with the surfactant concentration but with TRITON-X, it increased with the concentration until the value of 500 ppm, and beyond this value, it did not exhibit a considerable increase. The rate of increase in the heat transfer coefficient starts to decrease with the higher values of surfactant concentration. The highest enhancement in the heat transfer coefficient over that of the distilled water was observed when using SDS solution at concentration 1500 ppm on brass surface, whose heat flux is  $120 \text{ kW.m}^{-2}$ , and this enhancement was about 185 %.

**Keywords** Enhancement, Heat, tube, Pool Boiling, surfactant

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### Nomenclature and Abbreviations

#### Alphabetic

|                                |   |
|--------------------------------|---|
| A                              | the heated area of the test tube, $\text{m}^2$ .                                    |
| c                              | concentration, ppm.   |
| $c_l$                          | liquid specific heat, $\text{kJ.kg}^{-1}.\text{k}^{-1}$ .                           |
| D                              | discharge of the cooling water, $\text{m}^3.\text{s}^{-1}$ .                        |
| h                              | heat transfer coefficient of surfactant solution, $\text{w.m}^{-2}.\text{c}^{-1}$ . |
| I                              | current supplied to the test tube heater, Ampere.                                   |
| l                              | heated length of heater.  |
| q                              | heat flux from the tube surface, $\text{W.m}^{-2}$ .                                |
| Q                              | total heat produced from the tube surface, W.                                       |
| R                              | resistance of tube heater, Ohm.   |
| $R_a, R_q, R_t, R_y$ and $R_z$ | surface roughness parameters, DIN 4762 $\mu\text{m}$ .                              |
| T                              | fluid temperature, $^{\circ}\text{C}$   |
| V                              | Voltage across the test tube heater, Volt   |

#### Greek Symbols

|               |                                   |
|---------------|-----------------------------------|
| $\varepsilon$ | percentage of enhancement         |
| $\rho$        | liquid density $\text{kg.m}^{-3}$ |



**Subscripts**

|     |                        |
|-----|------------------------|
| ave | average                |
| in  | inlet cooling water    |
| L   | liquid condition       |
| o   | outlet cooling water   |
| s   | tube surface condition |
| w   | pure distilled water   |

**Abbreviations**

|                |  |
|----------------|--|
| CHF            | critical heat flux                                       |
| DTAC           | dodecyl trimethyl ammonium chloride                      |
| LCD            | Liquid-crystal display                                   |
| MPW            | Modulated pulse width                                    |
| PID            | proportional–integral–derivative controller              |
| S <sub>1</sub> | Brass alloy C44400                                       |
| S <sub>2</sub> | Aluminum alloy 6061                                      |
| S <sub>3</sub> | Stainless steel 316 L                                    |
| SDS            | sodium dodecyl sulfate                                   |
| SLES           | sodium lauryl ether sulfate                              |
| Triton-X 100   | octylphenol ethoxylate with 9-10 moles of ethylene oxide |

**Introduction**

Boiling process occurs; either in a superheated liquid, "homogeneous" or in vapor cavities on a heated surfaces, "heterogeneous". In practice, this process is essential in many heat transfer applications, such as air conditioning, refrigeration systems, water desalination, etc. The pool boiling process is that type of a boiling processes, which is characterized by a zero bulk fluid velocity and is encountered in many important engineering applications, such as; cooling the nuclear reactors, power generation, chemical, petrochemical industries, air conditioning, refrigeration, cryogenics, metallurgical quenching process, electronics cooling, desalination of seawater and nuclear power plants. A large number of system variables affect the characteristics of the boiling process, such as; heater geometry, surface finish, wetted area, contamination, liquid sub-cooling, flow velocity, gravity, pressure, thermal properties, additives which are added to the boiling liquid. Nucleate pool boiling phenomenon has attracted considerable research and practical attention, due to Its ability to transfer large amounts of heat with relatively small temperature differences. Many researchers investigated the factors that affect the heat transfer during the pool boiling such as; bubble growth, bubble dynamics, effects of heater surface characteristics, fluid-surface interaction, and fluid properties, among others. In recent years, attention is made to investigate the techniques that lead to enhance the pool boiling heat transfer, and one important technique is the addition of a surfactant to the boiling liquid. Surfactant is a chemical organic substance, which is added to the boiling fluid to change the surface properties of it. In practice, there are many types of surfactants in the form of wetting agents that lowers the fluid surface tension, allow easier spreading, and lower the interfacial tension between two phases. In addition, a surfactant was proved to affect greatly the heat transfer processes, and so, it is used in the electronic component cooling and desalination processes. Generally, it is believed that small amount of surfactant can increase boiling heat transfer. The extent of enhancement has been found to be dependent on additive concentrations, its type and chemistry, wall heat flux, and the heater geometry.

**Brief Survey of Previous Work**

Hao Peng et al, [1], investigated the effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based Nano-fluid. They used three types of surfactants including Sodium Dodecyl Sulfate (SDS), Cetyltrimethyl Ammonium Bromide (CTAB) and Sorbitan Monooleate (Span-80). The refrigerant-based Nano-fluid was formed from Cu Nano-particles and refrigerant R113. They stated that, the presence of surfactant



enhances the nucleate pool boiling heat transfer of refrigerant-based Nano-fluid on most conditions, but deteriorates the nucleate pool boiling heat transfer at high surfactant concentrations. Elghanam et al, [2], investigated the effect of adding three different surfactants to boiling distilled water on the nucleate pool boiling heat transfer performance using heated tube. They used sodium dodecyl sulfate (SDS) and sodium laurel ether sulfate (SLES) as anionic and Triton X-100 as nonionic. They achieved percentages of increase in the heat transfer coefficient, which ranged from 133% for Triton X-100, 185% for SLES and 241% for SDS. Zicheng et al, [3], investigated the nucleate pool boiling heat transfer characteristics for different aqueous surfactant solutions; 99% sodium dodecyl sulfate (SDS) and Triton X-114 for a range of heat flux ( $24.7-109.1 \text{ kW/m}^2$ ) and mass concentrations (50-8000 ppm for SDS and 20-1000 ppm for Triton X-114). They concluded that, the enhancement of boiling heat transfer by the addition of surfactants is the complex effects of surfactant species, the reduction of surface tension, the changes of the contact angle. Gajghate, [4], investigated the saturated nucleate boiling of aqueous ammonium chloride on a nichrome wire heater. The boiling performance is enhanced by using of ammonium chloride as an additive. They achieved a maximum level of enhancement, with 2,600 ppm concentration of additive. For concentrations more than 2600 ppm, significant enhancement is not recorded. They stated that, the enhancement in heat transfer is due to the change in the thermo-physical properties of the aqueous solution, and the addition of ammonium chloride to distilled water, the surface tension of the mixture considerably reduces. Qasim and Al-Sukaini, [5], investigated the pool boiling performance of water under atmospheric pressure in case when adding an ionic sodium lauryl sulfate (SLS), and in case of using structured surfaces. They found that, the optimum boiling heat transfer augmentation of SLS is 66.27%, and the bubble departure frequency is higher than that of pure water. Dikici et al, [6], studied the water pool boiling phenomena under the influence of sodium lauryl sulfate (SLS), ECOSURF™ EH-14, and ECOSURF™ SA-9, as surfactant. They stated that, times until boiling were found to be; 17, 10.3, and 19.6 % lower, for SLS, EH-14, and SA-9, respectively, compared to pure water, and the reduction in surface tension leads to a higher nucleation site density and more small bubbles on the boiling surface. Abdul Najim et al, [7], investigated the bubble growth in aqueous 2-Ethyl-1-Hexanol solution at 880 ppm concentration of 2-Ethyl-1-Hexanol which is critical micelle concentration (cmc). They generated a single bubble using the right angle tip of a hypodermic needle as a nucleation site. At heat flux ( $q = 20 \text{ kW/m}^2$ ), the bubble departure diameter was found to be almost equal for both water and aqueous surfactant solution, and at high heat flux ( $q = 100 \text{ kW/m}^2$ ), bubble departure diameter increases in water, but, decreases significantly in aqueous surfactant solution. Hetsroni et al, [8], conducted Experiments on sub-cooled boiling at  $30 \text{ }^\circ\text{C}$  on a heated wire,  $d = 50 \text{ }\mu\text{m}$ , and a heated tube,  $d = 1.5 \text{ mm}$ . For boiling of water on the wire, surface tension gradient played an important role in promoting the heat transfer, and for sub-cooled boiling on the wire, when it is submerged in surfactant solutions, jet flow was not observed. The boiling curves with the micro-scale heater did not depend on surfactant concentration. Wang et al, [9], carried out comparative experiments of boiling around a heated wire for different types of surfactant solutions, ethanol and silicone oil in order to explore the mechanism of surfactant, when added to enhance the boiling heat transfer. They used Cationic surfactant of CTAC, anionic surfactant of sodium dodecyl benzen esulfonate (SDBS) and nonionic surfactant of alkyl polyglycoside (APG). They stated that, in all three kinds of surfactant solutions, Bubble jet and bubble explosion phenomenon, exhibited excellent heat transfer effect. For the pool boiling in ethanol, only bubble jet around the heated wire exhibited better heat transfer efficiency than water. Xu and Zhao, [10], investigated the pool boiling heat transfer of gradient metal foams in saturated pure de-ionized water and surfactant solutions at atmospheric pressure. Pore density gradients are from 5 PPI to 100 PPI. They performed a parametric study by varying foam layer number and material. They also investigated Alumina Nano-particle and surfactant (SDS and Triton X-100) effects on the pool boiling heat transfer. They concluded that, They concluded that, They concluded that, They concluded that, for no-Nano-particle-deposited gradient metal foams, pool boiling heat transfer in deionized water is heavily dependent on foam layer number and material gradient. For Nano-particle-deposited gradient metal foams, pool boiling heat transfer in surfactant solutions is dependent on surfactant concentrations and Nano-particle deposition condition on the metal skeletons. Wang, [11], used an aqueous solution of cetyltrimethyl ammonium chloride (CTAC) with the addition of sodium salicylate (nasal) at the same mass concentration, and tested the boiling heat transfer performances of a horizontal platinum wire for different concentrations of CTAC/nasal solution (0-400 ppm).



They found that, the tested surfactant solution significantly augmented the boiling heat transfer as compared with water, and the best heat transfer performance was found at the concentration ranging from 5 to 100 ppm. They stated that, around the heated wire in CTAC/nasal solutions (at concentration beyond 0.1 ppm), the bubble explosion is apparently different from the previously reported boiling explosion due to homogeneous nucleation. Mosyak et al, [12], performed Experiments to study the enhancement of heat transfer from the wire of  $d = 50 \mu\text{m}$  and the tube of  $d = 1.5 \text{ mm}$  in sub-cooled pool boiling by ultrasonic waves. They used a clean water and Alkyl (8-16) Glucoside surfactant solutions of different concentrations. They stated that, for boiling on the wire of  $d = 50 \mu\text{m}$  in sub-cooled water,  $T_b = 30 \text{ }^\circ\text{C}$ , enhancement of heat transfer coefficient due to applied ultrasonic field is about 70% and 20% at heat flux  $q = 620 \text{ kW/m}^2$  and  $q = 1350 \text{ kW/m}^2$ , respectively. For boiling in surfactant solutions at the same boiling conditions, enhancement of heat transfer coefficient is in the range of 5–10% at heat flux  $q = 620 \text{ kW/m}^2$  and 10–16% at heat flux =  $1350 \text{ kW/m}^2$ . Abdul Najim, et al, [13], (2017) studied experimentally the saturated pool boiling of aqueous Nicotine (an innovative non-ionic surfactant) solutions, on a Nichrome wire heater. An optimum level of enhancement was observed in Nicotine solution concentration of 2500 ppm.

### Objectives of the Present Work

In the present work, it is intended to investigate the heat transfer from a heated horizontal tube that is surrounded by aqueous solution of surfactant during a nucleate pool boiling process. Three tube materials are used; Brass, Aluminum, and Stainless steel, each tube was tested with four liquids; pure water and three aqueous solutions of surfactants; TRITON-X, SLES, and SDS. The concentrations of each one of the three aqueous solution are 200, 500, 1000 and 1500 ppm. The test rig is prepared to be capable of changing and maintaining the experimental conditions as required, so that, it is possible to execute many experiments and investigate a wide range of values of a certain parameter with minimum time and effort. Table 1 illustrates the Investigated Cases.

**Table 1:** The Investigated Cases

| Brass Surface           | Aluminum Surface        | Stainless Steel Surface |
|-------------------------|-------------------------|-------------------------|
| Pure water              | Pure water              | Pure water              |
| TRITON-X 100, 200 ppm.  | TRITON-X 100, 200 ppm.  | TRITON-X 100, 200 ppm.  |
| TRITON-X 100, 500 ppm.  | TRITON-X 100, 500 ppm.  | TRITON-X 100, 500 ppm.  |
| TRITON-X 100, 1000 ppm. | TRITON-X 100, 1000 ppm. | TRITON-X 100, 1000 ppm. |
| TRITON-X 100, 1500 ppm. | TRITON-X 100, 1500 ppm. | TRITON-X 100, 1500 ppm. |
| SLES, 200 ppm.          | SLES, 200 ppm.          | SLES, 200 ppm.          |
| SLES, 500 ppm.          | SLES, 500 ppm.          | SLES, 500 ppm.          |
| SLES, 1000 ppm.         | SLES, 1000 ppm.         | SLES, 1000 ppm.         |
| SLES, 1500 ppm.         | SLES, 1500 ppm.         | SLES, 1500 ppm.         |
| SDS. 200 ppm.           | SDS. 200 ppm.           | SDS. 200 ppm.           |
| SDS. 500 ppm.           | SDS. 500 ppm.           | SDS. 500 ppm.           |
| SDS. 1000 ppm.          | SDS. 1000 ppm.          | SDS. 1000 ppm.          |
| SDS. 1500 ppm.          | SDS. 1500 ppm.          | SDS. 1500 ppm.          |

### Experimental Preparations

#### The Test Rig

A *controlled* test rig is prepared to investigate the heat transfer in a nucleate pool boiling process in which, different horizontal heated tubes are cooled by an aqueous surfactant solution with different concentration values. Figure 1 shows a Schematic diagram of the experimental test rig, which consists of the following main components;



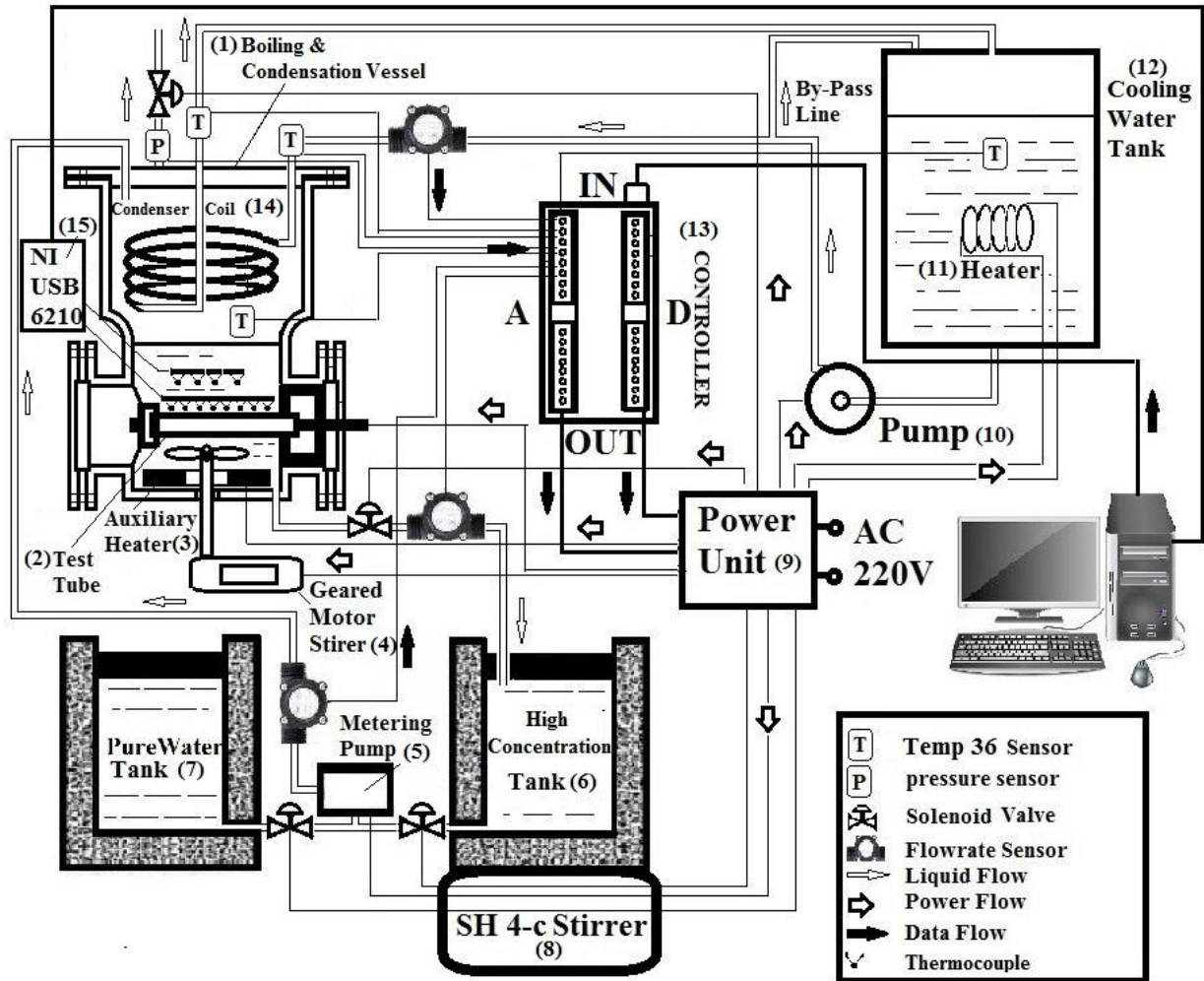


Figure 1: The Experimental Test Rig

#### Boiling and Condensation Vessel, (1)

It consists of two stainless steel (316 L) hollow cylinders of different diameters connected by semi conical shape 80 mm height. The upper cylinder has dimensions of 264 mm inner diameter, 280 mm outer diameter, and 200 mm length, and it contains a cooling coil, which is used in condensing the vapors of the aqueous solution. The lower cylinder has inner diameter, outer diameter and length of 150 mm, 166 mm and 200 mm, respectively, and it contains the test tube, (2), the auxiliary heater, (3), whose diameter and maximum power are 120 mm and 2kW, respectively, and a motor driven stirrer, (4). It has two glass windows (90 mm diameter each), which are perpendicular to each other, and whose centerlines are at level of 100 mm from the bottom. These two glass windows are used for visual observation of bubble formation at the test tube. The vessel is well insulated by a 2 cm-thickness layer of Polyurethane foam (Thermal conductivity is  $0.023 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ ). A pressure sensor, (P) is fitted to the top wall of the vessel, and two temperature sensors, (T), are fitted to the inlet and outlet of the condensing coil. The test tube is fixed to the sidewall flange so that; they have the same centerline. The vessel bottom is provided with drainage port that discharges the required amount of the aqueous solution to the high concentration tank. Another sealed port surrounds the stirrer shaft, which has the same centerline as the auxiliary heater. Another temperature sensor is secured inside the vessel in the gas side, which monitors the saturation temperature. The three temperature sensors and the pressure sensor are connected to the controller through a breadboard





### Test Tubes (Boiling Surface), Figure 1, Part 2

The test section consists of a horizontal hollow tube (made of either brass, aluminum alloy 6061 or stainless steel 316L), whose outer diameter, inner diameter, and length are 22, 15, and 120 mm, respectively. It contains an electric cartridge heater (100 mm long, 220 V and 1 kW), whose insulated lead wires are press-fitted inside the test tube using conductive grease. This grease fills any remaining air gaps, and provides a good heat transfer. The heater is centrally located inside a copper tube, and insulated from both ends to minimize the axial heat loss. The outer surface of each one of the three test tubes is treated mechanically by applying successive sand papers with different roughness degrees; 400, 800, 1000, 1200, 1500, 2300, and 4000 grit).

After that, the surface is polished with a polishing powder, cleaned with acetone, rinsed with distilled water and dried by a hot dry air. The roughness of the three surfaces are then tested using a surface profile-meter, which checks the parameters  $R_a$ ,  $R_q$ ,  $R_t$ ,  $R_y$  and  $R_z$ , that are defined by DIN 4762. The tube surface temperature is taken as the average of the readings that are measured by eight copper-constantan thermocouples. These thermocouples are fitted to the tube surfaces by embedding them in longitudinal grooves, that are notched underneath the test tube surface, and are 1 mm depth, and these the thermocouple are distributed uniformly through the surface. Another four copper- constantan thermocouples are distributed around the tube to measure the liquid bulk temperature. The twelve thermocouples are used in calculating the heat transfer coefficient and are connected to a data acquisition system that receives all their output signals, and converts them into a spread sheet data by the aid of a special software.

### Cooling Water Circuit

The cooling water circuit is used to absorb the boiling latent heat of the aqueous solution. This circuit works with the auxiliary heater to maintain the aqueous solution at constant saturation temperature. The water leaves the tank, (12) to the circulating pump, (10), which is controlled to produce the required discharge of the cooling water. The maximum power and head of the pump are, 0.33 kW and 20 m, respectively. The cooling water then enters a coiled tube heat exchanger, (the condenser coil, (14)), located inside the boiling and condensation vessel.

### The Tanks

Three tanks are used in this test rig;

- The cooling water tank, (12), whose capacity is 80 liters, and contains two ports on its top; one to receive the return water from the condensing coil, and the other is to receive the water from the bypass line. Another port is located in its bottom through which, the water is delivered to the circulating pump. The water temperature is maintained by a 2 kW heater, (11), which is switched ON, when the temperature decreases below the required temperature.
- The high concentration tank, (6), whose capacity is five liters, and it contains a surfactant aqueous solution of concentration 3000 ppm This tank is used to supply the vessel with a high concentration aqueous solution to produce the required mixture concentration in the vessel. The solution, which is returned from the vessel enters the tank through a port in the top cover. The tank bottom includes a port through which, the aqueous solution can move to the metering pump. The tank is supported by a magnetic stirrer in order to ensure a uniform concentration.
- The distilled water tank, (7), whose capacity is five liters too, and it contains a pure distilled water. This tank is used to supply the vessel with a distilled water to produce the required mixture concentration in the vessel. The required amount of distilled water leaves the tank to the metering pump through a port in the tank bottom.

The cover on the top of any one of the last two tanks is capable of sliding vertically up and down to allow the inner space to expand or contract, when it receives or supplies any amount of the aqueous solution. The cover weight on the top of the liquid slightly increases the pressure inside the tank, and that aids the discharging process from the tank to the metering pump, (5).

### Measuring and Control Devices

The following paragraph includes brief description of the used measuring and control devices, that are used in the test rig;



- The controller, (13), is a 8051 Architecture Microcontrollers; a rich Atmel portfolio of MCUs based on the 8051 instruction set.
- The acquisition system type is a NI USB- 6210, input, 16- bit resolution and 256 kS/s
- The metering pump is WEA, HY Series with a diaphragm PTFE. Its frequency is from 0 to 160 Strokes/minute. It works at 230 volt VAC 50/60 Hz and discharges from 0 to 3.0 Liters / Hour
- Flow Rate Sensor; Model Fs 300 A G, 3/4" Fitting, Flow rate: 1~60 L/min, Max, working Current: 15ma (DC5 V), Working Voltage: DC 5V~24V, and accuracy: 5%~10%.
- Temperature sensor; The TMP36, 10 mV/8°C Scale Factor,  $\pm 2^\circ\text{C}$  Accuracy, Less than 50  $\mu\text{A}$  Quiescent Current, and is located in the water tank.
- Pressure Transducer Sensor; SKU237545, and is located at the top of the condensation vessel
- Magnetic Stirrer; Faithfulsh-4c Ceramic, Model NO.: SH-4C, Certification: CE, ISO, Max Vol.: 5000ml, 220V/ 110V

### Experimental Procedure

Prior to performing the experiments, the test sections are cleaned routinely before and after each test run with a sequence of operations involving washing with alcohol, rinsed with distilled water several times and dried by a supply of hot dry air. Then, the system is evacuated to a pressure of about 15 mm Hg. If no leakage is detected over a 24 hours interval, the following *procedure* is followed;

- 1) To prepare five liters of the high concentration solution of the surfactant, ( 3000 ppm); the SDS surfactant is available as powder, so, using a precision electronic weighting device, we get 15.05 gm, and adding them to five liters of distilled water. This high concentration solution tank will stay on the stirrer to the end of the experiment.
- 2) The other two surfactants; SLES and TRITON X-100 are available in liquid form, so, to get five liters of a solution with concentration 3000 ppm, we have to consider the surfactant density. We need, then, to measure 15.00312 ml, which is beyond the pipette accuracy, so, approximating the amount to 15.003 ml will not considerably affect the concentration accuracy. Adding this amount to five liters of distilled water to get the high concentration solution, (approximately 3000 ppm).
- 3) To remove the dissolved non-condensable gases, the high concentration solution is delivered to a *separate* container, which includes a variable power electric heater, digital thermometer, and an adjustable check pressure valve. The heater is operated at a power of about 1375 W to heat the solution under atmospheric pressure. After boiling the solution, the heater is kept working for one hour, and During this process, the check valve maintains the pressure at atmospheric value. The heater power is then reduced gradually until the temperature is near the saturation value and then, is maintained for about 45 minutes, Elghanam (2011). Now, the test rig is ready to start the experiment.
- 4) After installing the test tube, the vessel is charged with three liters of the distilled water, that is enough to raise the liquid surface to about 120 mm above the top of the test tube surface.
- 5) The controller *starts the experiment* by increasing the power supplied to the auxiliary heater from zero to its maximum by the gradual increase of the MPW signal, which is sent to the power unit. After achieving the maximum power, the heater keeps working until the temperature sensor indicates the saturation temperature value. The controller is programmed to allow ten seconds delay between any two successive readings for either pressure or the temperature sensors inside the vessel in order to ensure a correct sensing of the trend of change in these quantities.
- 6) During the heating of the water, the controller keeps reading the pressure and temperature sensors inside the vessel. And if the pressure exceeds the atmospheric value, and the temperature is still below the saturation value, that corresponds to the atmospheric pressure, the controller sends a digital signal to the power unit to open the solenoid valve in the vessel until retrieving the atmospheric value. And if the temperature inside the vessel started to exceed the saturation, that corresponds to the atmospheric pressure, the controller does not allow the solenoid valve to open, even if the pressure exceeded the atmospheric pressure value because, this increase is caused by the increase of temperature above the



saturation value. In such case, the controller switches the auxiliary heater off, and sends a MPW signal to the power unit, that operates the circulating pump at its *lowest* power until retrieving the saturation temperature again.

- 7) Although the vessel is well isolated, but still loses heat to the low temperature surrounding, this unpredicted losses constitute a *steady disturbance* to the temperature. So, the controller always, uses the decrease in vessel temperature below the saturation temperature as a feedback to a PID technique, that determines the correction in MPW of the signal. This signal is sent to the power unit which determines the required power supplied to the auxiliary heater, which will maintain a saturation temperature value inside the vessel.

- 8) The *steady* values for both the atmospheric pressure and its corresponding temperature are recognized, when the percentage of difference between any two successive readings of at least five successive readings lies within the range of  $\pm 1\%$  of the preceding value. After achieving the steady state, the controller then, sends two analogue signals to the power unit, the first is to supply the test tube heater with about 124.3 Watts, which corresponds to a heat flux of  $15 \text{ kW.m}^{-2}$ , and the second is to supply the circulating pump with a power, that corresponds to a discharge, D, where;

$$D = V^2 / [ R \cdot \rho_w \cdot c_w (T_{in} - T_o)] \quad (1)$$

V is the voltage that is applied across the tube heater to produces the required heat flux and R is the heater resistance.  $T_{in}$  and  $T_o$  are the inlet and outlet cooling water temperatures, that are measured by the two temperature sensors as shown in figure 1.

It is important to ensure that, the accurate value of the cooling water flow rate is supplied to the vessel, because, it will absorb the tube heater energy to achieve a thermal equilibrium state. So, the program records the *calculated value* of 'D', and it continuously compares it with the current actual value, that is read by the flow rate sensor, figure 1, and the difference is used as a feedback to a PID technique. It adjusts the power signal to the circulating pump, until the error in the flow rate lies within  $\pm 1\%$  of its calculated value. The pressure adjustment procedure, that is mentioned in step (4) is still operated until achieving almost a steady state pressure and temperature inside the vessel, with a tolerance within the value of  $\pm 1\%$ .

- 9) The acquisition system is programmed to compare the temperature reading of each one of the twelve thermocouples with its previous one. It does not record any temperature reading unless it achieves its *steady state* condition, which is recognized by the same criteria, mentioned in step (7). And it calculates the heat transfer coefficient according to;

Calculation of  $h$  and  $h_1$ ;

$$q_s'' = V^2 / (R \cdot A_s) \quad (2)$$

$$h_1 = q_s'' / (T_s - T_1) \quad (3)$$

$$T_s = \sum_{i=1}^{i=8} T_i / 8 \quad (4)$$

$$T_1 = \sum_{i=1}^{i=4} T_i / 4 \quad (5)$$

Percentage of enhancement;

$$\delta h\% = 100 (h_1 - h_w) / h_w \quad (6)$$

- 10) When the temperature sensors inside the vessel and in the inlet and outlet ports of the cooling water circuit indicates steady readings according to the criteria, that is mentioned in step (7), the controller then makes five minutes delay to ensure that, the acquisition system accomplished its reading process.
- 11) Then, the controller starts a new run with a new predetermined heat flux. The new value requires to increase the previous power by 124.3 Watts. Then the steps from 4 to 9 is repeated, and so on until, achieving a heat flux of  $120 \text{ kW.m}^{-2}$ , then, the first experiment group is accomplished.
- 12) The current values of the *surfactant concentrations* in both the vessel and the high concentration tank, figure 1, are zero and 3000 ppm, respectively. To start a new group of experiments with a new surfactant concentration in the vessel, the new surfactant concentration in the *high concentration tank* must be calculated and updated by the controller. That is accomplished as follows;





- the controller opens the pressure port in the vessel *top cover* to compensate any little change of pressure during the change process, then, it opens the port in the vessel *bottom* to discharge the vessel solution for an *interval of time*,  $t_1$ . This time is required by the vessel to discharge an amount of solution,  $m$ , to the high concentration tank. This time interval is estimated from;

$$t_1 = m / D_{vh1} \quad (7)$$

$$m = \frac{15 (C_{v,old} - C_{v,new})}{[3 (C_{v,new} - C_{v,old}) + 5 (C_{v,old} - C_{h,old})]} \quad (8)$$

$C_{v,old}$  the old value of liquid concentration inside the vessel (before each mixing process), (initially, equals 200 ppm)

$C_{v,new}$  the new value of liquid concentration inside the vessel, (after each mixing process)

$C_{h,old}$  the old value of liquid concentration inside the high concentration tank, (before each mixing process), (initially, equals 3000 ppm)

$D_{vh1}$  discharge from the vessel to the high concentration tank,

and, it is supplied to the controller from a mass flow rate sensor, figure 1.

- The controller switches the vessel valve off, and opens the high concentration tank valve on. It then operates the *metering pump* to return the same solution amount,  $m$ , to the vessel. The metering pump works for a different time interval,  $t_2$ , where;

$$t_2 = m / D_{vh2} \quad (9)$$

$D_{vh2}$  is the discharge from the high concentration tank to the vessel and, it this value is supplied to the controller from another mass flow rate sensor, figure 1.

- During this process, the motor stirrer keeps mixing the solution, and remains working after the end of the mixing process for five minutes, until the controller switches it off.
- 13) The *changeover* from one aqueous *surfactant* solution to the other must be preceded by a reliable cleaning protocol for ensuring that there are no remaining remnants of the earlier sample inside the boiling condensation vessel. This is achieved by three-cycle operation of cleaning/rinsing with distilled water, acetone, and ethanol, and vacuum drying.
  - 14) The steps from 4 to 12 are repeated until accomplishing the experiments for the three surfactant types beside those of the distilled water

### Data Validation

For the purpose of validation, the results of the present experimental work, for the heat transfer coefficient, were compared to those of the previous work of R.I. Elghanam (2011). Figure 2 illustrates the compared data for the cases of surfactants, TRITON-X, SLES and SDS at concentration 500 ppm on the aluminum tube. Whereas, figure 3 illustrates the compared data for the cases of surfactants, TRITON-X, SLES and SDS at concentration 1000 ppm on the stainless steel tube. The heat flux in every experiment differs from that of the preceding one by 15 kW. It is obvious that, the curves of the present work have the same trends as those of Elghanam, but the data are slightly higher. This may be because, Elghanam used one thermocouple to measure the solution temperature, which does not ensure a uniform saturation temperature everywhere in the solution, especially, with the heat losses, which vary from position to another in the vessel. In such conditions, the acquisition system may receive temperature readings that indicate higher temperature differences and, accordingly, lower heat transfer values.

In the present work, four thermocouples are used to measure the solution temperature in different positions of the solution. That is beside a temperature sensor, which continuously allows the controller to adjust the cooling flow rate, the tube heater, auxiliary heater, and the stirrer in order to ensure that, no position in the liquid has a temperature *lower* than the saturation value. Lower temperature leads to a higher temperature *difference* and accordingly, a lower heat transfer coefficient



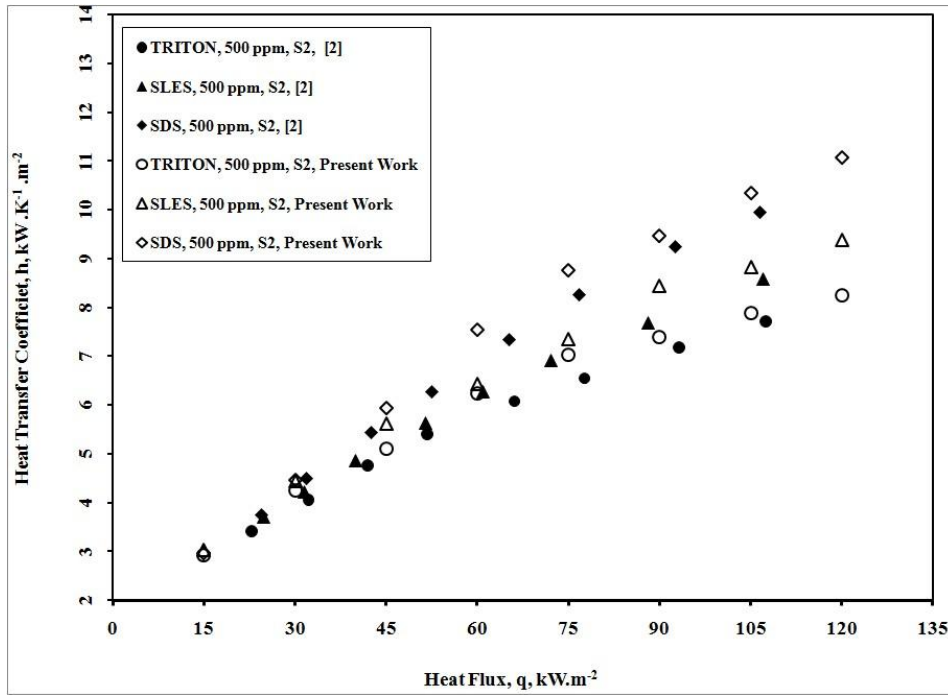


Figure 2: The compared data for surfactants, TRITON-X, SLES and SDS at concentration 500 ppm on the aluminum tube.

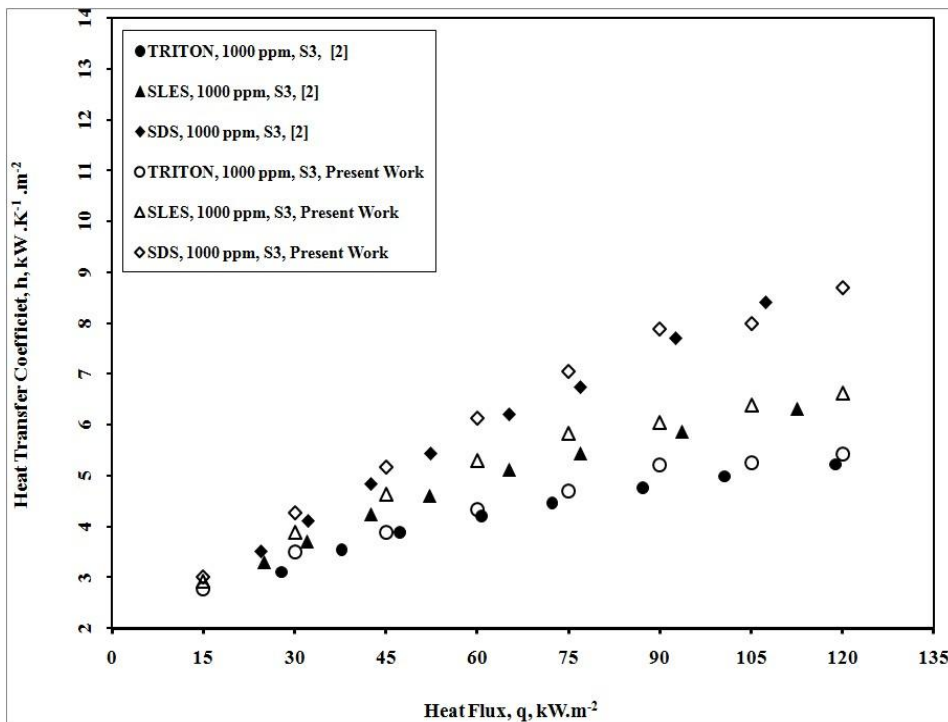
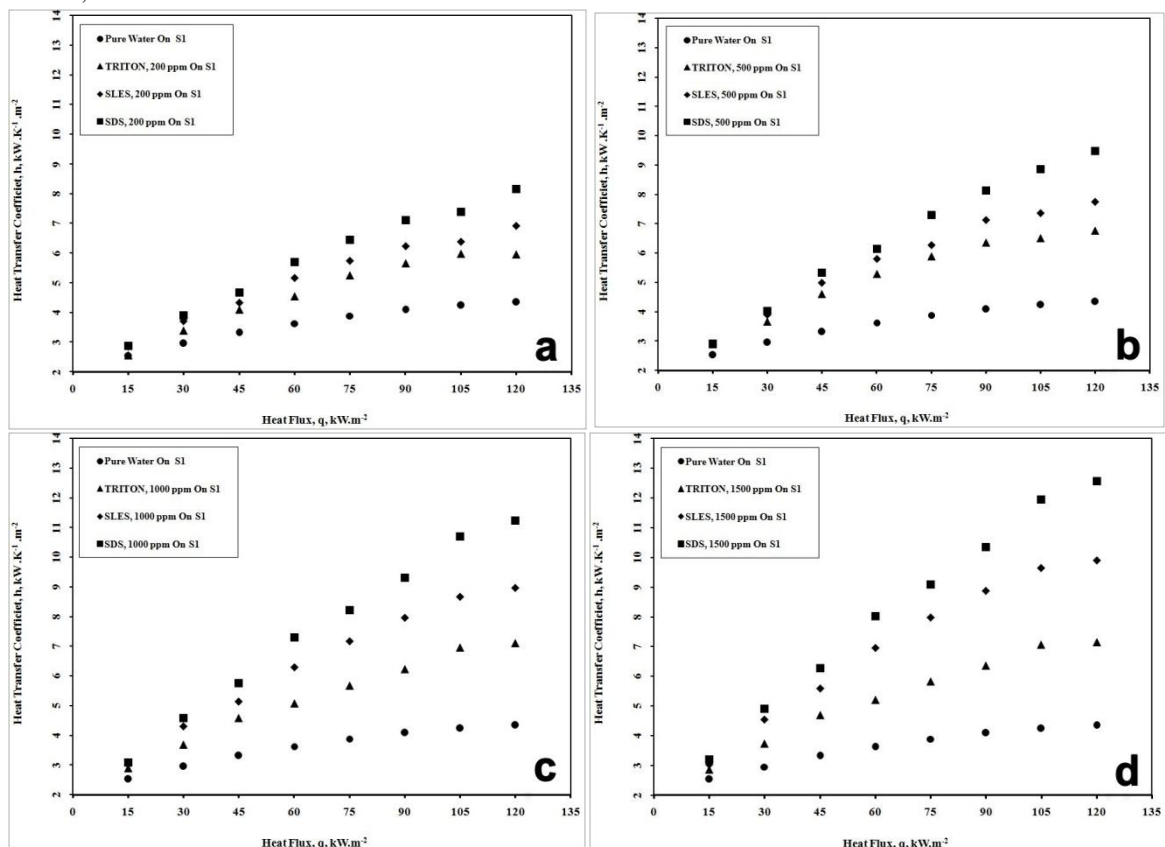


Figure 3: The compared data for surfactants, TRITON-X, SLES and SDS at concentration 1000 ppm on the stainless steel tube

**Results and Discussion**

Figure 4, (A to L), illustrates the experimental results of the present work. It is obvious that, for all studied cases, the heat transfer coefficient increased with the heat flux, which indicates that, as the heat flux increases with a fixed rate, the temperature difference ( $T_s - T_1$ ) increases with a decreasing rate. This may be because, the fluid molecules have higher mobility than that of solids, which helps

the thermal energy to transfer in the fluid faster and to increase the fluid bulk temperature with a rate, which does not allow the temperature difference to increase at the same rate as the heat flux. It is observed that, for all cases, the SDS surfactant solution exhibited the highest heat transfer coefficient. This is due to the higher surface tension *depression* caused by SDS, which enhances the bubble formation and the other nucleation characteristics. It is observed that, the *rate* of increase in the heat transfer coefficient starts to decrease with the increase of heat flux. The reason may be that, increasing the heat flux promotes for more bubble formation, and increases the possibility of coalescence that produces larger bubbles. the lower speed of the larger bubbles reduces the convective heat transfer, which in turn, reduces the rate of heat transfer. Figure 5 illustrates the variation trends of the heat transfer coefficient with the surfactant concentration on the three surfaces for the SLES and SDS surfactant solutions, at heat flux of  $75 \text{ kW.m}^{-2}$ . It is observed that, the heat transfer coefficient increased with the surfactant concentration for all cases of SLES and SDS. But the heat transfer with TRITON-X increased until concentration of 500 ppm. The reason may be as follows, the heat transfer through boiling is more efficient than through a single-phase convection because of the bubbles formation, which enhances the transfer process. Increasing the concentration of a surfactant decreases the surface tension of the liquid and accordingly, promotes for the bubble formation, and thus, increases the heat transfer. In case of TRITON surfactant, there is two opposing effects; increasing the concentration decreases the surface tension and improve the heat transfer, but increasing the concentration of this high molecular weight substance decreases the ability of transferring the internal energy. So, below concentration of 500 ppm, the first factor is dominant, and for a higher concentration, the second factor start to be considered. Figure 6 illustrates the cases of the highest percentages of enhancement in the heat transfer coefficient over that for the distilled water at the same surface, surfactant concentration and heat flux. From the figure, it is obvious that, the maximum percentage of enhancement is about 185 %, and it is achieved when using SDS solution at concentration 1500 ppm on brass surface, whose heat flux is  $120 \text{ kW.m}^{-2}$ .



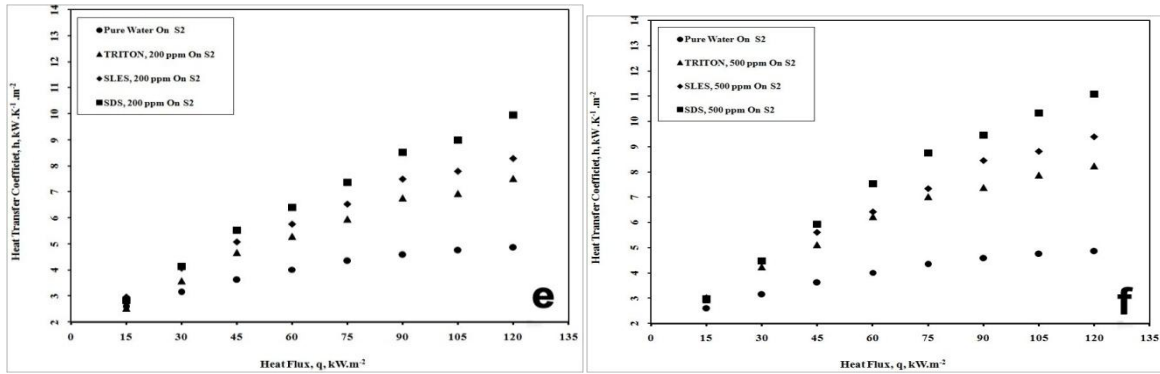


Figure 4: Results of the three surfactant types at four concentrations on three tube surfaces;  
 a) Surfactants; TRITON-X, SLES and SDS at concentration 200 ppm with water on brass tube.  
 b) Surfactants; TRITON-X, SLES and SDS at concentration 500 ppm with water on brass tube.  
 c) Surfactants; TRITON-X, SLES and SDS at concentration 1000 ppm with water on brass tube.  
 d) Surfactants; TRITON-X, SLES and SDS at concentration 1500 ppm with water on brass tube.  
 e) Surfactants; TRITON-X, SLES and SDS at concentration 200 ppm with water on aluminum tube.  
 f) Surfactants; TRITON-X, SLES and SDS at concentration 500 ppm with water on aluminum tube.

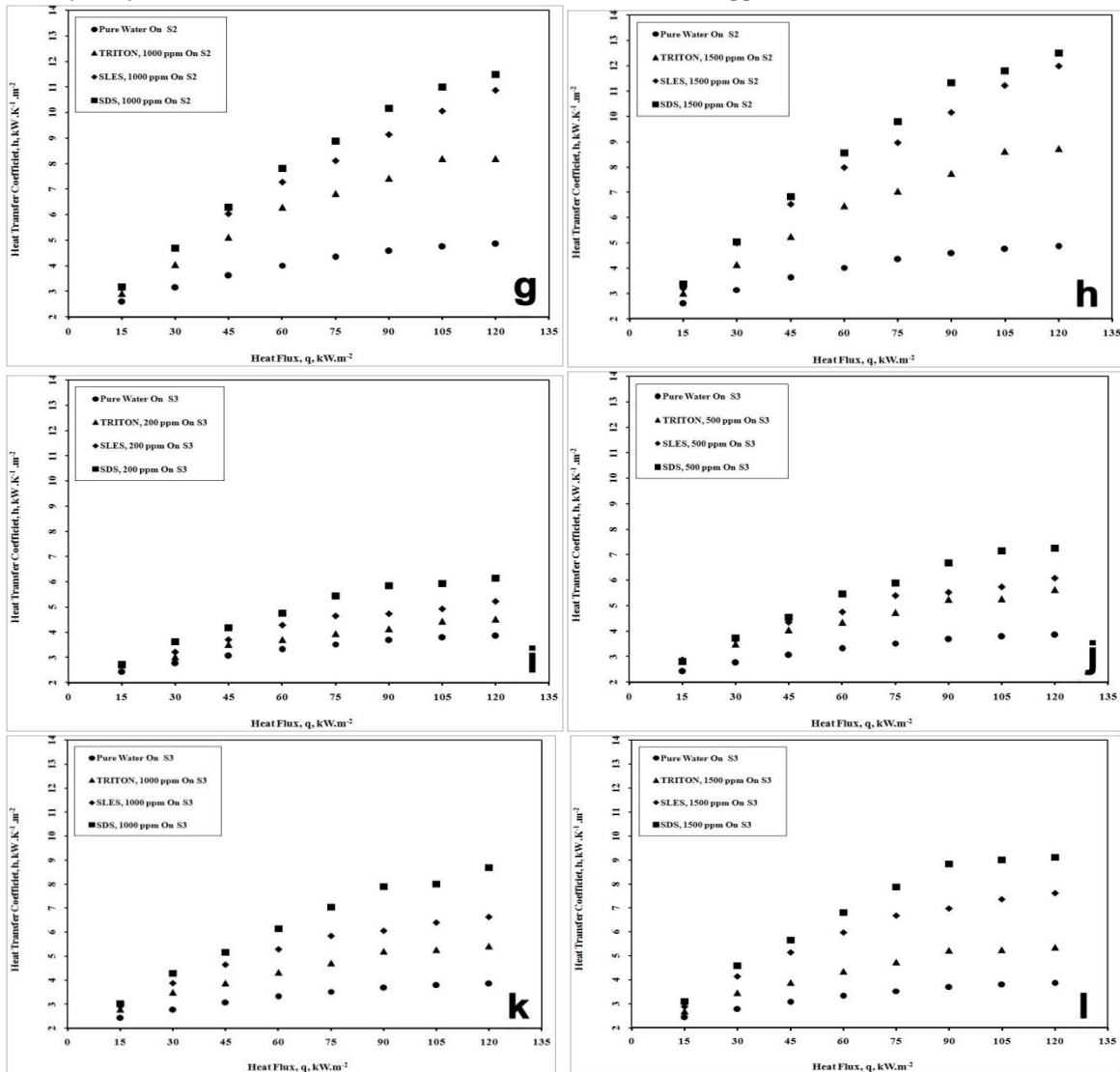


Figure 4, continue;

- g) Surfactants; TRITON-X, SLES and SDS at concentration 1000 ppm with Distilled water on aluminum tube
- h) Surfactants; TRITON-X, SLES and SDS at concentration 1500 ppm with Distilled water on aluminum tube
- i) Surfactants; TRITON-X, SLES and SDS at concentration 200 ppm with Distilled water on stainless tube.
- j) Surfactants; TRITON-X, SLES and SDS at concentration 500 ppm with Distilled water on stainless tube.
- k) Surfactants; TRITON-X, SLES and SDS at concentration 1000 ppm with Distilled water on stainless tube.
- l) Surfactants; TRITON-X, SLES and SDS at concentration 1500 ppm with Distilled water on stainless tube.

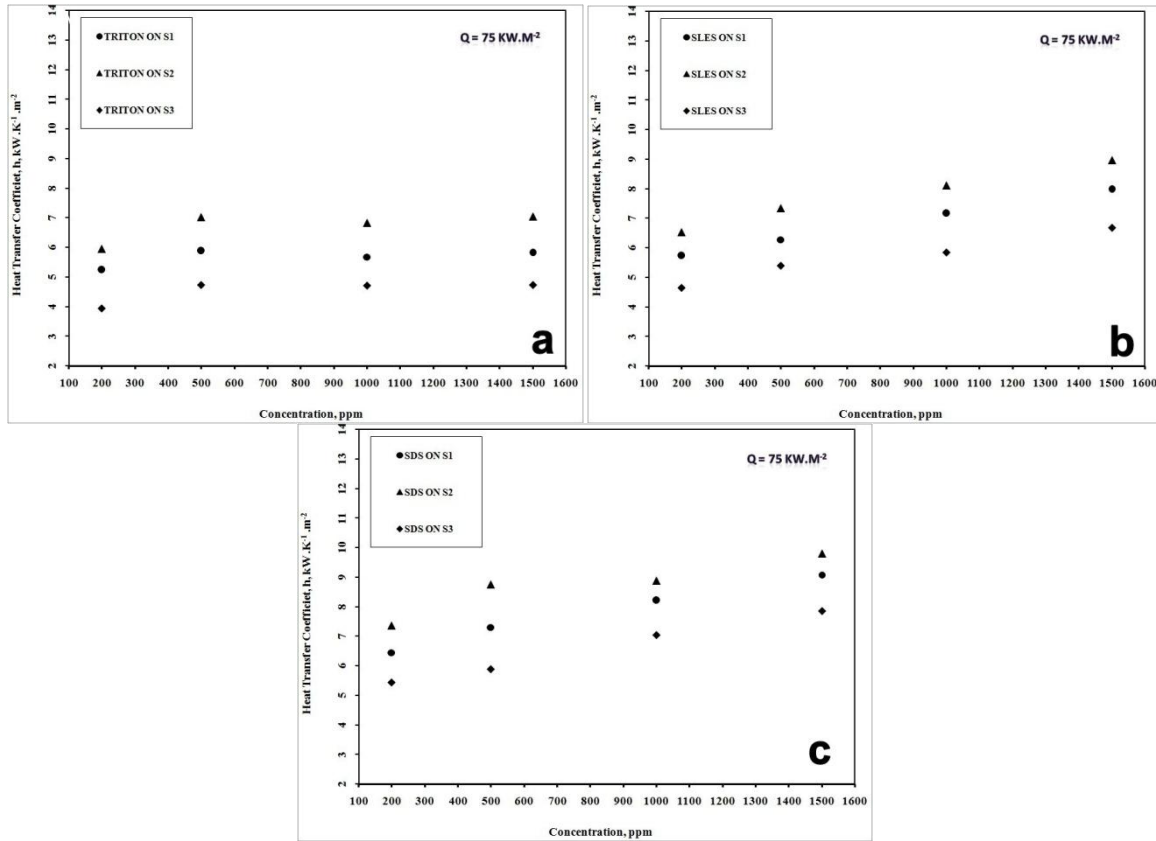


Figure 5: The variation of the heat transfer coefficient with the concentration,  $q = 75 \text{ kW.m}^{-2}$ .  
 a) TRITON-X      b) SLES    c) SDS

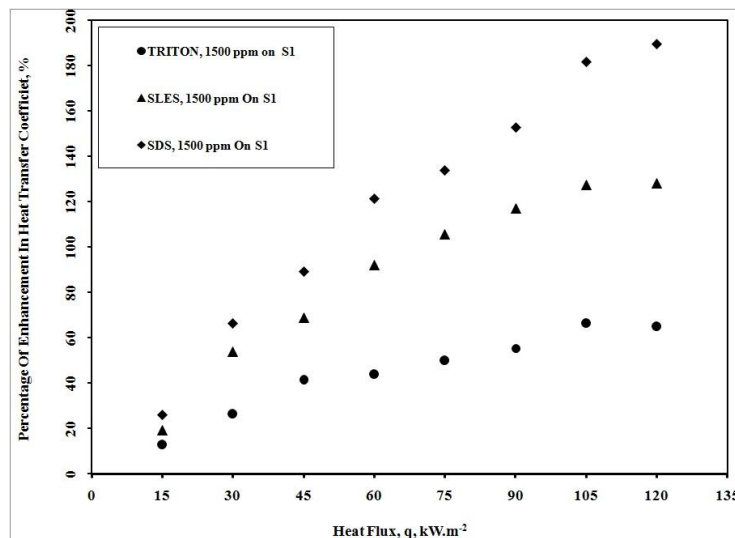


Figure 6: The percentages of enhancement in the heat transfer coefficient over that for a distilled water at the Aluminum tube and same surfactant concentration of 1000 ppm.



#### 4. Conclusion

In the present work, an automated test rig is implemented to investigate the heat transfer coefficient in a pool boiling of surfactant solutions on different tube surfaces. The heat transfer coefficient was investigated for aqueous solutions of three surfactant; TRITON-X, SLES and SDS. The surfactant concentration ranged from zero, (distilled water) to 1500 ppm. Each solution was tested on three surfaces; Brass, Aluminum, and Stainless steel, and the heat flux from each surface ranged from 15 to 120 kW.m<sup>-2</sup>. For all studied cases, the heat transfer coefficient increased with the heat flux. For all cases, the heat transfer coefficient increased with the heat flux, and for the same heat flux, the heat transfer increased considerably for the surfactant solution compared that of the distilled water case. For all cases of SLES and SDS, and for the same heat flux, the heat transfer coefficient increased with the surfactant concentration, but, with TRITON-X, it increased until concentration of 500 ppm, and beyond this value, it did not exhibit a considerable increase. All cases of SDS surfactant solutions exhibited higher heat transfer coefficient values compared to those of the other surfactants. The rate of increase in the heat transfer coefficient starts to decrease with the higher surfactant concentration. The maximum enhancement in the heat transfer coefficient over that of the distilled water was observed when using SDS solution at concentration 1500 ppm on brass surface, whose heat flux is 120 kW.m<sup>-2</sup>, and was about 185 %.

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