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BOILING HEAT TRANSFER FOR AQUEOUS SURFACTANTS SOLUTIONS ON FLAT SURFACE

"إنتقال الحرارة بالغليان لمحاليل ذات توتر سطحي صغير على سطح مستو"

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خلاصة البحث:

فى هذا البحث أجريت دراسة معملية لإنتقال الحرارة بالغليان من سطح مستو لمحاليل ذات توتر سطحى صغير مقارنة بالماء النقى. ولإتمام هذه الدراسة تم تصميم وتنفيذ دائرة إختبار معملية مزودة بأجهزة القياس المطلوبة لتسجيل القياسات الخاصة بدرجات الحرارة والضغط والتدفق وذلك لحساب كمية الحرارة المنتقلة بالغليان إلى هذه المحاليل ومقارنتها بالماء النقى كمائع تشغيل. وقد تم إستخدام فى هذه الدراسة محلول غير أيونى وأخر أيونى بتركيزات مختلفة مع تغيير الفيض الحرارى من ١٥٣٠٠ إلى ٣١٢٣٠ وات/م^{٢}. وبالتالى فقد تم حساب معامل إنتقال الحرارة بالغليان وحساب معامل تحسين معامل إنتقال الحرارة بالغليان عند إستخدام هذه المحاليل مقارنة بالماء النقى.

وقد أظهرت نتائج هذه الدراسة أنه عند نفس قيم الفيض الحرارى فإن درجة حرارة السطح تقل مع إستخدام المحاليل ذات التوتر السطحى الصغير مقارنة بالماء النقى وبالتالى فإن معامل إنتقال الحرارة بالغليان يزداد مع إستخدامها وكذلك يزداد أيضا مع زيادة الفيض الحرارى. قيمة معامل تحسين معامل إنتقال الحرارة بالغليان تتراوح مابين ١،٠٨ وحتى ١،٣ وذلك حسب تركيز المحلول ونوعه وقيمة الفيض الحرارى المستخدم. كما أظهرت النتائج أن أكبر قيمة لمعامل التحسين فى معامل إنتقال الحرارة بالغليان تكون عند قيمة معينة لتركيز المحلول الغير أيونى وهى ٢٠ جزء فى المليون وللمحلول الأيونى ٣٠ جزء فى المليون يبدأ بعدها فى الإنخفاض مع زيادة التركيز حتى يصل تقريبا إلى نفس قيمته للماء النقى. وقد وجد أن المحلول الغير أيونى يعطى قيم أكبر فى معامل إنتقال الحرارة بالغليان عن المحلول الأيونى عند نفس ظروف التشغيل. وقد تمت المقارنة بالأبحاث السابقة فكانت النتائج متوافقة.

Abstract

Experimental study for boiling heat transfer over a flat surface was achieved by using aqueous surfactants solutions and compared with pure water. An experimental test loop equipped with the required measuring devices was designed and constructed to assess the effects of surfactants type, concentration of aqueous surfactants solutions, and the applied heat flux on the boiling heat transfer process. The tested surfactants are Polyvinyl Alcohol (nonionic surfactant) and Sodium Lauryl Sulfate (anionic surfactant). Concentrations of aqueous surfactants solutions varied in this work from zero up to 3000 ppm and the applied heat flux from 15300 to 31230 W/m^2. The experimental measurements of temperature, pressure and volume flow rate are recorded and manipulated to calculate the boiling heat transfer coefficient and the enhancement factor for the boiling heat transfer coefficient.

The obtained experimental results showed that, the wall temperature of flat surface was reduced for the same heat flux by using aqueous surfactants solutions compared with pure water. Accordingly, the boiling heat transfer coefficient increased when using aqueous surfactants solutions and increased also with increasing heat flux in the range of the studied operating parameters. The enhancement factor of the boiling heat transfer coefficient reached to a maximum value with concentration 20 ppm for Polyvinyl Alcohol and concentration 30 ppm for Sodium Lauryl Sulfate, and then it decreased with increasing concentrations. The enhancement factor for the tested surfactants solutions in this work relative to the pure water is found to be 1.08 to 1.3 depending upon type of surfactants, its concentration and wall heat flux. This

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improvement in the boiling heat transfer coefficient characterized by a reduction in the bubble departure diameter, increased departure frequency, reduction in the coalescence and increased in the number of nucleation sites. Comparison with the previous work gave good agreement.

Key words: Surfactants, Aqueous solutions, Enhancement of boiling heat transfer.

1. INTRODUCTION

Nucleate boiling is a very efficient mode of heat transfer. It has been found in a wide range of applications such as various energy conversion systems, heat exchange systems, refrigeration, heat pump systems, and chemical thermal processes....etc. The presence of surfactant (surface active agent) additives or polymer at low concentrations in solvent has been found to improve the nucleate boiling heat transfer coefficient significantly. Traces of these additives cause no significant change in physical properties of the solvent except for surface tension and viscosity. The boiling behaviuor enhancement is dependent on additive concentration, heat flux and the heater geometry. Surface tension has been identified as an important property affecting the nucleation behaviuor. The nucleation criteria indicates that as the surface tension is lowered, the excess pressure requirement is lowered, as given by $\Delta P = 2\sigma/R$, where R is the critical radius of the nucleating bubble and σ is the surface tension. Many industrial applications, such as food, pharmaceutical, hygiene, and health care product processing, among others, involve boiling of aqueous surfactant and polymeric solutions as an important stage of product preparation.

Experimental results, obtained by Yang and Maa (1983), demonstrate that the heat transfer coefficient and critical heat flux of the boiling process can be improved considerably by the addition of small amount of surfactants. The surfactants used in this study are sodium lauryl benzene sulfonante (SLBS) and sodium lauryl sulfate (SLS). Because all experiments were carried out under very low concentrations, these additives had no noticeable influence over the physical properties of the boiling water, except surface tension, which was significantly reduced. This reduction in surface tension causes a considerable increase in the heat transfer coefficient and critical heat flux.

Saturated nucleate boiling of aqueous surfactant solutions which studied by Tzan and Yang (1990), from an electrically heated stainless steel tube (3.35-mm-OD) immersed in saturated water with varying concentrations of an anionic surfactant (sodium dodecyl sulfate). Their results showed an increase in nucleate boiling heat transfer versus surface tension reduction. This enhancement is characterized by a rapid departure of small-sized, regularly shaped bubbles from the heater surface, and an increase in the number of active nucleation sites.

An excellent review by Wasekar and Manglik (1999) gave many studies in nucleate pool boiling of aqueous surfactants and polymeric solutions. Several of these investigations have attempted to determine the influence of the type of additive, its molecular weight and concentration, heat flux level, heater shape and size on the enhanced boiling performance.

Saturated nucleate pool boiling of aqueous surfactant solutions on a horizontal cylindrical heater has been experimentally investigated by Wasekar and Manglik (2000). Sodium dodecyl or lauryl sulfates, an anionic surfactant, were employed. A considerable enhancement in heat transfer coefficient relative to that for pure water is found (10% -65%, depending upon concentration and wall heat flux).

Saturated nucleate pool boiling on a horizontal cylindrical heater in aqueous solutions of surfactants, which has different molecular weight, were investigated experimentally by Wasekar and Manglik (2002). The molecular weights for the used surfactants, (sodium dodecyl sulphate, sodium lauryl ether sulfate, Triton X-100 and Triton X-305) are 288.3, 422, 624 and 1526. The boiling performance is significantly enhanced, and the maximum enhancement increases with decreasing surfactant molecular weights.

Saturated and sub-cooled pool boiling of environmentally acceptable surfactant solutions (alkyl glycosides), on a horizontal tube, was experimentally investigated by Hetsroni et al., (2004). 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. The results showed that the bubble behavior and the heat transfer mechanism for the surfactant solution are quite different from those of pure water. Boiling of surfactant solutions, when compared with that in pure water, was observed to be more vigorous. Surfactant solutions promote activation of nucleation sites in a clustered mode, especially at lower heat fluxes.

A state-of-the-art review paper is presented by Cheng et al., (2007) with respect to studies of boiling phenomena of aqueous surfactant and polymeric additive solutions in the literature. It covers both experimental studies on boiling characteristics of various aqueous surfactant and polymeric additive solutions and theoretical studies on the boiling mechanisms such as the effect of surfactants and polymeric additives on nucleation process, bubble dynamics and interfacial phenomena by the methods of visualization and modeling.

Experimental analysis of bubble growth, departure and interactions during pool boiling on artificial nucleation sites (on a single and on two neighbouring nucleation sites) was studied by Siedel et al., (2008). Bubble growth appears very reproducible, the volume at detachment being independent of the wall superheat, whereas the growth time is dependant on the superheat. The bubble frequency has been found to be approximately proportional to the wall superheat.

According to this review, several important research directions related to boiling phenomena with surfactants and polymeric additives. In the long run, effort should be made to develop heat transfer models of boiling phenomena with surfactants and polymeric additives and it is suggested that more experimental work must be done to explore this research area and to verify these hypotheses.

2. EXPERIMENTAL TEST LOOP

A schematic diagram for the experimental test loop is shown in Fig. (1). It consists of a test chamber, a heating circuit and cooling circuit.

The test chamber is made of aluminum hollow box; inner dimensions are 100 mm×100 mm, and height 40 mm. The lower and upper bases are flat Aluminum tubes ended by two welded headers at both sides; each header has a diameter of 16 mm. The flat aluminum multi-channel tubes have 22 sub-channels. Rectangular sub-channels of dimensions 3.85 mm×3.6 mm. The wide of the flat aluminum tube is 100 mm and its length is 100 mm. The aluminum hollow box, lower base and upper base are welded together by aluminum welding, as shown in Fig. (2). The aluminum box has two valves on one side the first valve is used to charge the test chamber with the working fluid and the second one connecting to the vacuum pump suction line. The absolute value for pressure inside test chamber was fixed during the experiments at value equal to 0.2 bar (the corresponding saturation temperature was 60 °C).

Aqueous surfactants solutions and pure water used as working fluids. The specified amount of the working fluid was charged to the test chamber through the charging line to give a level equal to 10 mm. Nonionic surfactant (Polyvinyl

Alcohol) and anionic surfactant (Sodium Lauryl Sulfate; SLS) are used in this work with varying concentrations up to 3000 ppm and compared with pure water. It is known that; nonionic surfactant has lower surface tension and lower molecular weight than the anionic surfactants [3].

The lower base of the test chamber is heated by hot water circuit. The desired amount of hot water flow rate was controlled by using a control valve located after the hot water circulating pump, and the remaining return back to the electric heater tank. The hot water was pumping to flow inside the flat aluminum tube (lower base) and then is returned back to the electric heater (1.5 kW rated power). The basic dimensions of the electric heater are 0.4 m in diameter and 0.6 m height.

The vapor generated in the test chamber is naturally moved in the upward direction toward the lower surface of the upper base. Cold water was drawn from a constant head water tank by using a cold water circulating pump to flow inside the flat aluminum tube (upper base). The desired amount of cold water flow rate was controlled by using a control valve located after the centrifugal pump, and the remaining return back to the water tank. Then the generated vapor is condensed at the lower surface of the upper base. The condensate returned back by gravity inside the test chamber.

To ensure minimum heat loss to the surroundings, a layer of 50-mm of glass wool thermal insulation followed by additional aluminum foil sheet is wrapped on the outer surface of the whole parts of the test chamber.

3. EXPERIMENTAL MEASUREMENTS

Temperature recorder was used to measure the temperatures with minimum readable value of ±0.1 °C. Two thermocouples of K-type are attached inside the test chamber. The first thermocouple is suspended in the middle of the working fluid layer to measure its saturation temperature. The second one located on the center of the inner surface for the lower base to measure the wall temperature. These two thermocouples are induced in the aluminum box through four small diameter tubes fixed on it (where each wire of thermocouple enters through one of these tubes). The tubes are injected by adhesive material to prevent leakage. For the lower and upper bases, each header has two threaded holes for fixing thermocouples to measure inlet and outlet water temperatures, as shown in Fig. (2). Also, the temperature of the outer surface layer of insulation for the lower base and ambient temperature are measured.

Bourdon tube pressure gauge ranging from 0 to -1 bar was fixed at the side of the test chamber to measure the inside vacuum pressure.

Hot and cold water volume flow rates measured by using a turbine type flow meter having a range from 0 to 10 Lit/min with an accuracy of ± 0.2% from full scale. Water flow meter (type HFL2102A OMega Eng. Inc.) was calibrated using a constant volume tank and a stop watch.

The experimental apparatus was allowed to operate until the fluctuation in temperatures was about ±0.1 °C. Then, steady state condition was reached and the required measurements of temperature, pressure and volume flow rate were taken. The root-mean-square random error propagation analysis was carried out in the standard fashion using the measured experimental uncertainties of the basic independent parameters. The error analysis is done for the average values of the calculating parameters. The experimental uncertainties associated with these measurement techniques were estimated to be approximately equal to 7.8 % for boiling heat transfer coefficient.

4. DATA REDUCTION

The basic measurements were analyzed using a computer reduction program to calculate the boiling heat transfer coefficient for surfactant solutions and for pure water.

At steady state, the total input heat (Q_t) to the test chamber from the hot water which flows inside the flat aluminum tube (lower base of the test chamber) divided into useful heat which causes the boiling (Q_{us}) and the remaining amount of heat transferred from the outer surface of insulation for the lower base to the surroundings as heat loss (Q_{loss}).

The total input heat can be determined as;

$$Q_t = \dot{m}_h \, Cp_h \, (T_{h,i} - T_{h,o}) \qquad (1)$$

Where $\dot{m}_h$, Cp_h, $T_{h,i}$ and $T_{h,o}$ are the mass flow rate of hot water, specific heat of hot water, inlet and outlet hot water temperatures respectively. Hot water properties are calculated at average temperature ($T_{h,av} = (T_{h,i} + T_{h,o})/2$).

The amount of heat loss from outer surface of insulation to the surrounding air (Q_{loss}) can be determined as;

$$Q_{loss} = h_{free} \, A_{ins} \, (T_{ins} - T_{amb}) \qquad (2)$$

Where; h_{free}, A_{ins}, T_{ins} and T_{amb} are free convection heat transfer coefficient between outer surface of insulation and outside air (taken 10 W/m^2.°C), outer surface area of insulation for lower base, outer surface insulation temperature and ambient air temperature respectively.

Then the useful heat transfer at the test chamber (boiling heat transfer) can be calculated as;

$$Q_{us} = Q_t - Q_{loss} \qquad (3)$$

Heat flux (q") can be calculated from the following equation as;

$$q'' = Q_{us} / A_i \qquad (4)$$

Where; A_i = Inside surface area of the lower base for the test chamber (A_i = L×W). Also, L and W are length and width of the lower base of the test chamber.

The experimental boiling heat transfer coefficient (h_b) was defined by the ratio of heat flux (q") and the temperature difference between the lower base average wall-temperature (T_{wall}) and the saturation temperature for the working fluid (T_{sat}) as;

$$h_b = q'' / (T_{wall} - T_{sat}) \qquad (5)$$

The enhancement factor (EF) is defined as the ratio of the boiling heat transfer coefficient when using aqueous surfactants solutions ($h_{b,s}$) to the boiling heat transfer coefficient when using pure water ($h_{b,w}$);

$$EF = h_{b,s} / h_{b,w} \qquad (6)$$

5. RESULTS AND DISCUSSIONS

The main aim of the research workers in the field of boiling heat transfer are to transmit the largest heat flux by applying the smallest temperature difference between the heating surface and the boiling liquid and to bring the critical heat flux to the highest possible value. Various means have been developed with this aim in mind, including the use of surfactants solutions instead of pure water. Clearly, more nucleation sites would become active at a given superheat. Boiling curves for nonionic surfactant (Polyvinyl Alcohol) and anionic surfactant (Sodium Lauryl Sulfate; SLS) are plotted at different concentrations and compared with pure water (0 ppm), as shown in figures (3) and (4). It is noticed that, higher heat flux for surfactants solutions than pure water (for the same value of temperature difference; T_{wall}-T_{sat}). This increase takes its highest value at low concentration about, 20 ppm for Polyvinyl Alcohol and 30 ppm for SLS and then it decreases when increasing concentration. On the other hand, for the same value of heat flux the temperature difference; (T_{wall}-T_{sat}) was decreased for surfactants solutions than pure water.

The effect of heat flux on the boiling heat transfer coefficient was illustrated in Fig. (5) for different values of concentrations of Polyvinyl Alcohol. It is clear that, as expected boiling heat transfer coefficient increases with increasing heat flux for the same concentration. For low concentrations range (less than 100 ppm), as shown in Fig. (5.a), the boiling heat transfer coefficient increases with concentration and takes the highest value at 20 ppm. After this value for concentration the boiling heat transfer coefficient was decreased and takes an asymptotic value. As shown in Fig. (5.b) it is observed that, for higher values of concentrations the enhancement in boiling heat transfer coefficient was vanished because the calculated values lies in the range of the experimental errors (less than 7.8 %).

The same trend is noticed from Fig. (6) for Sodium Lauryl Sulfate (SLS) except the boiling heat transfer coefficient takes the highest value at concentration 30 ppm. It is noticed that; boiling heat transfer coefficient increases by a small value for nonionic surfactant (Polyvinyl Alcohol) than anionic surfactant (SLS) because it has lower values of surface tension.

Enhancement factor was plotted against heat flux for nonionic surfactant (Polyvinyl Alcohol) and anionic surfactant (Sodium Lauryl Sulfate), as shown in figures (7) and (8). The enhancement factor for the tested surfactants solutions in this work relative to the pure water is found to be 1.08- 1.3 depending upon type of surfactant, its concentration and wall heat flux. The responsible mechanism for the improvement in the boiling heat transfer coefficient for surfactants solutions compared with pure water, for the same heat flux, due to increasing the number of nucleation sites, reduction in bubble departure diameter, increase departure frequency and decreased tendency to coalescence. Also, it is observed that enhancement factor takes higher values at lower heat fluxes, especially at low concentrations. This can be explained as; under very low concentrations, these additives had no noticeable influence over the physical properties of the boiling aqueous solution, except surface tension, which is significantly reduced. Accordingly, the boiling in surfactant solutions was observed to be more active, especially at lower heat fluxes, when compared with that in pure water. Bubbles formed in surfactant solutions were much smaller than those in water and the surface became covered with them faster.

Comparison between the present work, and the previous work for boiling of Sodium Lauryl Sulfate solutions on a horizontal cylinder heater, which has been investigated experimentally by Wasekar and Manglik (2000). It is observed that, comparison between the present work and the previous work gave good agreement.

CONCLUSIONS

Experimental study for the boiling heat transfer over flat surface was achieved by using nonionic and anionic surfactants solutions compared with pure water. Experimental results indicate that, for the same value of heat flux the wall temperature was reduced when using surfactants compared with pure water, especially at low concentrations. Therefore, the boiling heat transfer coefficient increased for surfactants and also increased with increasing heat flux. The enhancement factor of the boiling heat transfer coefficient reached to the maximum value with concentration 20 ppm for Polyvinyl Alcohol (nonionic surfactant) and concentration 30 ppm for Sodium Lauryl Sulfate (anionic surfactant), and then it decreased with increasing concentrations in the range of the studied operating parameters. The enhancement factor for the tested surfactants solutions in this work relative to the pure water is found to be 1.08- 1.3 depending upon type of surfactant, its concentration and wall heat flux. Boiling heat transfer coefficient increases by a small value for the nonionic surfactant (Polyvinyl Alcohol) than the anionic surfactant (Sodium Lauryl Sulfate) because it has lower values of surface tension. The responsible mechanism for the improvement in the boiling heat transfer characterized by a reduction in bubble departure diameter, increased departure frequency, reduction in coalescence and increased in the number of nucleation sites. Comparison with the previous work gave good agreement.

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NOMENCLATURE

A : Surface area, m^2
Cp : Specific heat for hot water, J/kg. °C
L : Length of the lower base, m
EF : Enhancement factor, -
h : Heat transfer coefficient, $W/m^2.°C$
m' : Water flow rate, kg/s
Q : Heat transfer rate, W
q" : Heat flux, W/m^2
T : Temperature, °C
W : Width of the lower base, m

Subscripts:
amb : ambient
av : average
b : boiling
free : free convection
h : hot water
i : inlet, inner
ins : insulation
loss : loss
o : outlet
s : surfactant
sat : saturation
t : total
us : useful
w : pure water
wall : wall

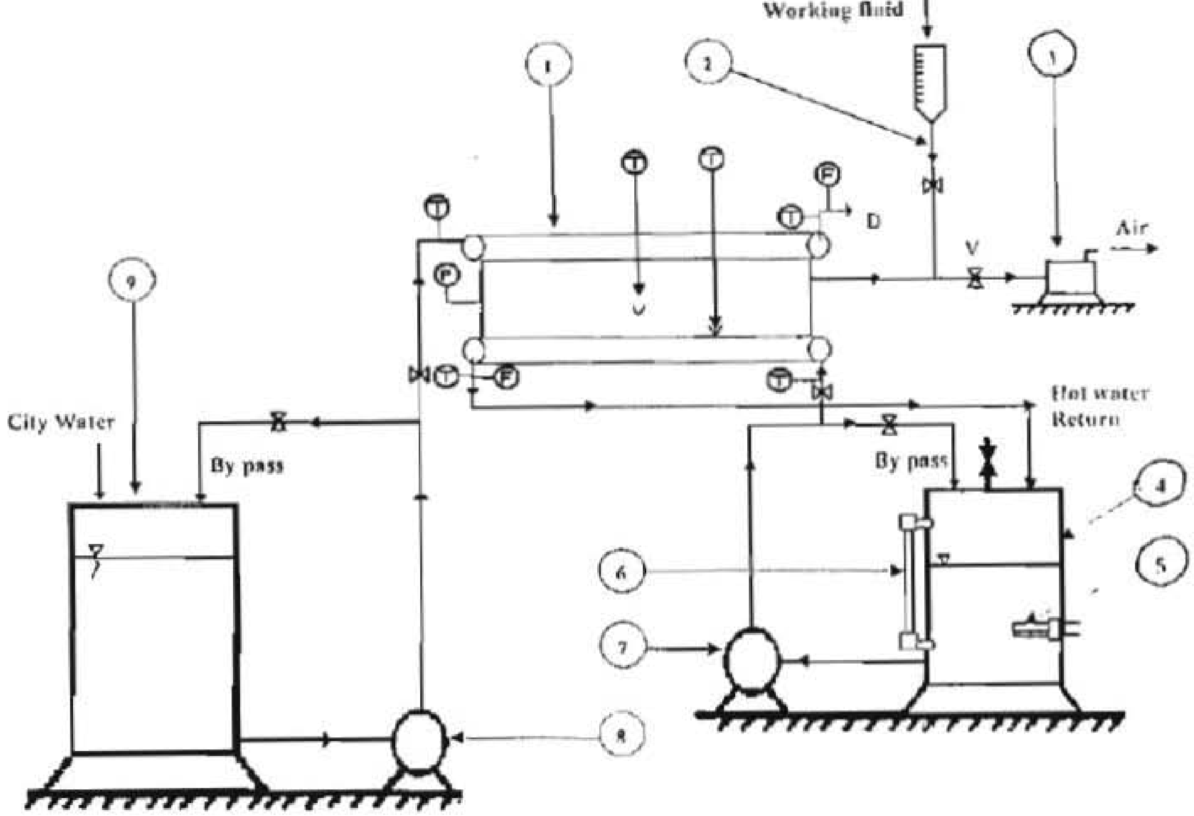
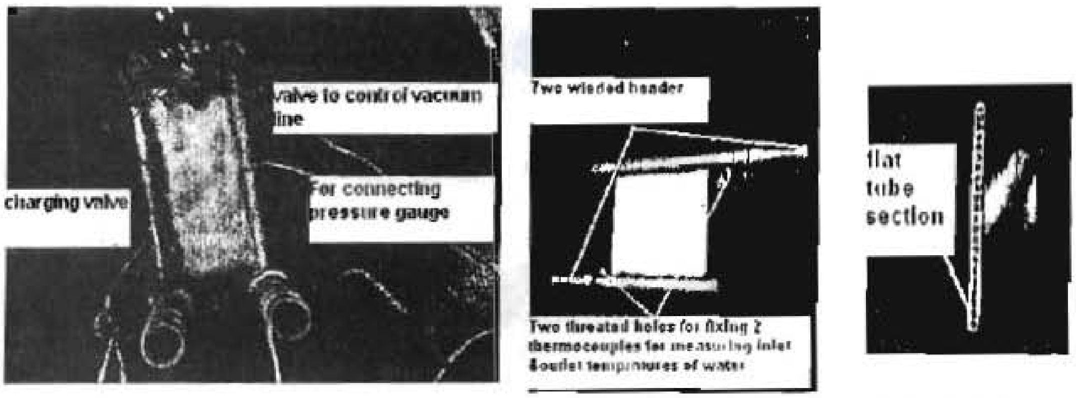


Fig. (1) Schematic diagram for the experimental test loop.
1. Test Chamber. 2. Charging Line. 3. Vacuum Pump. 4. Electric Heater Tank. 5. Electric Heater Element. 6. Glass Level Indicator. 7. Hot Water Circulating Pump. 8. Cold Water Circulating Pump. 9. Cold Water Tank.
D: Drain. F: Flow Rate. P: Pressure. T: Temperature. V: Control Valve.



(a) Test chamber (b) Base (c) Flat Tube

Fig. (2) Details of the test chamber.

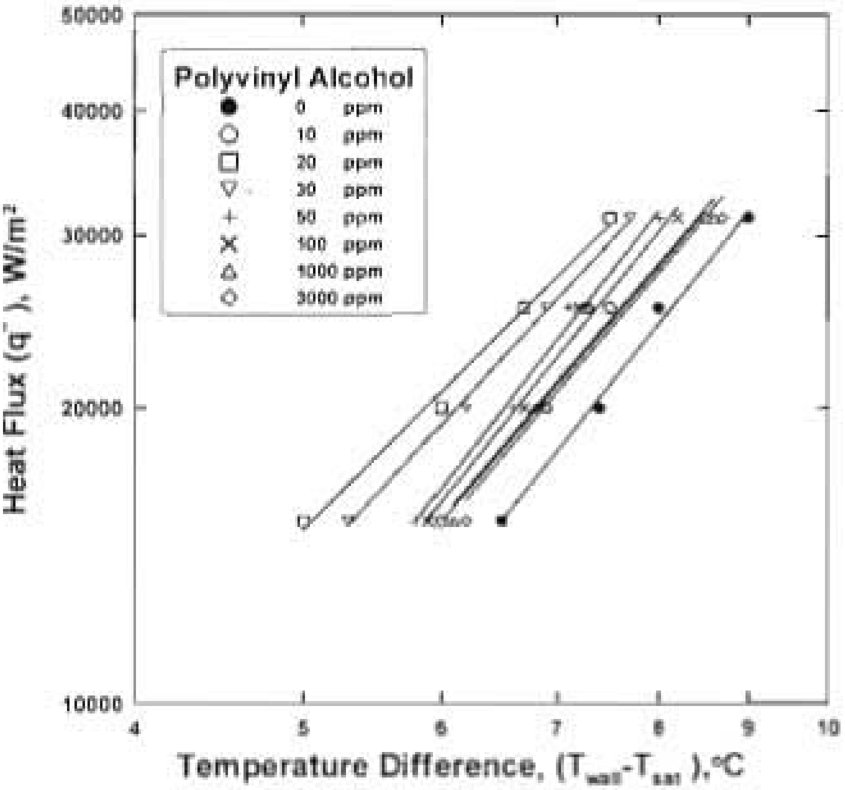


Fig. (3) Boiling curves for Polyvinyl Alcohol compared with pure water.

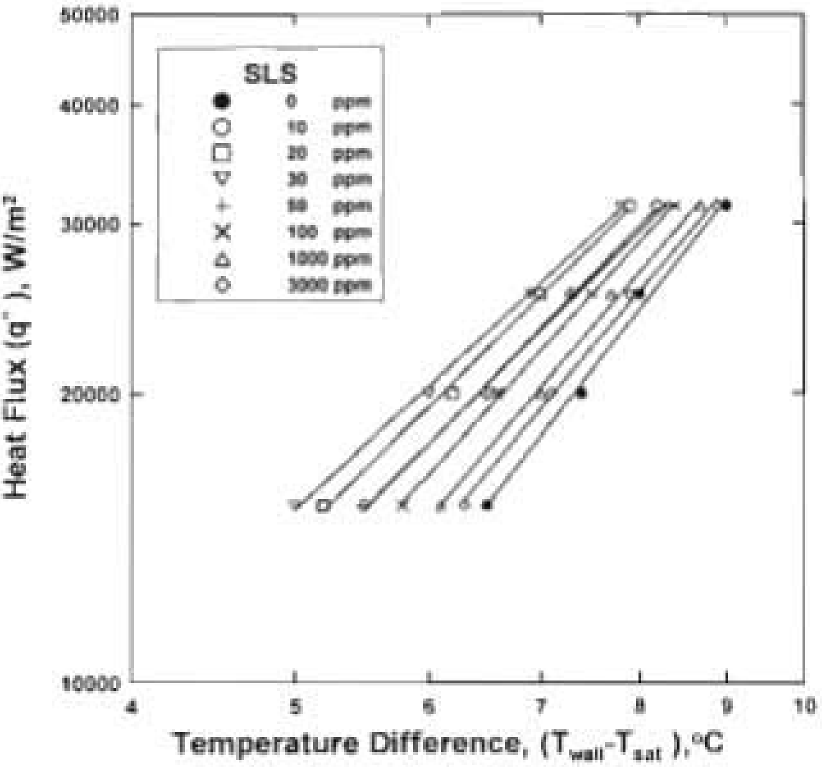


Fig. (4) Boiling curves for SLS compared with pure water.

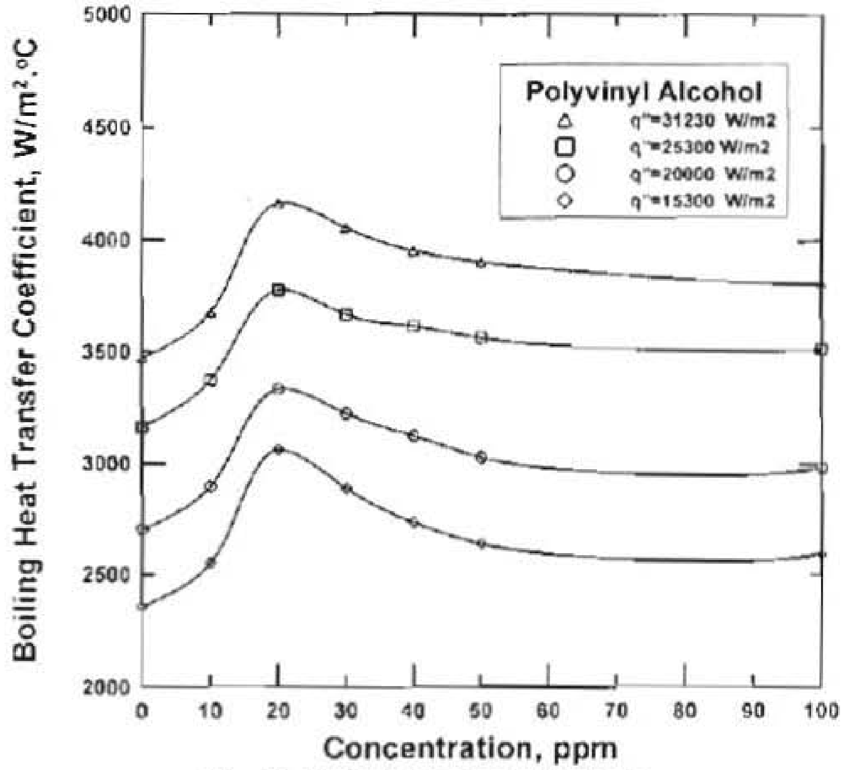


Fig. (5.a) For low concentrations

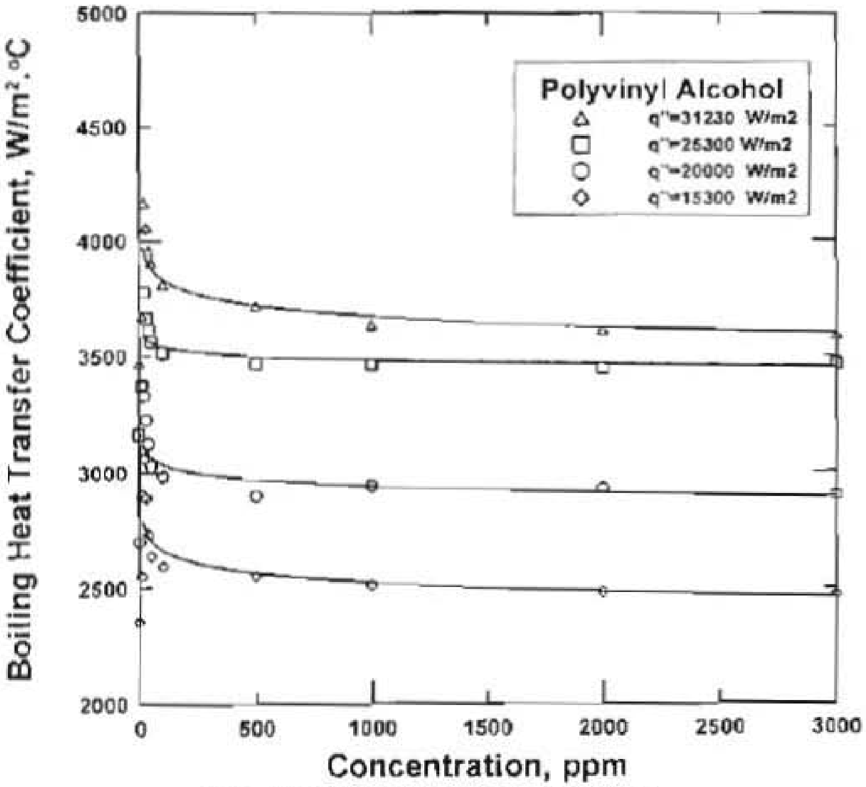


Fig. (5.b) For high concentrations

Fig. (5) Variation of boiling heat transfer coefficient versus concentration of Polyvinyl Alcohol for different values of heat flux.

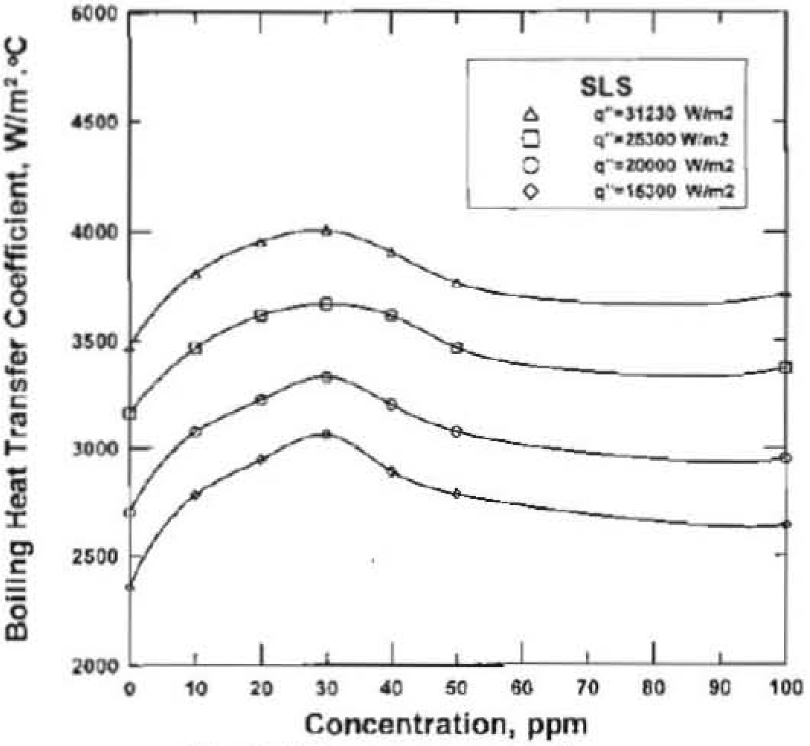


Fig. (6.a) For low concentrations

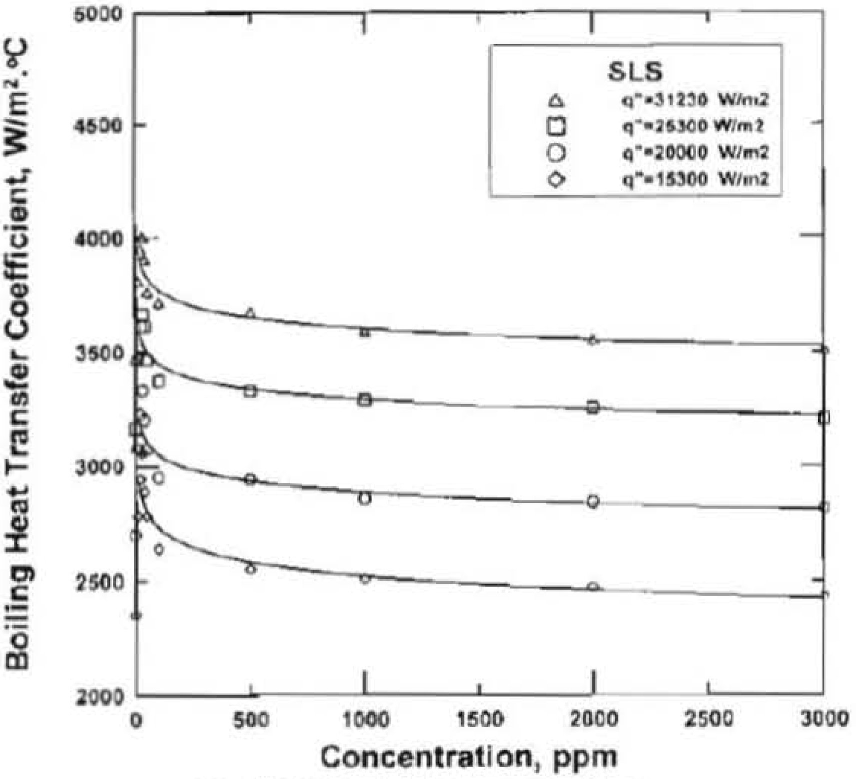


Fig. (6.b) For high concentrations

Fig. (6) Variation of boiling heat transfer coefficient versus concentration of SLS for different values of heat flux.

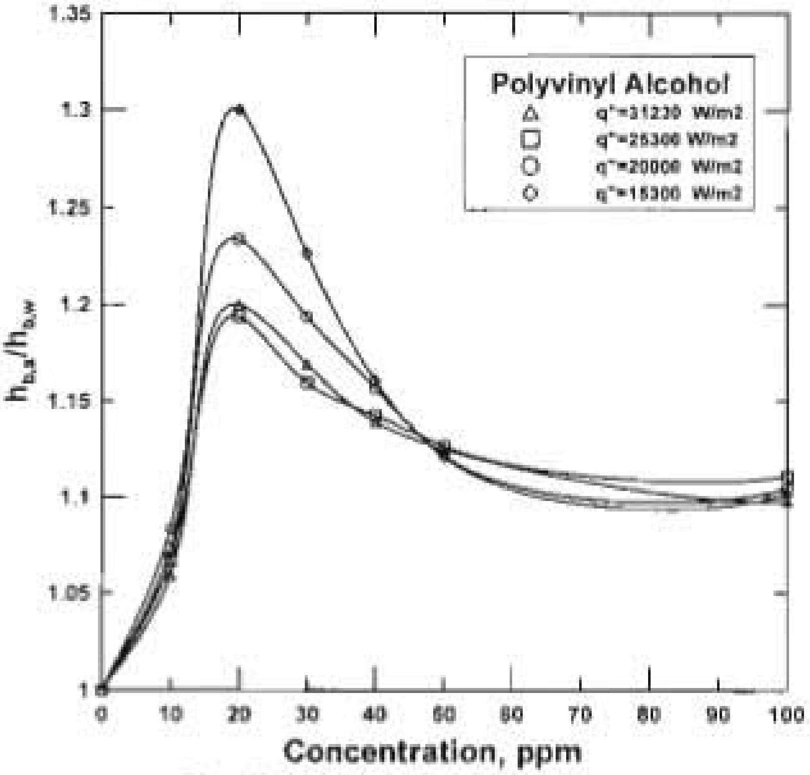


Fig. (7.a) For low concentrations

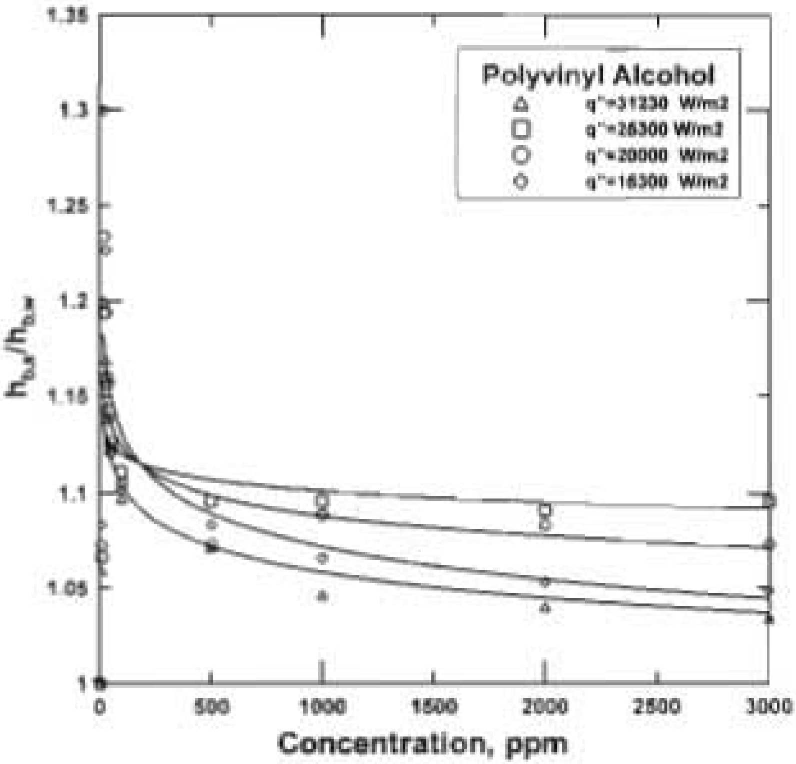


Fig. (7.b) For high concentrations

Fig. (7) Enhancement factor for boiling heat transfer coefficient versus concentration of Polyvinyl Alcohol for different values of heat flux.

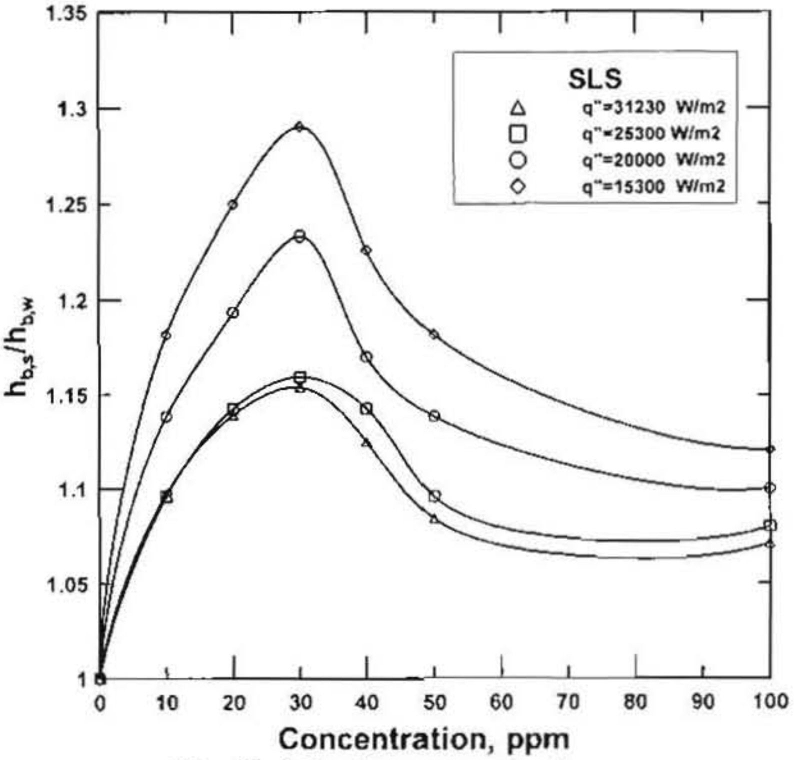


Fig. (8.a) For low concentrations

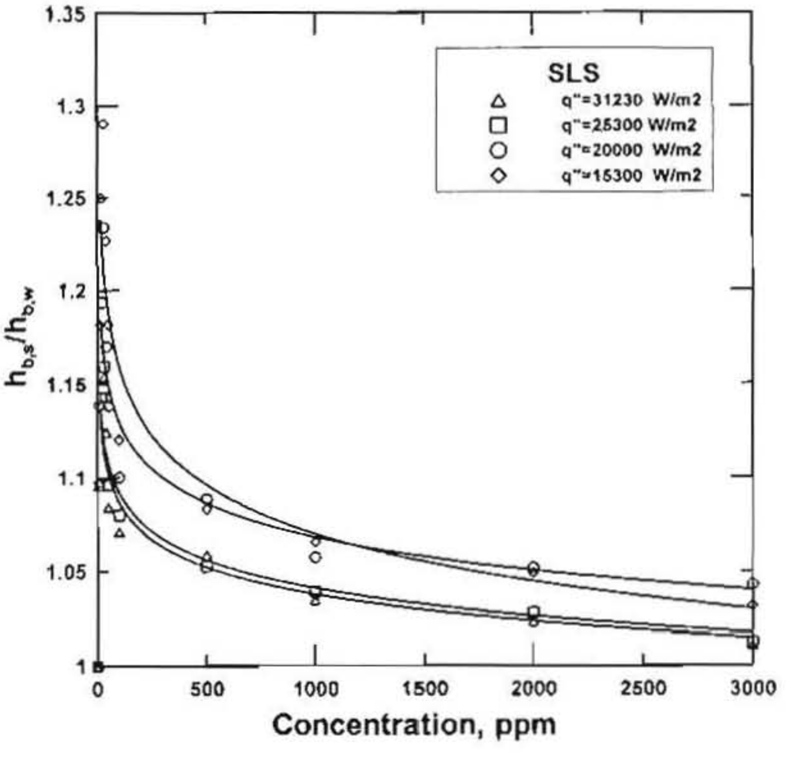


Fig. (8.b) For high concentrations

Fig. (8) Enhancement factor for boiling heat transfer coefficient versus concentration of SLS for different values of heat flux.

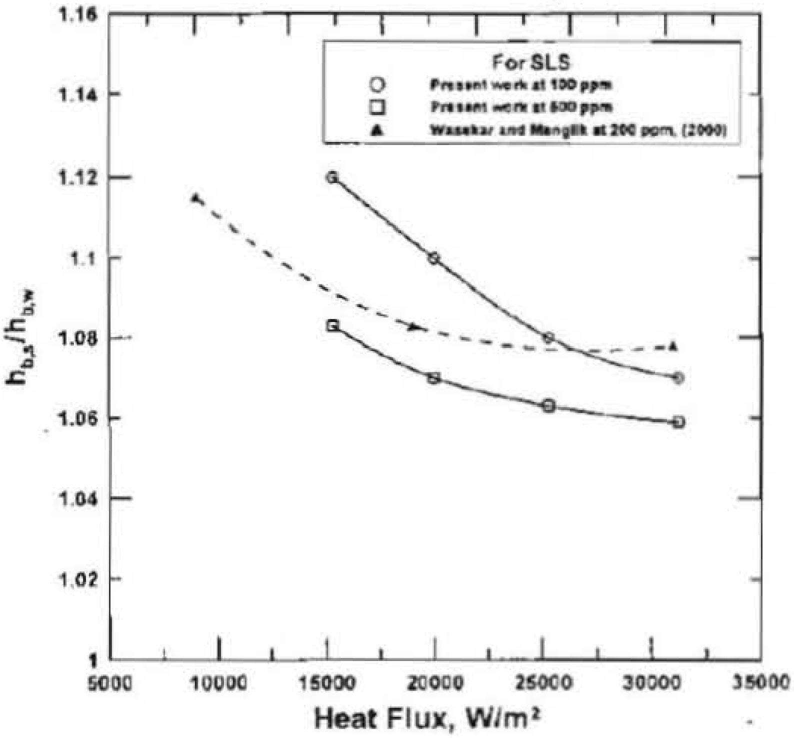


Fig. (9) Comparison between the present work and previous work.