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THE EFFECT OF HEATER PLATE THICKNESS ON BOILING HEAT-TRANSFER COEFFICIENTS

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Abstract—The effect of heater-plate thickness on boiling heat-transfer coefficients was observed for three liquids: water, ethanol, and *n*-heptane, using stainless steel plates with three thicknesses: 0.025 mm, 0.051 mm and 0.13 mm. Heat fluxes during boiling ranged from 30 000 to 100 000 W/m^2. It was found that plate thickness had only a small effect on the boiling heat-transfer coefficient in the range of variables studied. However, the heat-transfer coefficient did increase somewhat with increasing plate thickness for the larger measured values of ΔT; for the smaller values the trend was the opposite.

NOMENCLATURE

a, b, c,	linear regression coefficients:
h,	heat-transfer coefficient [w/m^2 °C];
ΔT,	temperature-difference driving force [°C].

Greek symbols

δ,	plate thickness [mm].

INTRODUCTION

RECENT investigations of nucleate boiling have shown that the thermal properties of a heating surface may affect the boiling heat-transfer coefficient. It has been proposed that the thickness of the heater wall will influence the heat-transfer coefficient only if the thickness is less than a certain limiting value, determined by the wall's thermal properties. However, there have been contradictory views as to what this effect would be. Some studies have led to the conclusion that the heat-transfer coefficient decreases as the thickness of the heater wall decreases. A more recent work shows that the effect may be just the opposite, or in some cases that there may be no effect at all.

An argument can be made that the thermal properties of the heating surface and the plate thickness are of importance in the microlayer evaporation theory because they determine the rate at which heat can be transferred to the heat sink created by the evaporating liquid. If the heater is considered to be thick-walled, i.e. the heater thickness is greater than the maximum depth within the plate in which the temperature is decreased by the presence of a bubble, and if the heater receives heat on its under side from an external heat source at a constant rate, then the rate of restoration of the temperature profile in the plate after a bubble has departed will be a function of the thermal diffusivity of the metal. If the plate is thin-walled, i.e. the temperature perturbation extends to the under side of the plate, then the thickness of the plate would have an effect on the restoration of the temperature profile because the length of the path from the heat source to the sink will be less than for a thicker heater.

For heaters that generate heat internally (as in the present study), the same influences may be important but to a different degree. A thin-walled heater will have a lower heat capacity than a thick-walled heater but will offer a shorter mean conduction path to the microlayer of liquid on its surface.

The experiments described in this paper were designed to investigate the effect of heater wall thickness on the boiling heat-transfer coefficient. Boiling was done on thin, horizontal, stainless steel plates of three thicknesses (0.025 mm, 0.051 mm and 0.13 mm). The plate material was stainless steel shim supplied by Precision Steel Warehouse, Inc. with nominal sizes of 1, 2 and 5 ml. The surfaces were not polished or treated in any manner before boiling. The liquids studied were water, ethanol, and *n*-heptane. Results in terms of boiling heat-transfer coefficient vs temperature difference were obtained for each plate thickness and an analysis of the results was done to determine if wall thickness did in fact affect the boiling heat-transfer coefficient.

PREVIOUS WORK

Sharp [1] did experiments using heater walls of various materials. He concluded that the rate of heat transfer during boiling could be directly related to the thermal conductivity of the heating wall divided by the square root of its thermal diffusivity ($k/\sqrt{\alpha}$). He observed that as this ratio decreased, so did the boiling heat-transfer coefficient. Others have observed the same effect [2, 3]. Sharp also hypothesized that the thickness of a heater wall influences heat transfer during boiling. He estimated that the effect of the temperature drop beneath the bubble on the heater's surface would penetrate the wall a few hundredths of an inch. From this it was suggested that the heat transfer to the base of the bubble in heaters thinner than a few hundredths of an inch would be controlled by the heater's thermal capacity. Sharp proposed that as the thickness of the heater wall decreased, the boiling heat-transfer coefficient should decrease also. Frost and Dzakowic [4] predicted the same result based upon a mathematical model of the microlayer evaporation theory. However, when Magrini and Nannei [3] investigated the influence of thickness of an internally heated surface on heat-transfer coefficients they found that heat-transfer coefficients increased as the heater thickness decreased. This influence was only observed in heaters below a certain limiting thickness. The limiting thickness varied with different heater materials. Magrini and Nannei postulated that in thin heaters the heat flux to the bubble site decreased, thus, the heat transferred to each bubble came from a small localized area of the heater wall. They hypothesized that this caused smaller bubbles to be formed on a thin heater than on a thick heater, and also increased the number of bubble sites. They thought the increased number of bubbles caused a greater mixing of the fluid near the heater wall which in turn resulted in an increased heat flux to the fluid.

Research in this area is relatively recent. Predictions and theories have sometimes contradicted experimental results and the significance of heater thickness is far from being established.

EXPERIMENTAL APPARATUS AND PROCEDURES

The boiler used for the experiment was a square vessel 6 in across and 10 in deep, constructed of stainless steel 1/8-in thick. A flange of stainless steel, 1/8-in thick and 1 1/2-in wide, was welded to the base of the boiler. Gaskets of 1/8-in thick Viton® rubber and 1/16-in thick asbestos were cut to fit the dimensions of the stainless steel flange. A transite base, 1/2-in thick, was also cut to fit against the flange. The heater plate was placed between the two gaskets and then was placed on top of the transite base. The transite base was then bolted to the stainless steel flange.

Heater plates of three different thicknesses were used (0.025, 0.051 and 0.13 mm). All three plates were made of type 302, brightly finished stainless steel shim and were 6-in long by 6-in wide. Two copper electrodes were soldered onto the back of each stainless steel plate. The electrodes were 1/8-in thick, 1/2-in wide, and 4-in long and were positioned on the plate 3 1/2-in apart. Boiling occurred only in the space between the two electrodes.

Sixteen chromel–alumel thermocouples (20 gage) were calibrated and soldered to the back of each plate between the copper electrodes. Twelve of these thermocouples were located so as to represent equal areas over the portion of the plate on which boiling took place. The other four were placed to help in estimating the temperature of the surface on which natural convection heat transfer occurred. Glass wool insulation (1/2-in thick) was used to cover the boiler and the bottom of the hearing plate to minimize heat loss to the surroundings.

During each run successive sets of thermocouple readings were taken until the readings at each specific heat flux differed only by random amounts so that averages were duplicated. This was taken to be an indication that the boiling process was at steady state. The procedure was repeated for each plate thickness and for three liquids: water, *n*-heptane, and ethanol. It generally took three to four hours of boiling before steady-state was reached.

The heat flux for nucleate boiling was taken as the total heat generated electrically divided by the area on which nucleate boiling took place, i.e. the area between the electrodes. Some heat was transferred to the liquid by natural convection but readings from thermocouples plus calculations showed that the natural convection heat transfer never exceeded 6% of the total heat generated.

ANALYSIS AND DISCUSSION OF RESULTS

The results were plotted on log–log graph paper and analyzed statistically using the Minitab II computer program on the UCSB IBM 360/75 computer. A linear regression analysis using the least squares method was used to determine the best-fitting straight line for what were taken to be the steady-state results. Figure 1 shows a typical plot of an entire set of results from experimental data and a straight-line fit through the steady-state data. The numbers beside the points give the sequence in which the data were obtained with lower numbers indicating results obtained after boiling for only a short period of time. The larger numbers indicate results obtained after 3–4 h of boiling. In Fig. 1 it can be seen that the heat-transfer coefficients decreased as reproducible conditions were approached (Run 9). Such a trend was observed for all three liquids but so was the opposite trend in which coefficients increased towards reproducible values.

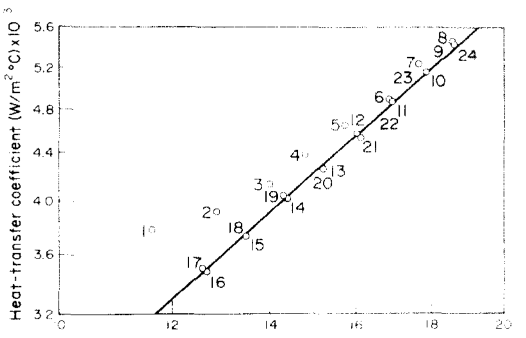

Fig. 1. Approach to steady state boiling for water with 0.025 mm plate.

The standard deviations of the steady-state data points about the regression lines were calculated and found to be small. The results for water and *n*-heptane had the smallest spread (standard deviations ranging from 0.0041 to 0.0098) and the ethanol results the largest (standard deviations of 0.012–0.015). Figure 2 shows the steady-state results for ethanol for all three plate thicknesses; Figs. 3 and 4 show the points for water and *n*-heptane respectively. It is evident that the effect of plate thickness on the magnitude of the heat-transfer coefficients is small. However, it appears that there is a small increase in the slopes of the three lines with increasing plate thickness for all three liquids.

To analyze the data further, it was assumed that the plate thickness did affect heat-transfer coefficients during boiling and that the plate thickness could

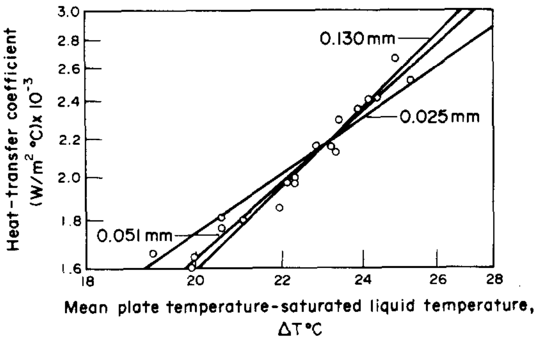

Fig. 2. Results for ethanol with three plate thicknesses.

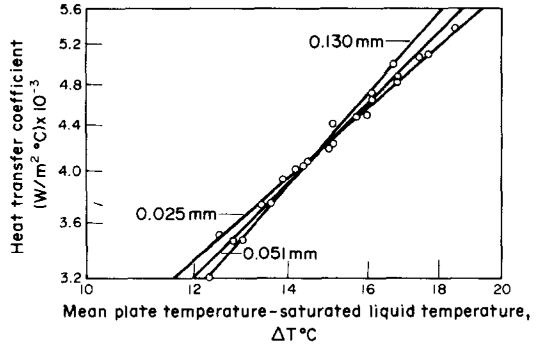

Fig. 3. Results for water with three plate thicknesses.

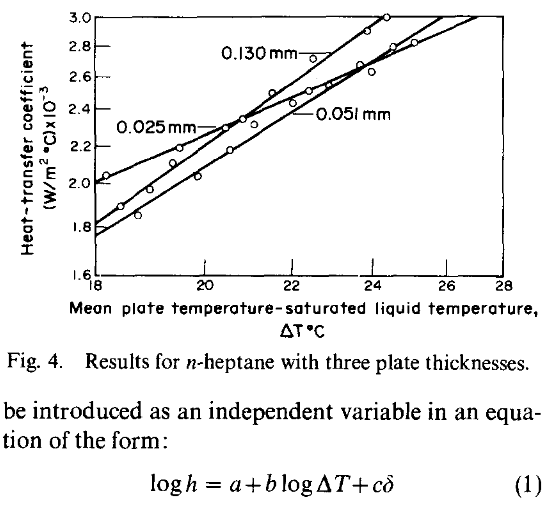

Fig. 4. Results for n-heptane with three plate thicknesses.

be introduced as an independent variable in an equation of the form:

$$\log h = a + b\log \Delta T + c\delta \qquad (1)$$

where δ is the plate thickness. The results for the three plate thicknesses were pooled for the three liquids and the coefficients a, b, and c determined. The coefficient of the thickness variable, c, was found to be quite small compared to the other two coefficients for all three liquid cases (see Table 1 below).

Table 1. Linear regression coefficients

	a	b	c
Ethanol	0.807	1.855	−0.0631
Water	2.19	1.219	0.0269
n-heptane	1.741	1.225	−0.1076

A statistical test was used to determine if the calculated regression coefficient was significantly different from zero [5]. In all three cases it was found that the thickness coefficient was not significantly different from zero over a 95% confidence interval. Nevertheless, Figs. 2–4 do show a definite pattern in the slope of the line for each plate thickness. For all three liquids, the 0.025 mm plate has the smallest slope, and the 0.13 mm plate has the largest slope. If there is no effect of plate thickness on the heat-transfer coefficient it would follow that the order in which the slopes of the regression lines occur would be completely random. For a given liquid there are six possible sequences for the three regression lines to fall in as far as the magnitude of their slopes is concerned. Therefore the probability of the slopes falling in the order that they did is 1/6. The probability that the slopes would fall in this same order for all three liquids is 1/216. However, there is an equal probability that the slopes may have fallen in one of the other five possible orders for all three liquids. Thus the probability of the slopes falling in one of the six possible orders is 1/36, which is quite small. The probability is so small that it seems to indicate that plate thickness does influence the slope of the heat-transfer coefficient curves.

From Figs. 2–4, it can be seen that at high values of ΔT the heat-transfer coefficients increase as the plate thickness increases. For small values of ΔT the trend is just the reverse. The fact that the effect appears to be a function of ΔT might resolve the conflict between the work of Sharp [1] and that of Magrini and Nannei [3]. Sharp hypothesized that as the heater plate thickness decreased below 0.250 mm, heat-transfer coefficients would decrease because the thin heater would not have a large enough thermal capacity. Sharp also mentioned that when the heater plate got thin that lateral heat conduction would be hindered, there would be a further decrease in the heat-transfer coefficient. However, Magrini and Nannei investigated the effect of plate thicknesses for plates thinner than 0.250 mm and found that the heat-transfer coefficient increased as plate thickness decreased. They hypothesized that the thermal capacity of the plate was not the controlling factor, but that the increased resistance to lateral conduction in thin heating plates was the important influence. When the microlayer of liquid beneath a bubble evaporates, a substantial amount of heat is withdrawn from the heating plate. Lateral conduction of heat is reduced in thin plates relative to thick plates. Because of this, Magrini and Nannei concluded that when the bubbles grew they would only be drawing heat from small localized areas of the heating plate. The rate of heat transfer to the base of the bubble would be reduced. As a result, smaller bubbles would be formed. Thus a thin plate would, at the same heat flux as a thick plate, produce bubbles of decreased size, but the number of bubble sites would be increased considerably. The larger number of bubbles on the thin plate would cause more mixing of the fluid near the heater wall. Magrini and Nannei concluded that this increased mixing would explain the increased heat-transfer coefficients during boiling on thin plates.

These two theories may be used in an attempt to explain why the thicker plates had higher heat-transfer coefficients when the ΔT was relatively high, but had lower heat-transfer coefficients when the ΔT was relatively low. When the ΔT is high, the rate of evaporation of the microlayer of liquid beneath the bubble will be increased. Bubble growth rates and bubble departure frequencies should increase. As a result, increased amounts of heat will be drawn from the heater plate. The high rate of heat withdrawal will be limited in the thinner plates because of the reduced heat content of the thin plate relative to the thick plate and because the rate of heat conduction to the bubble site is decreased in thin plates. Therefore, at high values of ΔT, the thicker plates should have higher heat-transfer coefficients. Even though the thinner plates may have a larger bubble population and an increased mixing near the wall as Magrini and Nannei proposed, the thermal capacity of the plate may still be the dominant factor.

The evaporation of the microlayer of liquid beneath the bubble causes a sharp reduction in the temperature of the plate near the surface of the plate. The penetration depth of this temperature pulse will be deeper when the bubble growth rate and departure frequency is high. Magrini and Nannei hypothesized that the thinner plates would have smaller bubbles, but an increased number of bubbles. The smaller bubbles would not have as large a temperature pulse as the larger bubbles on the thicker plates. Therefore, the penetration depth should be reduced and the influence of thermal capacity may not be as important as would be expected on thin plates. Still, at high ΔT values even the smaller bubbles on the thin plate would have a greater temperature pulse which may make the thermal capacity important. When the plate is at a lower ΔT, however, the bubble growth rate and departure frequency is decreased. The temperature pulse is decreased and therefore the penetration depth should decrease even more. At the lower value of ΔT the thermal capacity of the plate may not be the major influence dominating the heat-transfer mechanism. The smaller bubbles from thin plates would reduce the importance of thermal capacity. At lower ΔT values the importance of thermal capacity is reduced even more. It may be that at these values the dominant factor influencing the heat-transfer mechanism is the agitation of the fluid near the heater surface. The thinner plates would have greater agitation near the surface because of the larger number of small bubbles produced as hypothesized by Magrini and Nannei. This would enhance the rate of heat transfer. Thicker plates would not have such a large mixing effect near the surface because of the larger bubble size and the smaller bubble population. Thus at low ΔT the thinner plates may have higher heat-transfer coefficients than the thicker plates.

SUMMARY AND CONCLUSIONS

The effect of heater plate thickness on boiling heat-transfer coefficients was observed for three liquids: water, ethanol, and *n*-heptane using three plate thicknesses: 0.025, 0.051 and 0.13 mm. Thermocouples were attached to the bottom of the heater plate to obtain an average plate temperature which was then used to calculate the temperature difference, ΔT, between the plate temperature and the bulk liquid temperature. The heat fluxes during boiling ranged from 30 000 W/m^2 to 100 000 W/m^2. The heat-transfer coefficients were calculated and plotted as a function of ΔT which ranged from 13 to 25°C. The observed ranges of the boiling heat-transfer coefficients were from 1600 to 3000 W/m^2 °C for ethanol and *n*-heptane and from 3100 to 5400 W/m^2 °C for water. The experimental results were analyzed and it was found that the heater plate thicknesses had only slight influence on the values of the boiling heat-transfer coefficient in the range studied. The effect of plate thickness on the heat-transfer coefficient seemed to be a function of the magnitude of ΔT since the coefficient increased with increasing plate thickness for the larger measured values of ΔT but decreased with increasing plate thickness for the smaller values of ΔT.

A theory proposed by Sharp [1] predicted that heat-transfer coefficients should decrease as the plate thickness decreases, while Magrini and Nannei [3] hypothesized that the effect would be just the reverse. Both of these trends were observed in the present experimental results, but at opposite ends of the range of measured values of ΔT. The work described in this paper may reconcile the conflicting results of the previous investigators.

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L'EFFET DE L'EPAISSEUR DE LA PLAQUE CHAUFFANTE SUR LES COEFFICIENTS DE TRANSFERT THERMIQUE PAR EBULLITION

Résumé—On étudie l'effet de l'épaisseur de la plaque chauffante sur le coefficient de transfert thermique par ébullition, pour trois liquides, eau, éthanol et *n*-heptane, en utilisant des plaques d'acier inoxydable possédant trois épaisseurs, 0,025 mm, 0,051 mm et 0,13 mm. Les flux thermiques sont compris entre 30 000 W/m^2 et 100 000 W/m^2. On trouve que l'épaisseur de la plaque joue un rôle faible dans le domaine étudié. Néanmoins le coefficient de transfert thermique augmente sensiblement lorsque l'épaisseur de la plaque croît, ceci pour les valeurs de ΔT les plus élevées; pour les petites valeurs, la tendance est contraire.

DER EINFLUß DER HEIZFLÄCHEN-DICKE AUF DIE WÄRMEÜBERGANGSKOEFFIZIENTEN BEIM SIEDEN

Zusammenfassung—Der Einfluß der Heizflächen-Dicke auf die Wärmeübergangskoeffizienten beim Sieden wurde an drei Flüssigkeiten untersucht: Wasser, Aethanol und *n*-Heptan. Als Heizflächen dienten rostfreie Stahlplatten mit 0.025 mm, 0,051 mm und 0,13 mm Dicke. Die Wärmestromdichten beim Sieden lagen zwischen 30 000 und 100 000 W/m^2. Es zeigte sich, daß im untersuchten Bereich die Heizflächen-Dicke nur einen geringen Einfluß auf den Wärmeübergangskoeffizienten hatte. Für die höheren gemessenen Temperaturdifferenzen nahm der Wärmeübergangskoeffizient mit steigender Heizflächen-Dicke etwas zu—für die kleineren Werte war die Tendenz umgekehrt.

ЗАВИСИМОСТЬ КОЭФФИЦИЕНТА ТЕПЛООБМЕНА ПРИ КИПЕНИИ ОТ ТОЛЩИНА ПЛАСТИНЫ НАГРЕВАТЕЛЯ

Аннотация — Исследовалась зависимость коэффициентов теплообмена при кипенни от толщины пластины нагревателя для трех жидкостей: воды, этанола и н-гептана. Пластины были выполнены из нержавеющей стали толщиной 0,025, 0,051 и 0,13 мм. Тепловые потоки при кипении изменялись от 30 000 Вт/м^2 до 100 000 Вт/м^2. Было установлено, что толщина пластины лишь незначительно влияла на коэффициент теплообмена при кипении в исследуемом диапазоне переменных. Однако, для больших значений ΔT коэффициент теплообмена несколько увеличивается с увеличением толщины пластины, и наоборот, уменьшается для меньших значений ΔT.