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Nucleate boiling in a thin film on a horizontal tube at atmospheric and subatmospheric pressures

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Abstract—This investigation pertains to nucleate boiling in a thin film on a horizontal tube at atmospheric and subatmospheric pressures. The experiments are carried out with distilled water and sodium chloride solutions (35 000 and 50 000 p.p.m.) in the pressure range 60–100 kN m^{-2}. An enhancement in the nucleate boiling heat transfer coefficient is noted for boiling in the horizontal tube falling film. A correlation is proposed to predict the boiling heat transfer coefficient for distilled water and sodium chloride solution in a thin film on a horizontal stainless steel tube at atmospheric and subatmospheric pressures.

INTRODUCTION

HORIZONTAL tube evaporation (HTE) is an important thermal desalination process where water vapour gets condensed inside and boiling takes place in the thin film on horizontal tubes. The investment in the heat transfer surface of desalination plants is considerable. The performance of heat transfer tubes strongly affects the economic competitiveness of the thermal desalination system. The present work is confined to nucleate boiling of distilled water and sodium chloride (35 000 and 50 000 p.p.m.) solutions in a thin film on a horizontal tube at atmospheric and subatmospheric pressures as the published data on saline water boiling are very scarce.

EXPERIMENTAL APPROACH

Figure 1 shows the flow diagram of the horizontal tube falling film apparatus used in this experimentation. Boiling occurs on the outer surface of the 19 mm o.d. stainless steel tube which is heated by the dry saturated steam. The steam is passed inside the tube and a thin film of liquid is maintained by spraying it over the steam heated tube. It gets condensed in the tube imparting its latent heat to the evaporating liquid on the outer surface of the tube. Accuracy of the experimental data on heat transfer depends upon the exact temperature measurement of the surface and boiling liquid [1]. The platinum resistance thermometers of 100 Ω normal resistance at 0°C have been used for temperature measurements. The liquid at the entrance to the boiling chamber is maintained near its saturation temperature corresponding to the pressure in the boiling chamber by controlled heating using dimmerstats. A 25 mm diameter stainless steel pipe with 20 holes called orifices has been used as a distributor. The liquid is sprayed on the experimental tube through orifices. A coil type condenser is used for condensing the water vapour generated during boiling. The condensate is recycled back to the boiling chamber. A water ring vacuum pump is used to maintain the desired vacuum in the boiling chamber.

During a typical run, the salt concentration in the test liquid was first checked by a salinometer. Almost all dissolved gases were removed from the liquid by boiling it for 1 h. Flow rates and controlled pressures were continuously observed in order to ensure stability during the data collection. Enthalpy balance was carried out in each run to determine the adaptability of the experimental data. The range of variables studied is given in Table 1.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental data on the dynamics of liquid film and heat transfer from the tube surface to the falling liquid film were obtained. The reproducibility of the

Table 1. Range of variables

Systems	Distilled water and sodium chloride solutions (35 000 and 50 000 p.p.m.)
Heat flux (kW m^{-2})	100–200
Superheat (K)	5.0–16.0
Boiling temperature (K)	360–374
Absolute pressure (kN m^{-2})	60–100
Reflux density ($m^2\ s^{-1}$)	6×10^{-5}–17×10^{-5}
Velocity through orifice (m s^{-1})	0.15–0.75
Orifice diameter (mm)	3–5

NOMENCLATURE

C	constant in equation (6)
D	diameter
G	mass velocity
g	acceleration due to gravity
h	boiling heat transfer coefficient
k	thermal conductivity
p	pressure
q	heat flux
v	velocity
z_1	exponent in equations (5) and (6)
z_2	exponent in equations (5) and (6)
z_3	exponent in equation (6)
z_4	exponent in equation (6).

Greek symbols

Γ	reflux density
λ	latent heat of vaporization
μ	viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension.

Subscripts

b	bubble departure
L	liquid
o	orifice
V	vapour.

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number.

experimental data was ensured by repeating the experiment under the same conditions after a number of runs under different conditions. The heat transfer rate to the boiling liquid was evaluated indirectly by measuring the condensate flow rate and temperature.

The difference in boiling phenomena

The boiling behaviour of the test liquid was very different from that of nucleate pool boiling. In nucleate pool boiling, the bubbles grow from the cavities along the heating surface [2] and growth is confined to the thickness of the superheated thermal layer next to the heating surface [3, 4]. A bubble in nucleate pool boiling grows due to transient conduction from the thermal layer and due to evaporation from the superheated microlayer. Once the bubble departs from its site, it rises through a pool of saturated liquid. Bubble nucleation in the falling film on the horizontal tube, on the other hand, takes place with rapid bubble growth and the sliding around the tube circumference

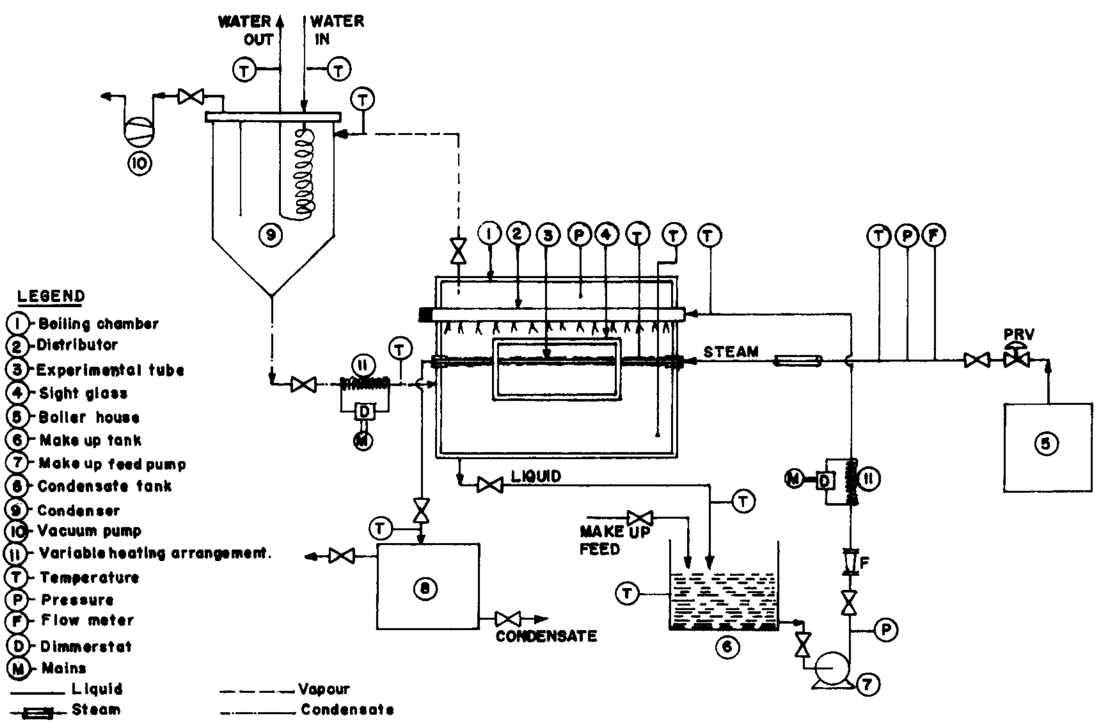

FIG. 1. Schematics of the horizontal tube falling film boiling setup.

taking place simultaneously after the bubble gets detached from the nucleation site (Fig. 2). The application of forced convection due to the liquid spray on the tube increases the convective contribution and results in early removal of the bubbles adhering to the surface which increases the bubble frequency. The bubbles were seen to detach from their sites at diameters larger than the liquid film thickness. This mechanism causes a rapid local rate of boiling heat transfer to take place depending on the number and size of the bubbles.

The effect of saturation pressure

The experimental data in Figs. 3–5 for distilled water and sodium chloride solutions (35 000 and 50 000 p.p.m.), boiling in the falling film on the horizontal tube shows that, in the nucleate boiling regime, the heat transfer coefficient decreases with a decrease in the saturation pressure as noted in the case of pool boiling [5, 6].

The effect of reflux density

It is seen that, within the reflux density range used in this work, the boiling heat transfer coefficient increases with the reflux density for atmospheric and subatmospheric pressures. Reflux density is defined as the volumetric flow rate per unit length of the tube. The dependence of the boiling heat transfer coefficient on the reflux density is a function of thermal conductivity of the liquid layer caused by turbulent pulsations, intensive mixing of the liquid through layer thickness, bubble nucleation and bubble growth.

A monotonic character of increase in the heat transfer coefficient is noted from the log–log plot of h vs Γ

$$h \propto \Gamma^n.$$

Close observation of Figs. 3–5 shows that n is approximately equal to 0.7.

Bubble growth, bubble detachment and heat transfer

A vapour bubble in a falling superheated liquid film on the horizontal tube has three stages of growth: a

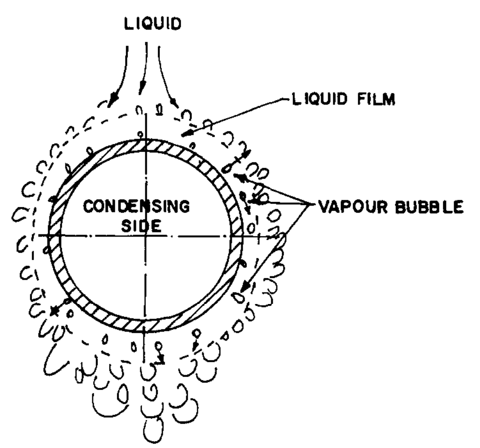

FIG. 2. Liquid boiling on the horizontal tube surface.

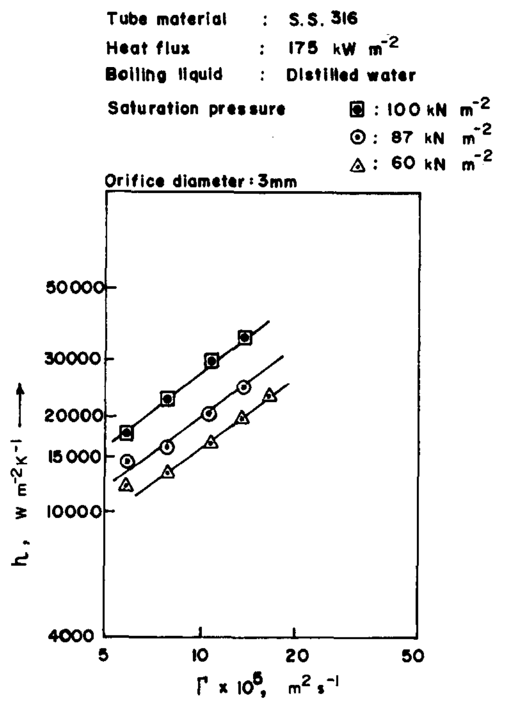

FIG. 3. Variation of nucleate boiling heat transfer coefficient with reflux density for distilled water at atmospheric and subatmospheric pressures.

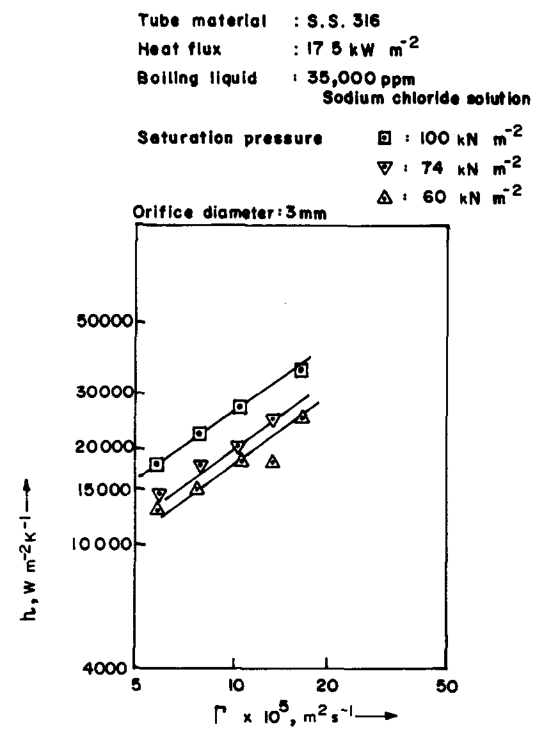

FIG. 4. Variation of nucleate boiling heat transfer coefficient with reflux density for 35 000 p.p.m. sodium chloride solution at atmospheric and subatmospheric pressures.

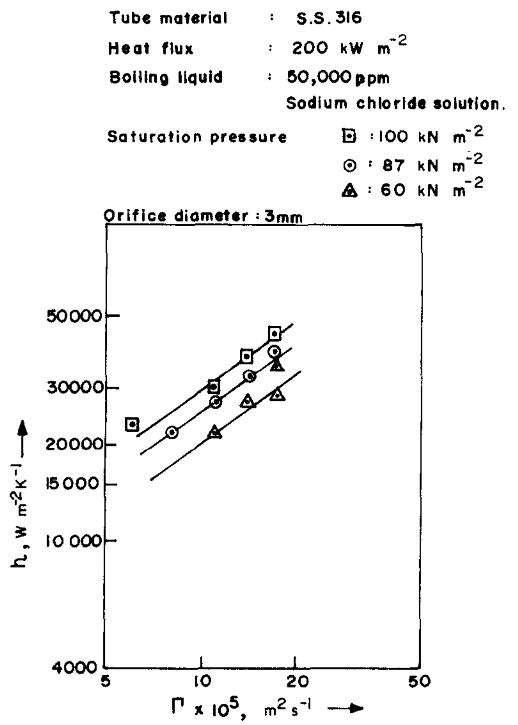

FIG. 5. Variation of nucleate boiling heat transfer coefficient with reflux density for 50 000 p.p.m. sodium chloride solution at atmospheric and subatmospheric pressures.

waiting stage, an unbinding stage and a freestream stage. The waiting stage is the time between the departure of a bubble and appearance of the next bubble at that nucleation site. A bubble grows after the waiting stage is over. Initially the bubble growth rate is controlled by the momentum equation since the surface tension and inertial effects of the surrounding fluid are very large. During the unbinding stage, the bubble tries to liberate itself from the surface tension and inertia effects of the surrounding fluid. During the freestream period or detachment period, the buoyancy force and heat transfer effects are dominant compared to the surface tension force and the thermal layer is thinned down by the growing bubble.

The bubble departure diameter is obtained by equating buoyancy and surface tension forces

$$D_b = (\sigma/g(\rho_L - \rho_V))^{0.5}. \quad (1)$$

The superficial liquid mass velocity towards the heating surface can be written as

$$G_b = q/\lambda. \quad (2)$$

The Nusselt number and Reynolds number for bubble departure are

$$Nu_b = (h/k_L)(\sigma/g(\rho_L - \rho_V))^{0.5} \quad (3)$$

$$Re_b = (q/\lambda\mu_L)(\sigma/g(\rho_L - \rho_V))^{0.5}. \quad (4)$$

In the nucleate boiling region, the surface temperature increases very slowly for a relatively large change in surface heat flux. The dimensionless relationships have been published by analogy with the relationship for forced convection heat transfer of single phase fluids [7]

$$Nu_b = C\, Re_b^{z_1}\, Pr^{z_2}. \quad (5)$$

The effect of saturation pressure and surface tension of the boiling liquid is taken into account by introducing a dimensionless group known as the bubble coverage factor

$$P/(\sigma g(\rho_L - \rho_V))^{0.5}.$$

The liquid is sprayed from the orifice in the distributor on the tube. A liquid film forms on the outer surface of the tube. The orifice diameter, velocity through the orifice and reflux density play an important role during the boiling in the thin film on the horizontal tube. These parameters are included in a dimensionless group as follows:

$$(D_o v_o \Gamma/\nu_L^2).$$

Equation (5), after introducing the dimensionless groups given above, can be written as

$$Nu_b = C\, Re_b^{z_1}\, Pr^{z_2} (P/(\sigma(\rho_L - \rho_V)g)^{0.5})^{z_3} (D_o v_o \Gamma/\nu_L^2)^{z_4}. \quad (6)$$

The exponents and constants are found by the method of averages and the final correlation is written as

$$Nu_b = 1.25 \times 10^{-7} (Re_b)^{0.7}\, Pr^{0.35} \times (P/(\sigma(\rho_L - \rho_V)g)^{0.5})^{0.7} (D_o v_o \Gamma/\nu_L^2)^{0.7}. \quad (7)$$

The dimensionless groups formulated are similar to those used by the previous investigators [8, 9]. A comparison of the calculated values of Nusselt number (Nu_b) from equation (7) with the experimental values is shown in Fig. 6. The experimental results are in agreement with equation (7) with a percent standard deviation of 30%.

CONCLUSIONS

An enhancement in boiling heat transfer is noted for a horizontal tube falling film compared to nucleate pool boiling. The spray film eliminates the effect of pool depth on boiling because of spraying the liquid on to the outer surface of the tube in a thin film which reduces the liquid depth to a small value. The boiling heat transfer coefficient decreases with saturation pressure. An empirical correlation is proposed to predict the heat transfer coefficient based on the experimental data on boiling in a thin film on a horizontal stainless steel tube at atmospheric and subatmospheric pressures.

Legend	Boiling liquid	Saturation press. kN m^{-2}	Heat flux kW m^{-2}
⊡	Distilled water	100	135 - 200
⊙	Distilled water	87	165 - 200
◬	Distilled water	60	135 - 200
⊠	35000 ppm NaCl solution	100	165 - 200
⊗	35000 ppm NaCl solution	87	165 - 200
▽	35000 ppm NaCl solution	74	135 - 200
◬	35000 ppm NaCl solution	60	100 - 200
■	50000 ppm NaCl solution	100	165 - 200
●	50000 ppm NaCl solution	87	165 - 200
▲	50000 ppm NaCl solution	60	135 - 200

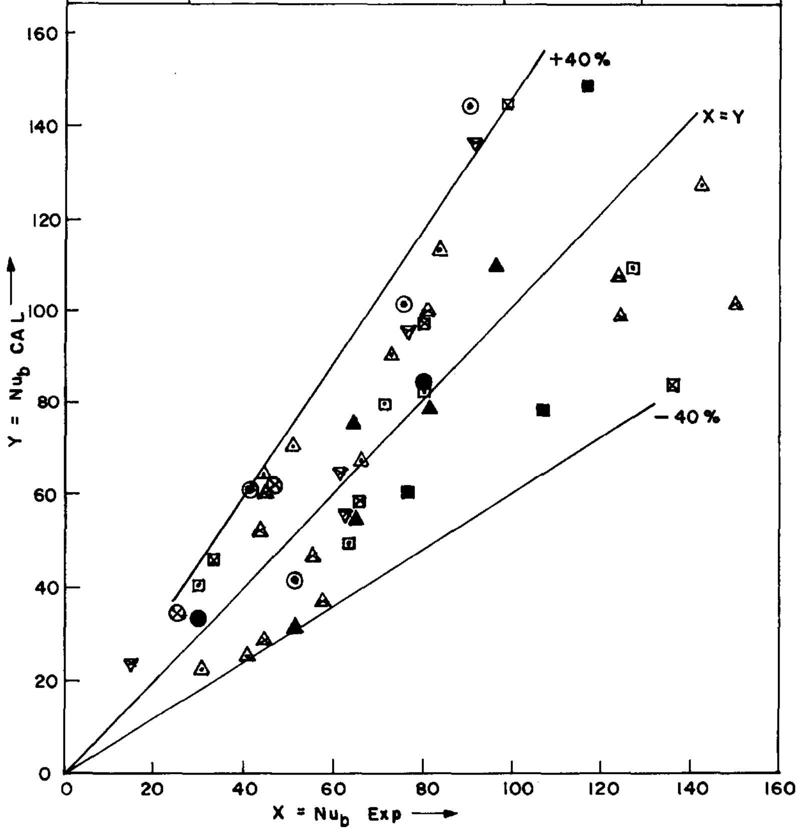

FIG. 6. Deviation in experimental and calculated Nusselt numbers.

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EBULLITION NUCLEEE EN FILM MINCE SUR UN TUBE HORIZONTAL, A DES PRESSIONS SUBATMOSPHERIQUES ET ATMOSPHERIQUE

Résumé—Cette étude concerne l'ébullition nucléée en film mince sur un tube horizontal, à des pressions subatmosphériques et atmosphériques. Les expériences sont faites avec des solutions de chlorure de sodium dans l'eau distillée (35 000 et 50 000 p.p.m.), dans le domaine de pression 60–100 kN m^{-2}. Un accroissement du coefficient de transfert thermique est noté pour l'ébullition nucléée d'un film tombant sur le tube horizontal. Une formule est proposée pour prédire le coefficient de transfert pour une solution de chlorure de sodium dans l'eau distillée, en film mince sur un tube d'acier inoxydable horizontal, à des pressions subatmosphériques et atmosphérique.

BLASENSIEDEN IN EINEM DÜNNEN FILM AN EINEM HORIZONTALEN ROHR BEI UMGEBUNGSDRUCK UND BEI UNTERDRUCK

Zusammenfassung—Diese Untersuchung behandelt das Blasensieden in einem dünnen Film an einem horizontalen Rohr bei Umgebungsdruck und bei Unterdruck. Die Versuche wurden mit destilliertem Wasser und mit Natriumchlorid-Lösungen (35 000–50 000 p.p.m.) in einem Druckbereich von 60–100 kN m^{-2} durchgeführt. Eine Erhöhung des Wärmeübergangskoeffizienten beim Sieden im Fallfilm am waagerechten Rohr wurde festgestellt. Zur Berechnung des Wärmeübergangskoeffizienten beim Blasensieden von destilliertem Wasser und Natriumchlorid-Lösungen in dünnen Filmen an einem horizontalen Rohr aus nichtrostendem Stahl bei Atmosphärendruck und bei Unterdruck wird eine Korrelation vorgeschlagen.

ПУЗЫРЬКОВОЕ КИПЕНИЕ В ТОНКОЙ ПЛЕНКЕ НА ГОРИЗОНТАЛЬНОЙ ТРУБЕ ПРИ АТМОСФЕРНОМ ДАВЛЕНИИ И ДАВЛЕНИИ НИЖЕ АТМОСФЕРНОГО

Аннотация—Проведены эксперименты с растворами хлорида натрия в дистиллированной воде (35 000 и 50 000 частей на миллион) в диапазоне давлений от 60 до 100 кН $м^{-2}$. Обнаружено, что при пузырьковом кипении в пленке, стекающей с горизонтальной трубы, коэффициент теплообмена возрастает. Предложено соотношение для расчета коэффициента теплообмена при кипении в тонкой пленке на горизонтальной трубе из нержавеющей стали.