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HEAT TRANSFER IN DROPWISE CONDENSATION AT LOW STEAM PRESSURES IN THE ABSENCE AND PRESENCE OF NON-CONDENSABLE GAS

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Abstract—Measurements are reported of steam-side heat-transfer coefficients during the dropwise condensation of steam on copper surfaces promoted by montan wax and dioctadecyl disulphide, over the heat flux range 5000–30000 Btu/ft²h and at steam pressures of 0·8–3-in mercury. The noncondensable gas concentration by volume was varied between <1 and 15000 ppm. At low non-condensable gas concentrations, the steam-side heat-transfer coefficients varied between 10000 and 28000 Btu/ft²hdegF over the steam pressure ranges studied which would indicate that the condensation coefficient for water is at least 0·1.

NOMENCLATURE

α, the condensation coefficient;
P_v, vapour pressure of the steam adjacent to the surface;
P_s, vapour pressure at the surface;
T_v, temperature of the vapour adjacent to the surface;
T_s, temperature of the condensing surface;
M, molecular weight of vapour;
R, gas constant.

INTRODUCTION

WHEN steam condenses on a cooled clean metal surface a continuous film of condensate is formed which creates a thermal resistance to the further flow of heat. If the metal is hydrophobic owing to the presence of dropwise condensation promoters, then the steam will condense to form discrete water droplets which, as they roll over the surfaces and coalesce, expose "bare" areas of metal surface to the steam. This dropwise mode of condensation results in greatly enhanced heat transfer. Thus the change from filmwise to dropwise condensation at atmospheric pressure results in a tenfold increase in the steam-side heat-transfer coefficient. Although this was first reported in 1930 by Schmidt *et al.*, [1] the design of heat exchangers is still based upon filmwise rather than dropwise condensation. Two reasons for this are the paucity of data for heat transfer during the dropwise condensation of steam at low pressures, i.e. in the range 0·5–3-in mercury and the uncertainty of maintaining dropwise condensation under practical conditions.

Gnam [2] reported values of the steam-side heat-transfer coefficient for dropwise condensation over the pressure range 5–27-in mercury and for heat fluxes between 30000 and 120000 Btu/ft²h. The coefficient was found to decrease with decreasing pressure and heat flux, the lowest value was about 10000 Btu/ft²hdegF at a pressure of 5-in mercury and heat flux of 36000 Btu/ft²h. Ma [3] investigated the pressure range 5–29-in mercury and also found that the coefficient fell with decreasing pressure and heat flux. At a pressure of 5-in mercury and a heat flux of 8000 Btu/ft²h the value of the coefficient was about 4000 Btu/ft²hdegF. Brown and Thomas [4] also reported a fall in the steam-side coefficient with decreasing pressure and higher coefficients at lower heat fluxes. Extrapolation of these results to conditions commonly found in practice (steam pressure 1–2-in mercury and heat flux 5000–10000 $\mathrm{Btu/ft^2h}$) would imply a further decrease in the steam-side heat-transfer coefficient and the possibility that dropwise condensation would offer no improvement over filmwise condensation. The conclusion that the coefficient decreases with decreasing pressure and heat flux is supported by the theoretical arguments of Silver [5, 6] who showed that a low value of the condensation coefficient for water (0·04) might set a limit on heat transfer during condensation at low pressures. That the steam-side heat-transfer coefficient decreases with decreasing pressure is also indicated by Wenzel [7, 8] and Le Fevre and Rose [9]. For these reasons it seemed desirable to measure steam-side heat-transfer coefficients for both modes of condensation over the heat flux range 5000–30000 $\mathrm{Btu/ft^2h}$ at steam pressure of 1–3-in mercury.

EXPERIMENTAL DETAILS

Apparatus

The condenser and vacuum system is shown in Figs. 1 and 2. One end of the 0·75-in O.D. copper rod, was the condensing surface and the other the cooled surface. Cooling water was supplied at constant velocity from a thermostated water bath the temperature of which was maintained within ±0·05°C. The method of measuring the heat flux through the condenser wall was similar to that described in our earlier papers and by other workers [2, 10, 11]. The temperature profile through the copper rod condenser was measured by four 40 s.w.g. shellac-insulated copper–constantan thermocouples inserted in 0·022-in holes 0·5-in deep which were situated at 90° intervals around the circumference and at accurately known intervals along the rod. The thermocouple outputs were measured on a Cambridge 6 channel potentiometric recorder.

The copper rod was located in the precision bore glass tube from which the condensation cell was fabricated, by means of two P.T.F.E. collars fitted with O rings to allow for the differential thermal expansion of glass and copper. The space between the two P.T.F.E. collars was evacuated continuously with a rotary vacuum pump thus providing good thermal insulation for the copper rod and a vacuum seal for the condensation cell.

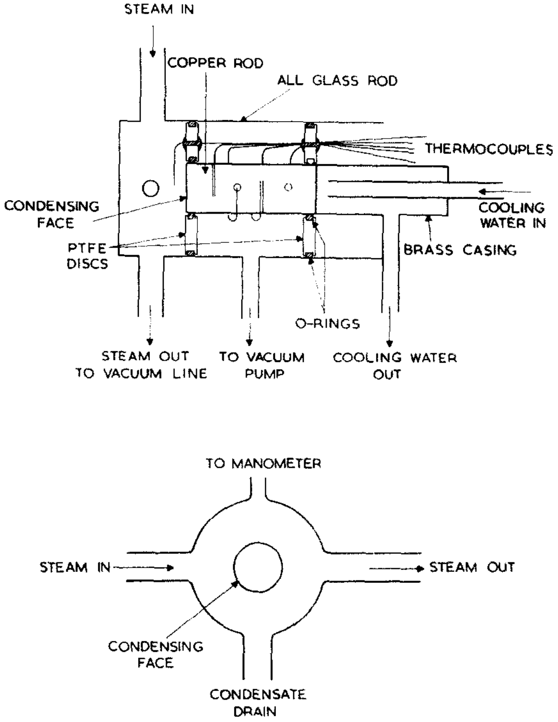

FIG. 1. Test cell for the evaluation of steam-side heat-transfer coefficients during the condensation of steam.

Steam was generated in a 3-l. glass flask fitted with an isomantle and internal heater. Thus steam could be generated either by surface film evaporation or nucleate boiling. Only a fraction of the steam ($\simeq 2$ per cent) was condensed in the cell, the remainder passed via a vacuum line to one of two traps cooled in liquid nitrogen. Any non-condensable gas in the steam was then passed by means of a mercury diffusion pump into a calibrated volume fitted with a McCleod gauge. In this way it was possible to determine the average non-condensable gas content of the steam. Finally the system could be pumped to waste through a rotary backing pump. Non-condens-

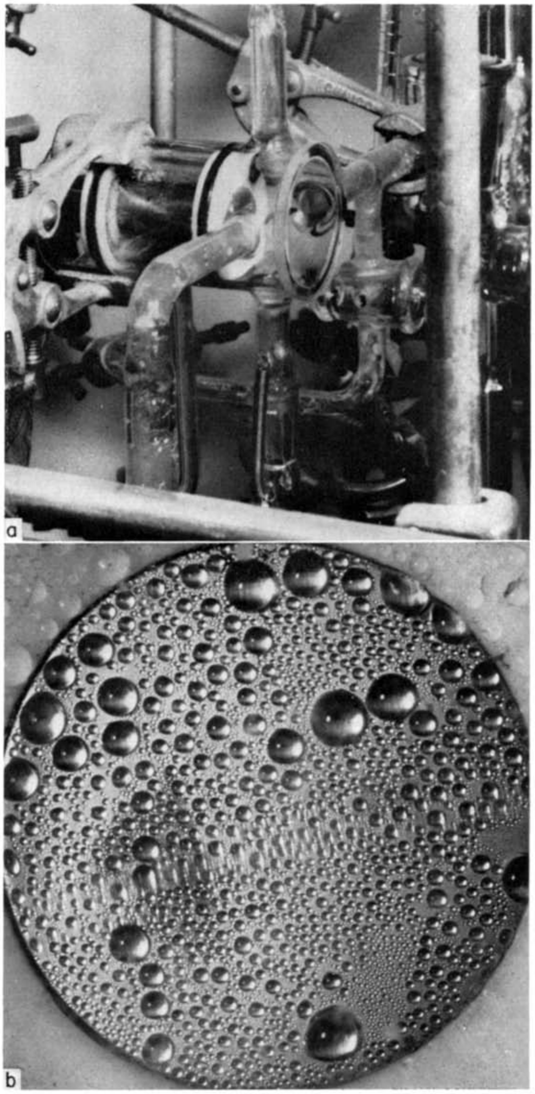

FIG. 2. (a) Experimental cell. (b) Dropwise condensation of condenser face at a steam pressure of 1·5 in Hg.

able gases could be introduced into the steam supply to the condensation cell through a side-arm situated before the cell. The gas flow rate was measured with a bubble flow meter and a rotameter. Figure 3 shows the general arrangement of the vacuum system.

the mercury diffusion and rotary backing pumps via the liquid nitrogen traps completed de-aeration. Finally, after isolating the boiler, the system was pumped down to 10^{-5} mm Hg.

During the condensation experiments readings of the thermocouples in the condensation cell and in the block were taken during rising and falling heat fluxes at three steam pressures (0·8-, 1·5- and 3·0-in mercury). The heat flux was controlled by variation of the cooling water temperature. The steam pressure was measured with a mercury manometer fitted to the condensation cell.

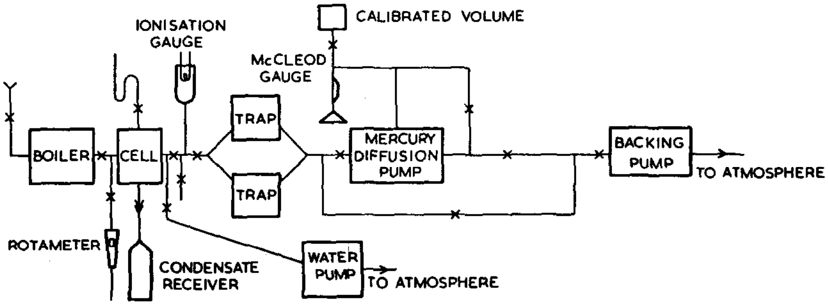

FIG. 3. Block diagram of vacuum line.

Procedure

The thermocouples were calibrated in a thermostatically controlled water bath against NPL certified thermometers calibrated in 0·1°C divisions and read with the aid of a meniscus viewer. The output of the thermocouples was measured to an accuracy of ±5 μV on the recording potentiometer. The thermocouples agreed among themselves to ±3 μV or ±0·04°C.

The condensing surface of the copper rod was polished with successive grades of metallurgical paper and diamond paste to a 1 μ finish. The surface was then electrolytically degreased [12], rinsed with distilled water and promoted with montan wax by absorption from a 5×10^{-3} M solution in benzene or by dioctadecyl disulphide by absorption from 1×10^{-2} M solution in benzene at 50°C.

The boiler was charged with Analar water and the pressure in the cell and boiler reduced to about 2-in mercury by means of a water pump. De-aeration of the boiler charge was then achieved by boiling for about 20 min, the steam and non-condensable gases being discharged to waste via the water pump. A further period of 15–20 min boiling at about 2–3 in mercury pressure whilst the system was pumped with

The velocity of the steam through the cell was too low to disturb the flow of condensate during dropwise condensation. However, at a steam pressure of 3-in mercury during filmwise condensation some disturbance of the condensate film was observed. During the experiments non-condensable gas was collected to obtain an average value for the concentration in the inlet steam. In some experiments nitrogen or oxygen was metered into the inlet steam at the point shown in Fig. 3. When the ambient temperature was above steam temperature, the cell and steam inlet pipe were wrapped with wet asbestos paper to prevent steam superheat. Comparison of the steam pressure and temperature never indicated more than 0·3°C superheat at any of the three pressures studied.

The temperatures through the copper block, as measured by the four thermocouples, fell closely about a straight line. The heat fluxes were calculated from the temperature profiles through the rod and the thermal conductivity of the copper which was taken as 220 Btu/ft h degF, the copper meeting British Standards specification No. 1861. A heat balance calculated by measuring the mass of condensate collected in the condensate receiver agreed to within 5 per cent with that obtained by the first method.

RESULTS

Heat flux

The variation of ΔT with the heat flux for filmwise and dropwise condensation is shown in Figs. 4 and 5 for the three steam pressures and two dropwise condensation promoters studied at non-condensable gas concentrations of <1 ppm. In the case of dropwise condensa-

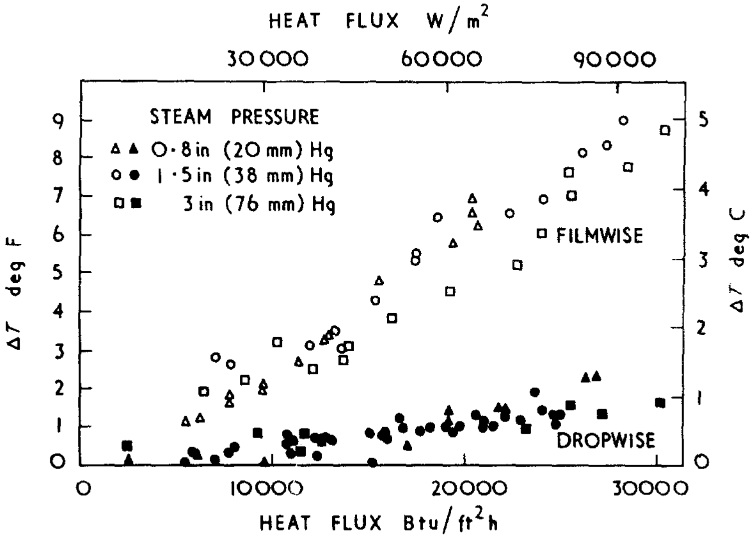

FIG. 4. Dropwise condensation: promoter montan wax (ΔT = difference between steam and condenser surface temperatures).

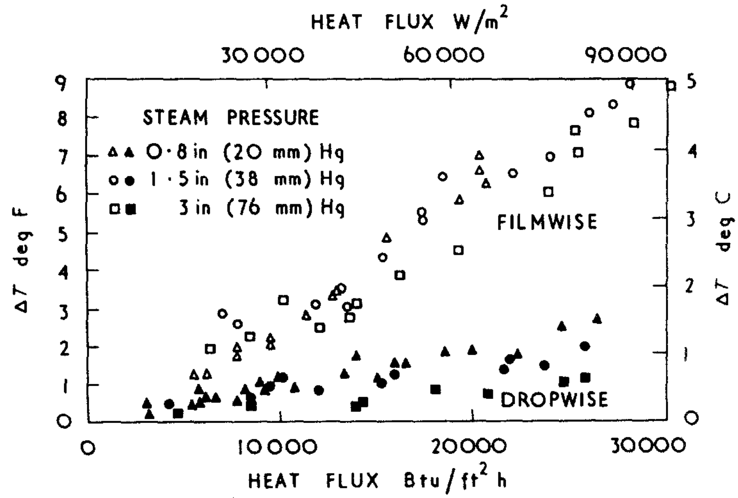

FIG. 5. Dropwise condensation: promoter dioctadecyl disulphide (ΔT = difference between steam and condenser surface temperatures).

tion the plot is approximately linear passing through the origin over the heat flux range 5000–30000 Btu/ft^{2}h. Hence, as shown in Fig. 6, the steam-side heat-transfer coefficient was constant with varying heat flux which contrasts with the decreasing coefficient with increasing heat flux implied by the filmwise curves, and with the increasing coefficient with heat flux as previously reported at atmospheric pressure [11]. Thus the dropwise condensation results show lower ΔT values than filmwise condensation at the three steam pressures studied and therefore a rate of increase of 200–600 per cent in the steam-side heat-transfer coefficient when the mode of condensation is changed from filmwise to dropwise over the steam pressure range 1–3-in mercury.

Comparison of the ΔT–heat flux plots in Figs. 4 and 5 for dropwise condensation shows that at constant heat flux, ΔT decreases as the steam pressure is raised so that the derived steam-side heat-transfer coefficient increases. Figure 7 compares the present results with those of Gnam, Ma and Brown and Thomas [2, 3, 4]. Since the rate of condensation of a vapor adjacent to the condensing surface is given by

$$r_1 = \alpha P_v/2\Pi RT_v/M)^{\frac{1}{2}} \quad (1)$$

and the rate of evaporation by

$$r_2 = \alpha P_s/(2\Pi RT_s/M)^{\frac{1}{2}} \quad (2)$$

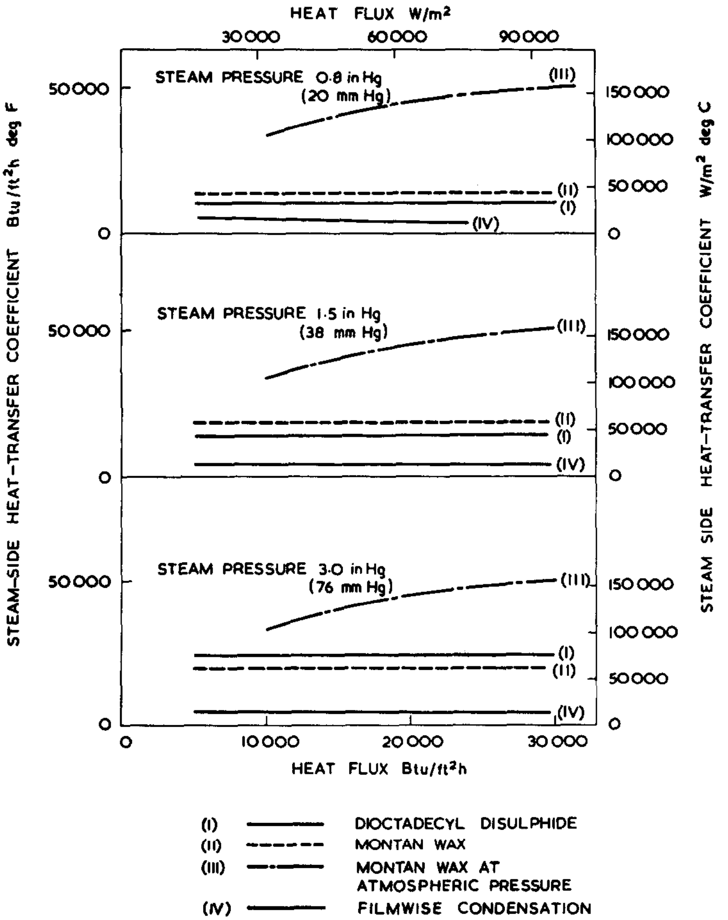

FIG. 6. Variation of the steam-side heat-transfer coefficient with heat flux and promoter.

the nett rate of condensation is

$$r_1 - r_2 = \frac{\alpha M^{\frac{1}{2}}}{(2\Pi R)^{\frac{1}{2}}}\left(\frac{P_v}{T_v^{\frac{1}{2}}} - \frac{P_s}{T_s^{\frac{1}{2}}}\right) \qquad (3)$$

Assuming a value of 0·04 for the condensation coefficient α, the solid line was calculated from equation (3).

It is well known that the presence of non-condensable gas lowers the value of the steam-side heat-transfer coefficient during steam condensation at atmospheric pressure; the effect at low steam pressures is less well known. The relative value of the reduction, i.e. the ratio of the coefficient in the presence of non-condensable gas to that obtained in the absence of non-condensable gas is plotted against the gas concentration (v/v) in the steam in Fig. 8. It can be seen that the sensitivity of the coefficient to the presence of non-condensable gas increases with rising heat flux and decreasing pressure. The addition of a chemically reactive gas such as oxygen did not affect the mode of condensation as previously reported at atmospheric pressure [13, 14].

Figure 9 is a comparison of the filmwise results with the Nusselt correlation, calculated for a vertical flat plate of height $\frac{3}{4}$-in, and shows that reasonable agreement was obtained at steam pressures of 0·8 and 1·5-in mercury. The lower experimental temperature differences be-

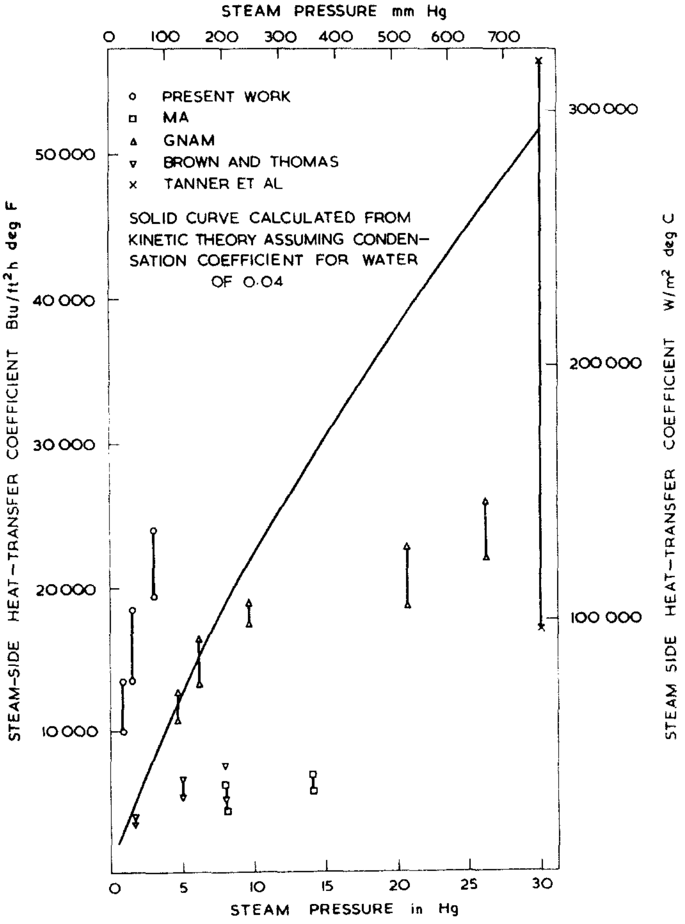

FIG. 7. Variation of steam-side heat-transfer coefficient with pressure.

tween the steam and condenser surface at a steam pressure of 3-in mercury is probably caused by the disturbance of the condensate film by the steam flow that was noted at this pressure.

DISCUSSION

The present results show that during the condensation of steam the resistance to heat transfer on the steam-side is at least halved by changing the mode of condensation from filmwise to dropwise at the lowest steam pressure studied (0·8-in mercury). The relatively high values of the steam-side heat-transfer coefficient obtained in this work are believed to be a consequence of minimizing the effects of non-condensable gas by reducing the gas concentration in the inlet steam to <1 ppm as described, and condensing only a small fraction of the inlet steam.

The values of the steam-side heat-transfer coefficient imply that the condensation coefficient for water is $\geqslant 0{\cdot}1$ and that the condensation coefficient does not set a limit to heat transfer during steam condensation at low pressures and over the heat flux range 5000–30000 Btu/ft^{2}h. Other workers [15–20] also report high values; Jamieson [17, 18] measured the rate of condensation of steam on a jet of water and found that the coefficient varied with the age of the liquid surface, low values being obtained at high residence times. However, when working with a residence time of about 2×10^{-5} s he reports a value of 0·35. Johnstone and Smith [20] measured temperature changes in quiescent liquids and found for water,

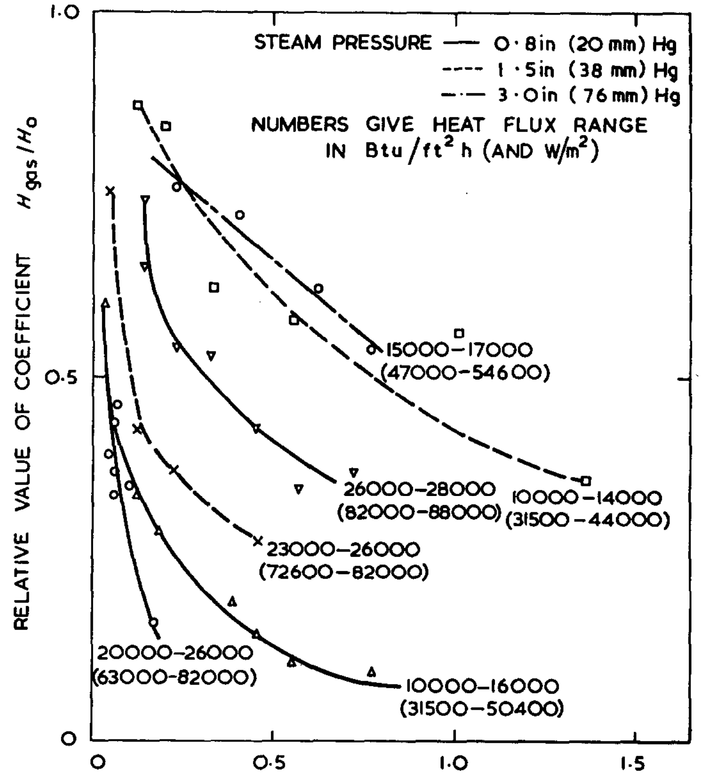

FIG. 8. Effect of non-condensable gas on the steam-side heat-transfer coefficient.

coefficients of 0·01–0·14, the low values also being obtained at high surface residence times. Careful de-aeration and short experimental duration times precluded the possibility of the results being lowered owing to the presence of non-condensable gas. The lower results of Ma, (Gnam in his higher pressure region) and Brown and Thomas could possibly be explained as being caused by the presence of non-condensable gas.

The addition of non-condensable gas to the inlet steam reduced the steam-side heat-transfer coefficient when the steam was condensed at pressures of 0·8–3·0-in mercury. The magnitude of the reduction in the coefficient was dependent upon:

(i) heat flux;
(ii) steam pressure;
(iii) concentration of non-condensable gas in the bulk steam.

It is to be expected that the rate of arrival of non-condensable gas at the vapour–liquid interface will depend upon the heat flux which determines the rate of arrival of molecules of the vapour–gas mixture. This will reach a steady state so that the concentration of non-condensable gas at the interface reaches a value at which the diffusion of gas back into the bulk steam balances that arriving. Thus a change in the heat flux will result in a change in the concentration of non-condensable gas at the interface, an increase in heat flux increasing the gas concentration and lowering the thermal driving force and hence lowering the steam-side heat-transfer coefficient. The theoretical arguments of Lin and Sparrow [21] and Minkowycz and Sparrow [22] predicts an increasing interfacial non-condensable gas concentration with falling bulk steam pressure for a constant non-condensable concentration and further predict the interfacial increase in non-condensable gas concentration with increasing bulk steam non-condensable gas concentration.

As reported in an earlier paper [14] at atmospheric pressure a rapid change from dropwise condensation was observed when oxygen was admitted to the inlet steam. In the present work oxygen was admitted for periods of up to 30 min under low pressure conditions. No permanent reduction in the steam-side heat-transfer coefficient was noted and the mode of condensation remained dropwise throughout the addition. The most likely explanation would seem to be the reduced rate of copper oxidation at the lower temperatures involved at low pressures.

The effect of the two different promoters on the steam-side heat-transfer coefficient was not

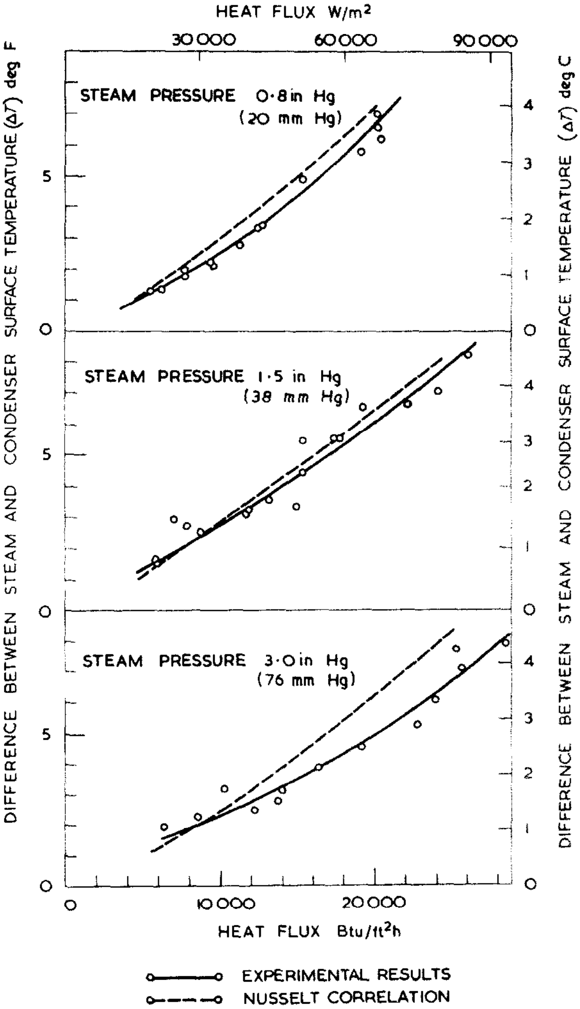

FIG. 9. Filmwise condensation.

clear. As is shown in Fig. 6, at steam pressures of 0·8 and 1·5-in mercury, montan wax appeared to give higher coefficients than dioctadecyl disulphide. At a steam pressure of 3-in mercury the order was reversed. Both materials promote dropwise condensation under low pressure conditions and offer greatly enhanced heat-transfer coefficients over filmwise condensation. The plots of the primary data shown in Figs. 4 and 5 show some scatter of individual points but it is believed that differing rates of adsorption and desorption of the two promoters may result in varying amounts of promoter being adsorbed and remaining on the surface. The adsorption of multi layers of sulphur promoters and fatty acids has been reported [14, 23] and this could introduce a further thermal resistance on the steam-side. The desorption of these multi layers under low heat flux and temperature conditions would be very slow so that over the period of an experiment no increase in coefficient would be observed owing to the reduction in thermal resistance on desorption.

CONCLUSIONS

1. Dropwise condensation promotion increases the steam-side heat-transfer coefficient at 0·8–3-in mercury pressures by a factor of two to six times.
2. The presence of non-condensable gas reduces the rate of heat transfer, the reduction being dependent upon the heat flux, concentration and steam pressure. Oxygen in the steam at low steam pressures does not produce the dramatic change from dropwise to filmwise condensation that has been observed at at atmospheric pressure.
3. The values for the steam-side heat-transfer coefficient indicate that during dropwise condensation at steam pressures of 0·8–3-in mercury the condensation coefficient of water is not limiting and is probably $\geqslant 0{\cdot}1$.

ACKNOWLEDGEMENT

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Résumé—On décrit les mesures des coefficients de transport de chaleur du côté de la vapeur pendant la condensation par gouttelettes de la vapeur d'eau sur des surfaces de cuivre recouvertes de cire "montan" et de bisulfure de dioctadécyle, dans la gamme de flux de chaleur allant de 15,8 à 94,7 kW/m^2 et à pressions de vapeur de 19,5 à 73 mm de mercure. La concentration en volume de gaz non-condensable variait entre 1 et 15000 ppm. Pour de faibles concentrations de gaz non-condensable, les coefficients de transport de chaleur du côte de la vapeur variaient entre 56,9 et 159 kW/m^2 °C, dans les gammes étudiées de pression de vapeur, ce qui indiquerait que le coefficient de condensation pour l'eau est au moins égal à 0,1.

Zusammenfassung—Es wird über Messungen der dampfseitigen Wärmeübergangszahl bei Tropfenkondensation von Wasserdampf berichtet. Die Kondensationsflächen bestanden aus Kupfer und waren mit "Montan wax" bzw. "dioctadecyl disulphide" hydrophobiert. Die Wärmestromdichte lag zwischen 15000 und 95000 W/m^2, der Dampfdruck zwischen 20 und 75 Torr. Die Inertgaskonzentration wurde zwischen 10^{-6} und $15 \, . \, 10^{-3}$ Volumenteilen variiert. Bei niedrigen Inertgaskonzentrationen lagen die Wärmeübergangszahlen im untersuchten Druckbereich zwischen 55000 und 160000 W/m^2. Dieses Ergebnis deutet darauf hin, dass der Kondensationskoeffizient von Wasser mindestens 0,1 beträgt.

Аннотация—Приводятся результаты измерения коэффициентов теплообмена в паровой фазе при капельной конденсации пара на медных поверхностях, покрытых буроугольным воском и диоктодекан-сульфидом при тепловых потоках от 5000 до 30000 БТЕ/фт^{2}час и давлениях пара от 0,8 до 3 дюймов рт. ст. Объемная концентрация неконденсирующегося газа была от 1 до 15000 единиц на миллион. При низких концентрациях неконденсирующегося газа коэффициенты теплообмена в газовой фазе были от 10000 до 28000 БТЕ/фт^{2}час °F в исследуемом диапазоне давлений, что указывает на то, что коэффицеинт конденсации для воды не меньше 0,1.