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HEAT TRANSFER IN DROPWISE CONDENSATION—PART I

THE EFFECTS OF HEAT FLUX, STEAM VELOCITY AND NON-CONDENSABLE GAS CONCENTRATION

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Abstract—Measurements are reported of surface temperature during the dropwise condensation of steam at atmospheric pressure on copper surfaces promoted by montan wax, over the heat flux range 10 000–200 000 Btu/ft^{2}h. Steam flow rate was varied between about 10 and 80 ft/s and the non-condensable gas concentration from 2 to 500 ppm. The steamside heat-transfer coefficient was found to increase with increasing heat flux and steam velocity. The addition of non-condensable gas lowered the coefficient, carbon dioxide having a greater effect than nitrogen. Maximum values of the coefficient exceeded 50 000 Btu/ft^{2}h degF, which would indicate that the condensation coefficient for water exceeds 0·04.

INTRODUCTION

SINCE THE observation reported in 1930 by Schmidt *et al.* [1] that the heat-transfer coefficient for the dropwise condensation of steam was roughly five times greater than that for filmwise condensation, there has been a continuing interest in dropwise condensation as offering a means of improving the performance of heat exchange equipment. In considering practical applications, the emphasis has naturally been placed on overall heat-transfer coefficients but, for an understanding of the mechanism, measurements of the steamside coefficient are essential. The value of this coefficient depends on both physical and chemical factors. Of the former, heat flux [2–15], surface geometry [2–5], steam pressure [4, 6, 7], steam velocity [6, 8, 9] and non-condensable gas concentration [4, 10, 11] have been examined. Chemical factors, such as the nature of the surface and promoter, have been less widely studied [7, 15].

Earlier work on dropwise condensation has usually laid stress either on heat transfer or on promoter chemistry. The object of the present work was to combine these aspects in a single study, attempting to relate heat-transfer results to the surface chemistry. To do this, it was first necessary to examine the physical factors influencing heat transfer, and the results of this study are given below for the system copper–montan wax. The wax promoter was chosen as representing one of the main promoter types—the fatty acids—and also because it is preferred to sulphur-based promoters for certain practical applications [16]. The chemical factors will be examined in Part II, where the fatty acid and sulphide promoters are compared.

EXPERIMENTAL DETAILS

The method of measuring heat transfer was similar to that used by earlier workers [2, 4, 6, 14, 15]. Four thermocouples accurately located in a thick water-cooled metal wall (see Fig. 1) served to determine the surface temperature during condensation (by extrapolation) and the heat flux (from the temperature gradient). The steamside coefficient was taken as heat flux/ΔT, where ΔT is the temperature difference between the steam and the surface.

Apparatus

The apparatus is shown diagrammatically in Fig. 1. The condensing surface was the face of a copper rod (area $3{\cdot}07 \times 10^{-3}$ ft^2) cooled at the other end by water circulated at constant velocity from a thermostatted water bath controlled to within $\pm 0{\cdot}05$ degC. The condensing face of the rod projected slightly ($\leqslant \frac{1}{64}$ in.)

through the wall of the stainless-steel steam chest. A PTFE collar round the bar reduced the heat flux from the stainless-steel wall to $\leqslant 800$ Btu/ft^{2}h (i.e. <10 per cent of the lowest flux from condensation). The heat flux from condensation was varied by altering the temperature of the cooling water.

Four thermocouples (Thermocoax mineral-insulated stainless steel-sheathed chromel–alumel) of nominal diameter $\frac{1}{2}$ mm were inserted in pockets spaced along the rod. The positions of the pockets were known to within $\pm\frac{1}{1000}$ in. The couples were calibrated in the thermostatted water bath against an N.P.L.-standardized thermometer which could be read to ±0·05 degC. The output from the couples against an ice–water cold junction was recorded with an accuracy of ±5 μV on a six-channel potentiometric recorder with variable stepped zero covering the range 0–5 mV in steps of 1 mV for full scale deflexion. During measurements the range was altered manually to bring each signal on scale. Steam temperature was also recorded. The printing interval was 3 s. Initial calibrations of the couples agreed to within 0·2 degC and repeat calibrations showed no change in output over a period of several months.

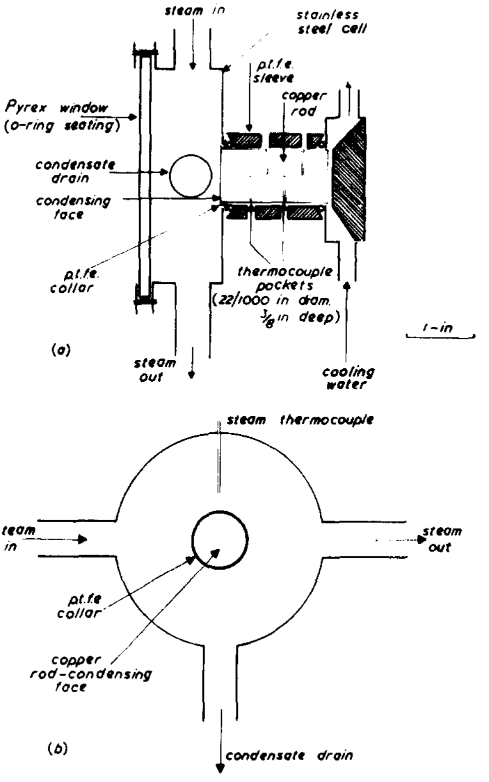
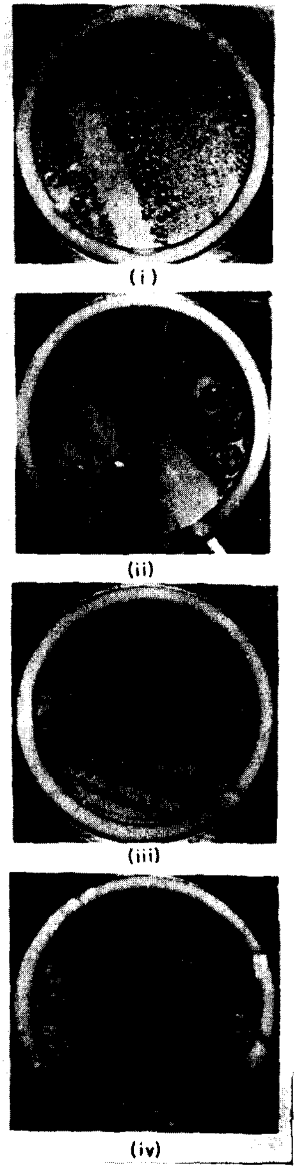


FIG. 1. Diagram of heat-transfer apparatus: (a) section, from above; (b) front view.

Steam was supplied to the condenser at a pressure of 4-in w.g. above atmospheric from a Pyrex flask with chromium-plated immersion heating elements (2 × 3 kW). The water, which was of analytical reagent grade, was deaerated by boiling, with venting, for at least an hour before beginning an experiment. The steam temperature agreed with the saturation value corresponding to the measured pressure to within 0·1 degC. The steam was free from organic contaminants and no difficulty was experienced in maintaining filmwise condensation when required. Even at the highest heat flux, less than 15 per cent of the inlet steam was condensed, the remainder passing out of the cell to waste via a secondary condenser. Some steam was also vented from the condensate drain. At the flow rate selected for most of the work (1·9 ft^3/min), the steam velocity in the inlet arm was calculated to be 23 ft/s. The flow of steam slightly deflected the falling condensate drops (see Fig. 2, i and ii).

The non-condensable gas content of the inlet steam was found to be 2 ppm both by the method of Furman and Hampson [17] and by the gas chromatographic method of Still [18]. The latter method showed the gas to be nitrogen plus oxygen in the approximate ratio 2:1. When required, higher concentrations of gas were fed into the inlet steam via a calibrated Rotameter.

The temperatures indicated by the thermocouples fell closely about a straight line when plotted against position. The mean surface temperature was obtained by extrapolation with an estimated accuracy of ±0·1 degC. The steam temperature was measured with a similar accuracy so that the values of ΔT had an estimated overall accuracy of ±0·2 degC. This is considered to be the maximum error. In most



(i)

(ii)

(iii)

(iv)

FIG. 2. Effect of steam flow on the appearance of dropwise condensation:

(i) Flux 3200 Btu/ft^{2}h, $\Delta T = 0{\cdot}3(8)°F$ } Steam flow 1·9 ft^3/min
(ii) Flux 173 000 Btu/ft^{2}h, $\Delta T = 3{\cdot}2(4)°F$ }

(iii) Flux 4200 Btu/ft^{2}h, $\Delta T = 0{\cdot}3(8)°F$ } Steam flow 6·5 ft^3/min
(iv) Flux 173 000 Btu/ft^{2}h, $\Delta T = 2{\cdot}9(3)°F$ }

experiments the steam temperature was constant and the relative accuracy is probably better than ±0·1 degC. The thermal conductivity of the copper was taken as 220 Btu/ft h degF and the accuracy of the heat flux thus derived was estimated as $\leqslant \pm 0{\cdot}5$ per cent. The copper was oxygen-free high conductivity material obtained from a commercial supplier, and meeting British Standards specification No. 1861. The value of the thermal conductivity was taken as that for pure copper as given in the *American Rubber Co. Handbook*, 1959–60, 41st edition. A heat balance obtained by collecting condensate gave values of the heat flux agreeing with those obtained by the first method to within 5 per cent.

Procedure

The front face of the copper rod was initially polished with metallurgical emery paper and with successive grades of diamond paste down to $\frac{1}{10}$ μ (in succeeding experiments polishing began at the 3 μ stage). It was degreased by making it cathodic in 2·5 per cent w/v methanolic sodium hydroxide at a current density of 0·7 A/cm^2 for 2 min. After rinsing with distilled water followed by ethyl alcohol, the surface was dried in a stream of nitrogen, washed with purified benzene and promoted by adsorption from a solution of the wax in benzene (2g/l) for 30 min at 30°C. The surface was then rinsed quickly in clean benzene and the copper rod inserted in the cell. During an experiment the heat flux was usually varied from high to low values, the temperature of the cooling water being raised in stages from 15 to 98°C. Closely similar results were obtained on going from low to high heat fluxes.

Materials

Steam-bleached montan wax was obtained from W. J. Towers & Co. Analysis of the wax which was published earlier [19] showed it to consist of a 50:50 mixture of long chain fatty acids and paraffin hydrocarbons. The components active in promotion are montanic acid, $C_{27}H_{55}COOH$, and its neighbouring homologues [20]. Cylinder carbon dioxide and nitrogen ("white spot", $\leqslant$5 ppm O_2) were used without further purification.

RESULTS

Heat flux

Results are shown in Fig. 3 for the variation of ΔT with heat flux for filmwise (i) and dropwise condensation (ii) at constant steam velocity. The calculated Nusselt curve (iii) for filmwise condensation on a rectangular surface $\frac{3}{4}$ in. high is also shown. The results for dropwise condensation differ from the filmwise values (a) in the much higher value of the coefficient and (b) in that the coefficient *increases* with increasing heat flux. This latter feature (seen in Fig. 3 as the different directions of curvature of curve i and ii) was observed in all the systems examined, viz. copper promoted by montan wax, montanic acid and dioctadecyl disulphide, and stainless steel promoted by montanic acid (see Fig. 7 and Part II). It should be noted that, although the steamside coefficients change with heat flux in such a way that the values for filmwise and dropwise condensation approach one another as the heat flux decreases, nevertheless, at the lowest heat fluxes examined, corresponding to those encountered in condenser practice (around 10 000 Btu/ft^{2}h), the value of ΔT for dropwise condensation was still lower than that for filmwise by a factor of 2 to 3 times and the coefficients correspondingly greater.

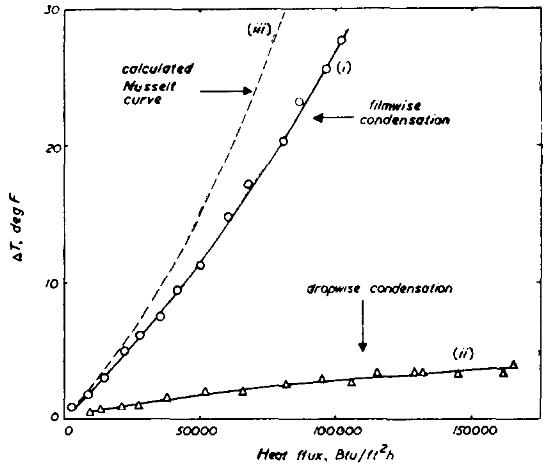


FIG. 3. Variation of ΔT with heat flux at constant steam velocity.

Steam pressure and velocity

The values of ΔT and the derived coefficient showed no clear dependence on steam pressure at constant heat flux and constant steam velocity, varying by less than ±10 per cent over the range 2 to 20 in w.g. above atmospheric pressure. A value of 4 in w.g. was selected for the rest of the work.

Steam velocity had a marked effect on ΔT at high heat fluxes but very little effect at low fluxes. At fluxes in excess of 50 000 Btu/ft^{2}h, the value of ΔT (at constant flux) was found to decrease with increasing steam flow, as shown in Fig. 4. In this experiment, the steam velocity in the inlet pipe ranged from 9 to 78 ft/s; the exact value in the cell was not known. Extrapolation to a steam flow equal to the rate of condensation gave a coefficient of 46 000 Btu/ft^{2}h degF while at the highest velocity the value rose to 70 000 Btu/ft^{2}h degF. At low steam flow rates the pressure in the cell became unsteady and a rate of 1·9 ft^3/min was chosen as a standard condition.

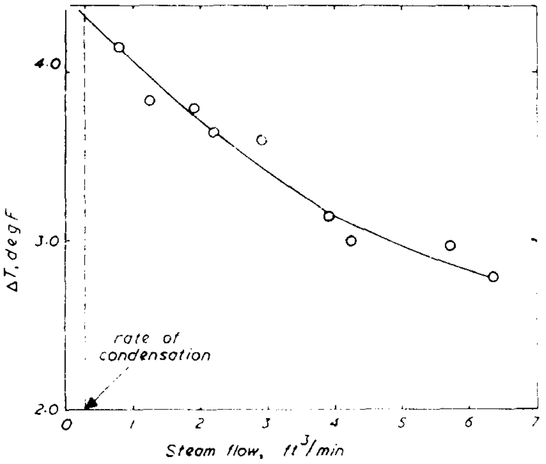


FIG. 4. Variation of ΔT with steam flow during dropwise condensation at constant heat flux (198 000 Btu/ft^{2}h).

The influence of steam flow on the ΔT-heat flux curve is shown in Fig. 5. The effect diminished with decreasing heat flux becoming negligible below about 50 000 Btu/ft^{2}h. Increased steam velocity produced a radical change in the appearance of the condensing surface both at high and at low heat fluxes (compare photographs i and iii, and ii and iv in Fig. 2). At all heat fluxes the effect of increasing velocity was to decrease the amount of condensate on the surface and the average drop size. In view of this the small effect of velocity on coefficient at low heat fluxes was somewhat unexpected.

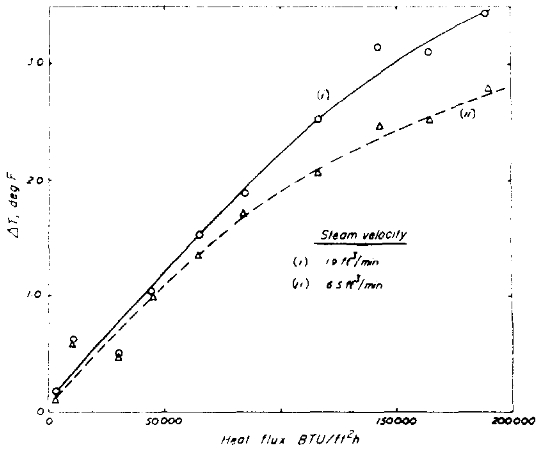


FIG. 5. Variation of ΔT with heat flux at two steam flow rates during dropwise condensation.

The observations described in the next section on the mass transfer introduced by the presence of non-condensable gas, which increases as the heat flux is *increased* or the steam velocity *decreased*, show that the presence of gas could have accounted for the greater influence of steam velocity at high than at low heat fluxes seen in Fig. 5. On the other hand, in the presence of gas, the steamside coefficient would have been expected to fall with rising heat flux. The curvature of the lines in Fig. 5 indicates the contrary. Further arguments for the absence of a diffusional resistance under these conditions are given below.

Venting arrangements and the addition of N_2 *and* CO_2

The value of the steamside coefficient for dropwise condensation is known to be sensitive to the presence of non-condensable gas and several workers e.g. [3, 4, 15] have commented on the need for adequate venting of the condensing surface. Despite the fact that no special precautions for venting were taken in the present work, the results obtained at the standard steam flow rate are believed to be free from extraneous effects of non-condensable gas for these reasons. (i) The values of the coefficients are high and compare favourably with published values obtained with venting (cf. Fig. 7 and below). (ii) For fixed waterside conditions and gas-free steam the signal from the thermocouple nearest to the condensing surface was steady to within 5 μV. As reported by other workers, it was found to fluctuate when gas was present in the steam. (iii) The gas content of the inlet steam was low—2 ppm—and less than 15 per cent of the steam was condensed. (iv) No rise in surface temperature was observed when steam was vented from a probe placed at a distance ⩾3 mm from the surface. It was found that the probe nullified the effect of added nitrogen up to 10 ppm. The vent test was done at a high heat flux (170 000 Btu/ft²h) at which a diffusional resistance would be most pronounced.

The addition of nitrogen or carbon dioxide was found to increase the value of ΔT, i.e. decrease the coefficient, as illustrated in Fig. 6.

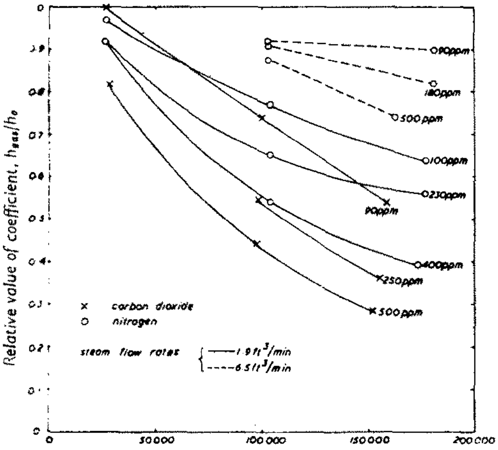


FIG. 6. Reduction in steamside coefficient by non-condensable gas—for dropwise condensation.

From these results it may be seen that the lowering of the coefficient was greater (i) as the heat flux and non-condensable gas content increased; (ii) as the steam velocity decreased; (iii) with carbon dioxide than with nitrogen, at comparable concentrations. Neither gas caused any permanent change in the heat-transfer coefficient under the present conditions although carbon dioxide was found to bring about permanent changes on oxidized copper surfaces (as discussed in Part II).

DISCUSSION

Present results for the steamside heat-transfer coefficient during dropwise condensation are compared with published data in Fig. 7. The only promoter common to this and earlier work was dioctadecyl disulphide. The data for this promoter are in reasonable agreement with those of Le Fevre and Rose where they overlap (cf curves ii and 15, Fig. 7). Attention is drawn to three features of the present results—the high values obtained for the coefficient, the decrease in coefficient with decreasing heat flux, and the effects of steam velocity.

The high values obtained in the present work are believed to be a consequence of minimizing the effects of non-condensable gas. As discussed by Silver [21] the magnitude of the diffusional resistance resulting from the presence of gas depends on (i) the concentration of gas in the inlet steam, (ii) the fraction of steam condensed, and (iii) the flow pattern near the surface (i.e. geometry and venting). In the present work, an appropriate combination of these factors is believed to have given values of the coefficient entirely free from a diffusional resistance. It may be noted that among the published data, higher values of the coefficient were reported when particular care was taken to eliminate the effects of non-condensable gas by deaeration and venting [3, 4, 10, 15]. It seems possible that, in those cases where relatively low values of the coefficient were obtained, some diffusional resistance was present arising from non-condensable gas.

The highest reported coefficients are those of Shea and Krase [Fig. 7, curve 8], obtained at steam velocities of 10–40 ft/s. Comparably high values were obtained in the present work at high steam velocity (Fig. 7, curve v). As discussed below, steam flow past a condensing surface was found to increase heat transfer both by removing non-condensable gas and by affecting the flow of condensate. In the work of Shea and Krase both effects were probably present since the coefficients obtained at lower velocities (1–3 ft/s)

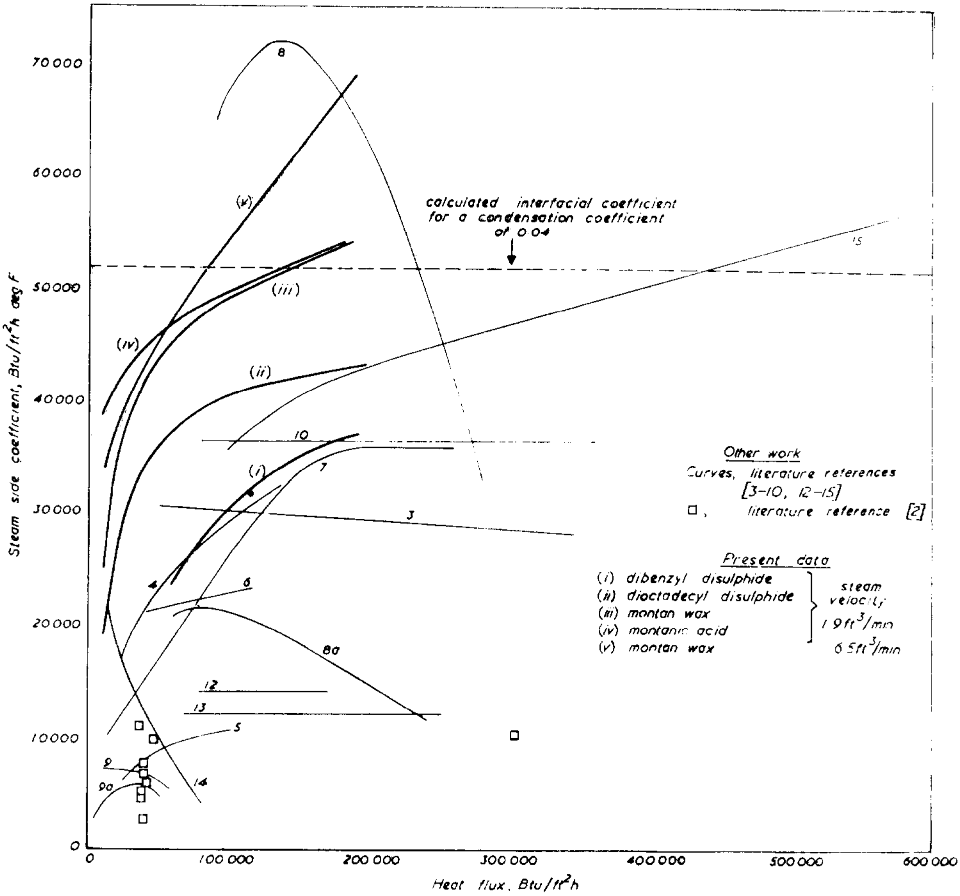


FIG. 7. Summary of present data and published results for steamside coefficient as a function of heat flux during dropwise condensation.

were considerably reduced (Fig. 7, curve 8a). In the present work a value of 46 000 Btu/ft²h degF was obtained for zero net steam flow at a flux of 198 000 Btu/ft²h, i.e. sufficiently high to indicate the absence of a diffusional resistance.

The decrease in coefficient with decreasing heat flux is in marked contrast with filmwise condensation. A similar decline has been reported by other workers [4, 6, 7, 15] and, on the basis of this and present results, it is believed to be an intrinsic feature of the mechanism of dropwise condensation. It cannot be an artifact resulting from the presence of non-condensable gas since such effects are absent from the present results, as argued above. Even if non-condensable gas were present the coefficient should *increase* rather than decrease with decreasing heat flux, as may be seen from the results given in Fig. 6.

Steam flow past the condensing surface was found to have a dual effect on heat transfer. In the presence of non-condensable gas an increase in steam velocity increased the coefficient, presumably by reducing the diffusional resistance at the interface (cf Fig. 6). In the virtual absence of non-condensable gas the coefficient was again found to increase with steam flow (cf Figs. 3 and 4). This change may have been related to the alterations in drop size distribution and condensate flow though it is not clear why the coefficients at low fluxes were relatively less affected.

The value of the steamside coefficient can be used to obtain information about the condensation coefficient of water. As pointed out by Silver and others [22, 7], the maximum rate of condensation, determined by the number of molecules striking and adhering to the surface minus the number evaporating, is proportional to the condensation coefficient. For a value of 0·04 and for steam at atmospheric pressure, a value of 51 700 Btu/ft^{2}h degF may be calculated for the so-called interfacial coefficient from simple kinetic theory. As may be seen from Fig. 7, this value is exceeded both by present values and by those of Shea and Krase, and Le Fevre and Rose. When it is further considered that only about half of the surface is effective in heat transfer during dropwise condensation [2, 3, 14, 23], it may be seen that under these conditions the highest values of the heat-transfer coefficient indicate that the value of the condensation coefficient must exceed 0·04 and is probably $\geqslant$0·08.

CONCLUSIONS

From a study of the variation of surface temperature during the dropwise condensation of steam at atmospheric pressure on copper surfaces promoted by montan wax it is concluded that:

(i) the equivalent steamside heat-transfer coefficient rises from about 35 000 to 55 000 Btu/ft^{2}h degF as the heat flux increases from 20 000 to 200 000 Btu/ft^{2}h.

(ii) the reduction in coefficient by added non-condensable gas is greater (a) with CO_2 than with N_2, (b) with decreasing steam velocity, (c) with increasing heat flux.

(iii) an increase in steam velocity past the condensing surface increases the heat-transfer coefficient both by removing non-condensable gas and by altering the flow of condensate.

(iv) the maximum values found for the heat-transfer coefficient indicate that during dropwise condensation the value of the condensation coefficient of water is probably $\geqslant$0·08.

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Résumé—Des mesures de température de surface pendant la condensation par gouttes de la vapeur d'eau à la pression atmosphérique sur des surfaces de cuivre par la cire de montan sont données dans la gamme de flux de chaleur de 3,17 à 63,4 W/cm^2. La vitesse d'écoulement de la vapeur d'eau variait entre environ 3 et 24 m/s et la concentration en gaz non condensable de 2 à 500 ppm. On a trouvé que le coefficient de transport de chaleur du côté de la vapeur augmentait lorsque le flux de chaleur et la vitesse de la vapeur croissaient. L'addition de gaz non condensable abaissait le coefficient, le gaz carbonique ayant un effet plus important que l'azote. Les valeurs maximales du coefficient dépassait 29 $W/cm^2.°C$ ce qui indiquerait que le coefficient de condensation pour l'eau dépasse 0,04.

Zusammenfassung—Für Wärmestromdichten von 3,2 W/cm^2 bis 63 W/cm^2 werden Messungen von Oberflächentemperaturen bei Atmosphärendruck an Kupferflächen während der Tropfenkondensation von Dampf, die durch aufgebrachtes "Montan"-Wachs gefördert wird, angegeben. Die Dampfgeschwindigkeit wurde zwischen 3 und 24,4 m/s, und die Konzentration des nicht kondensierbaren Gases von 2 bis 500 ppm variiert. Es ergab sich, dass die Wärmeübergangszahl auf der Dampfseite mit zunehmender Wärmestromdichte und Dampfgeschwindigkeit grösser wurde. Die Beigabe eines nicht kondensierbaren Gases erniedrigte die Übergangszahl, wobei Kohlendioxyd stärkeren Einfluss hatte als Stickstoff. Maximalwerte der Wärmeübergangszahl überschritten 28,4 $W/cm^2 grd$, was wiederum anzeigen würde, dass der Kondensationskoeffizient für Wasser 0,04 übersteigt.

Аннотация—Приводятся результаты измерений температуры поверхности при капельной конденсации пара и атмосферном давлении на медных поверхностях, активированых монтан-воском, в диапазоне тепловых потоков 31,5–630 квт/$м^2$. Скорость пара изменялась от 3,05 м/сек до 24,4 м/сек, а концентрация неконденсирующегося газа составляла от 0,2 до 50%. Найдено, что коэффициент теплообмена со стороны пара увеличивается с увеличением теплового потока и скорости пара. Добавление неконденсирующегося пара снижало коэффициент, причем добавление двуокиси углерода, оказывало большее влияние, чем добавление азота. Максимальные значения коэффициента превышали 283,525 квт/$м^2$ град, что говорит о том, что коэффициент конденсации для воды превышает 0,04.