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DROPWISE CONDENSATION—THE EFFECT OF THERMAL PROPERTIES OF THE CONDENSER MATERIAL

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Abstract—There exists conflicting evidence for the effect of the thermal properties of the condensing surface on heat-transfer during dropwise condensation of steam. In order to help to settle this issue, further precise measurements have been made using vertical copper and mild steel condensing plates, both of which were copper-plated to ensure identical surface conditions. The thickness of the copper plating was 0·012 mm for both plates. Dioctadecyl disulphide was used as promoter. Several tests were carried out at near-atmospheric pressure on different days using each plate in turn. Consistent results were obtained. The results for the two plates did not differ significantly and were in good agreement with earlier measurements for dioctadecyl disulphide-promoted vertical copper surfaces.

NOMENCLATURE

$\dot{Q}''$, heat flux;
ΔT, vapour-to-surface temperature difference.

1. INTRODUCTION

MANY of the uncertainties arising from the diversity of heat-transfer measurements during dropwise condensation have now been settled. Following very wide disagreement between the results of earlier workers and considerable scatter in most individual investigations, measurements from a growing number of more recent investigations into dropwise condensation of steam exhibit relatively small scatter and are in good agreement with each other. Figure 1 shows results for copper surfaces with various promoters. The shaded region contains the results of 7 more recent studies.

The main factors influencing the validity of dropwise condensation heat-transfer measurements are errors due to the presence in the vapour of non-condensing gases and precision of measurement of the condensing surface temperature. In the more recent investigations, the non-condensing gas problem has been overcome by first minimising the gas concentration and secondly, using local venting or cross flow to prevent significant accumulation of gas at the condensing surface. Precise measurement of the surface temperature has been achieved by extrapolation from temperatures observed at different depths in the condensing plate.

There now exists a considerable body of consistent measurements of the relationship between heat flux and vapour-to-surface temperature difference for steam condensing on vertical copper surfaces at pressures ranging from atmospheric down to about 3 kPa (0·03 bar) [11–19]. It is now known that promoter [12, 14, 15] surface finish [14, 17], vapour velocity (in the absence of non-condensing gas) [13, 17] and surface inclination (except for large departures from the vertical) [23, 24] have relatively small effect.

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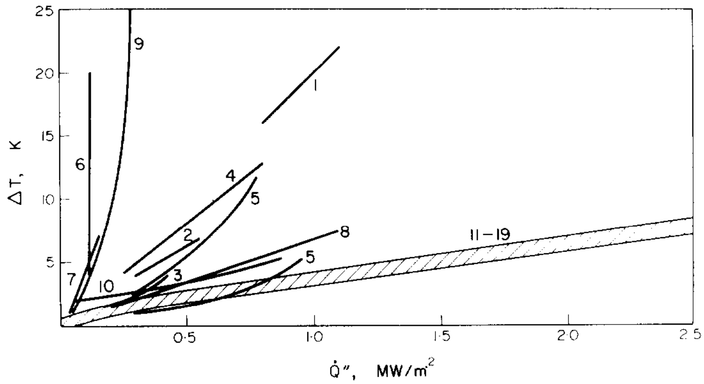

FIG. 1. Heat-transfer measurements for dropwise condensation of steam at near-atmospheric pressure.

One aspect of the problem which remains to be settled is that of the effect of the thermal properties of condensing surface material. Copper has been used in most investigations on account of its high thermal conductivity and the fact that it is more readily promoted than most other materials. Two investigations [14, 20] have been carried out into the effects of condenser material on the vapour-to-surface heat-transfer coefficient and significant differences reported.

Tanner *et al.* [14] made measurements on vertical copper and stainless steel surfaces using montanic acid as promoter. The surface temperature and heat flux were found from observed temperature distributions in the plates. The maximum heat flux obtained in the case of the stainless steel was about 30 kW/m^2. They report that the steam-side coefficient for the stainless steel plate was lower than that for the copper plate by a factor of about 5 at the highest heat flux, and by an even greater amount at lower heat fluxes.

Griffith and Lee [20] used horizontal downward-facing flat plates of copper and composite zinc–copper (soft-soldered) and stainless steel–copper (silver soldered) plates, the zinc and steel being on the condensing side. To provide identical and readily promotable surfaces all three condensing surfaces were gold plated (thickness 0·13 mm). Oleic acid was used as promoter. Thermocouples located at different positions in the plates, were used to determine the heat flux and surface temperature. The steam-side heat-transfer coefficients were found to be independent of heat flux and to have values of about 56 kW/m^2 K, 26 kW/m^2 K and 11 kW/m^2 K for copper, zinc and stainless steel surfaces respectively. (The respective maximum heat fluxes obtained were about 0·45 MW/m^2, 0·4 MW/m^2 and 0·2 MW/m^2.) These results suggest a systematic dependence of the steam-side heat-transfer coefficient on the thermal conductivity of the plate material, whose approximate values were 380 W/m K, 110 W/m K and 17 W/m K for copper, zinc and stainless steel respectively.

By contrast to the above-mentioned works the results of Graham [17] and Wilmshurst and Rose [18], who used teflon-coated copper surfaces, suggest that the vapour-to-surface heat-transfer coefficient on a teflon surface (thermal conductivity 0·25 W/m K) is very close to that found when using "mono-layer" promoters on copper. The teflon layer thickness used in [17] and [18] were 0·0015 mm and 0·01 mm respectively. In both cases thermocouples located in the copper plates served to measure the heat flux and, by extrapolation, the temperature at the copper–teflon interface. When the temperature at the teflon surface was estimated assuming simple one-dimensional steady conduction in the teflon layer, the remaining temperature difference between the vapour and the teflon surface was found to be very close, in both cases, to that obtained with dioctadecyl disulphide-promoted copper surfaces. Since the ratio of the thermal conductivity of copper to that of teflon is about 1500, these results are in very sharp contrast to [14] and [20].

During dropwise condensation, the presence on the surface of a wide range of drop sizes inevitably leads to non-uniformities in heat flux in the condenser material near to the surface. Mikic [21] has recently put forward a model showing how such non-uniformities might lead to an additional heat-transfer resistance. This model indicates that the additional resistance is greater for lower conductivity condenser materials in a manner similar to that found in [14] and [20].

The present paper reports new measurements using copper and mild steel condensing surfaces. To ensure identical surface conditions *both* plates were copper plated. Care was taken to minimize errors associated with non-condensing gases and those resulting from inadequate precision of thermocouple location and insufficient isothermal immersion of thermocouple leads in the plates.

2. APPARATUS AND PROCEDURE

With the exception of the test plates, the apparatus was basically that described elsewhere [15]. The condensing surfaces of the copper and mild steel test plates were each 62 mm high and 70 mm wide. The thicknesses of the plates were 8·4 mm and 9·52 mm for the copper and steel plates respectively. In order to obtain adequate precision in the location of the thermocouples at different depths in the plates and to ensure sufficient isothermal immersion of the thermocouple leads (i.e. to provide very small holes of sufficient depth) the "split-plate" technique [15] was adopted. An improvement was made in the present work in that after machining the grooves (0·25 mm square, parallel to the condensing surface) in the mating face of one half of a plate, the two halves were rejoined by "diffusion welding*". The resulting plates thus had 0·25 mm square holes running parallel to the condensing surface down the central vertical plane from top to bottom edge, a

* The mating surfaces were ground smooth and flat. All traces of oxide were removed before the two halves were assembled in a clamp and placed in an induction vacuum furnace for about two hours at temperatures of 800°C and 1100°C for the copper and mild steel respectively. The authors are grateful to Mr. S. Necmi, Department of Mechanical Engineering, Queen Mary College, for demonstrating this technique.

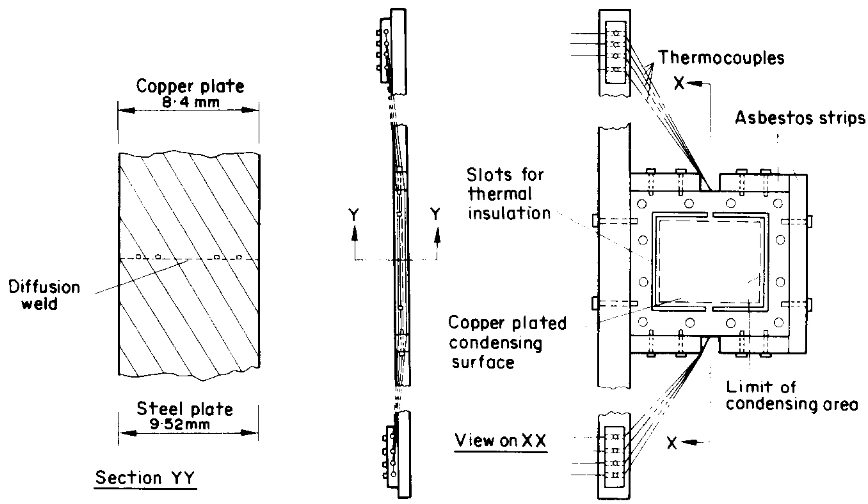

FIG. 2. Condensing plate.

distance of 9·5 cm. The condensing surfaces of both plates were copper plated to a thickness of 0·012 mm. Four butt-welded enamel-insulated copper–constantan thermocouples (0·15 mm dia.) were inserted in the grooves so that the junctions were situated at the mid-height of the plate. Details of the plates are illustrated in Fig. 2.

The procedures used for the thermoelectric measurements and thermocouple calibration were the same as those described elsewhere [15] giving a precision of temperature measurement better than 0·05 K. Non-condensing gases were reduced to a minimum by preliminary boiling while purging the boiler and steam chamber to atmosphere. The effects of remaining traces of gases were obviated by using the "close venting" technique [15, 16]. The surfaces were cleaned and promoted with dioctadecyl disulphide as described earlier [15].

3. RESULTS

Thermal conductivity of the test plates

Several tests were conducted using each plate while measuring the temperature increase and mass flow rate of the coolant as well as the temperatures in the test plate. By equating the heat flux, as found from the coolant measurements to that given by the temperature gradient in the plate (found by linear regression of the temperatures on the distances) the conductivities of the plates were found to be 380 W/m K and 46 W/m K for the copper and mild steel respectively. (In earlier work [15] using the same cooling box and a plate of known thermal conductivity, heat fluxes as determined separately from coolant and plate measurements agreed to within 2 per cent.)

Initial transient behaviour of the steam-to-surface temperature difference

Earlier work [16, 17] has indicated that for newly promoted (with dioctadecyl disulphide) copper surfaces, some time elapses, under steady coolant and steam conditions, before the vapour-to-surface temperature difference settles down to a steady value. Several runs were made while the coolant flow rate and steam pressure were held constant. Measurements were made after about 30 minutes from the onset of boiling, during which time air was expelled from the apparatus. No significant variation with time was found over intervals of up to six hours.

The above finding is in contrast to that of Citakoglu and Rose [16] who observed that the steam-side heat-transfer coefficient for a newly promoted surface increased steadily with time during the first two or three hours of operation before reaching a steady value. Graham [17] reports a similar increase in coefficient followed by a sharp decrease before attaining a steady value.

The differences in initial transient behaviour are difficult to explain and might perhaps be attributable to degassing of apparatus or differences of promoter-surface characteristics in the different investigations. The initial increase in steam-side coefficient found earlier [16, 17] was attributed to removal of excess promoter. It is noteworthy that the final steady values in the earlier investigations are in good agreement with the present observations.

Dependence of steam-to-surface temperature difference on heat flux

Using each plate in turn, measurements were made of the plate and steam temperatures for a range of coolant flow rates. The steam pressure in all cases was about 150 mmH_2O above that of the atmosphere. The results of these tests are shown in Fig. 3, together with earlier measurements with dioctadecyl-disulphide promoted vertical copper plates.

While the maximum heat flux obtained with the steel plate was much less than that when using the copper plate, it is clear from the range of overlap, that there are no significant differences in the results for the two plates. The fact that in some cases the values of ΔT for the steel plate are *smaller* than those for the copper plate is not thought to be significant. This is most probably due to systematic error in the surface temperatures resulting from the fact

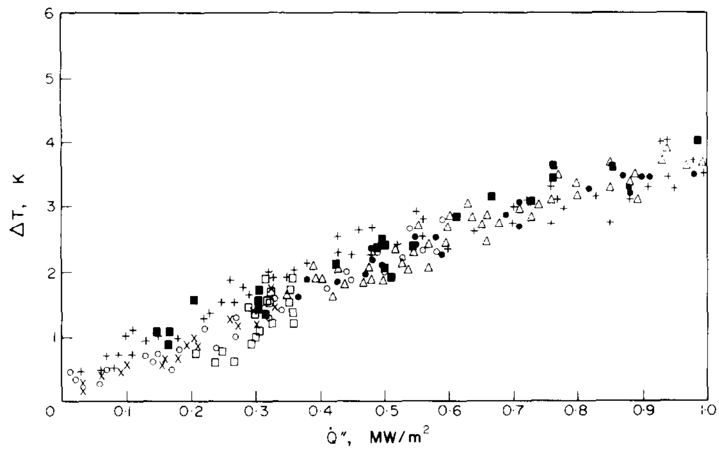

FIG. 3. Heat-transfer measurements for dropwise condensation of steam at near-atmospheric pressure on dioctadecyl disulphide-promoted copper surfaces.
● [12, 15], O [13], + [16], × [17]
△ [18]
□ present, mild steel plate
■ present, copper plate

that the temperatures recorded by the plate thermocouples are not precisely those at the centre lines of the holes. Wilcox and Rohsenow [22] have earlier drawn attention to the fact that unless the thermocouples are withdrawn from their holes and replaced after each test, the resulting error in surface temperature is systematic and increases with decreasing plate thermal conductivity. The analysis of Wilcox and Rohsenow [22] may be used to estimate the standard deviation of the surface temperature for the plates used in the present work. This gives values for the copper plate varying from about 0·03 K, at a heat flux of 0·15 MW/m^2, to about 0·2 K, at a heat flux of 1 MW/m^2. For the steel plate the estimated standard deviation varied from about 0·3 K, at a heat flux of 0·2 MW/m^2, to about 0·6 K at a heat flux of 0·37 MW/m^2. The standard deviations of the calculated surface temperatures in the present work (using the observed plate temperatures at the centre lines of the holes) were found on average to be about 0·1 K for the copper plate and about 0·3 K for the steel plate.

4. DISCUSSION

The present results apparently disagree with [14] and [20]. In the case of Tanner and co-workers [14], whose results for the copper surface agree well with the present and earlier work, there are two possible explanations for the apparent difference in heat-transfer results for copper and stainless steel surfaces. In the first instance it should be noted that the maximum reported difference in ΔT for the two cases was only about 0·5 K which might easily be attributed to systematic error in the surface temperature, in the case of the low-conductivity plate, as discussed above. Moreover, since the surfaces were not plated with the same metal, differences in ΔT could result from a difference in promoter effectiveness in the two cases. The apparent dependence of the heat-transfer coefficient on thermal conductivity of plate found by Griffith and Lee [20] might be attributable in part to systematic errors arising from location of the thermocouples as well as to errors associated with possible temperature discontinuities at the soldered interfaces between the different metals.

It is also to be noted that, for the copper surface, the steam-side heat-transfer coefficient was much lower than values reported recently [23] for a horizontal downward-facing copper surface.

5. CONCLUDING REMARKS

The present results for both copper and mild steel plates are in good agreement with earlier work using dioctadecyl disulphide-promoted vertical copper plates and indicate, at least for heat fluxes in the range 0·2–0·37 MW/m^2, that there is no significant effect of the thermal properties of the condensing surface materials. The earlier suggestion [18] that the rapid coalescences between drops might lead to an essentially uniform surface temperature, and thus to the absence of a surface conductivity effect, would indicate that this effect might possibly be significant at very low condensation rates. The fact that the vapour-to-surface temperature differences at such low condensation rates would, for all materials, be very small, renders measurements very difficult and the results largely of academic interest. In this context it is perhaps worth noting that the heat fluxes obtained by Tanner *et al.* [14] for the stainless steel surface were lower than those used in the present work (for the range and overlap of the results for the two plates) by a factor of about 10. It is thus not entirely impossible that, in the case of Tanner *et al.*, the effect of thermal conductivity of the surface played some part.

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CONDENSATION EN GOUTTES—L'EFFET DES PROPRIETES THERMIQUES DU MATERIAU CONDENSEUR

Résumé—Il existe des contradictions sur l'effet des propriétés thermiques de la surface de condensation sur le transfert thermique pendant la condensation en gouttes de la vapeur. Afin d'aider cette étude, des mesures précises ont été faites à l'aide de plaques verticales en cuivre et en acier doux, deux d'entre elles étant cuivrées pour réaliser des conditions superficielles identiques. L'épaisseur du recouvrement de cuivre est de 0, 012 mm pour les deux plaques. On a utilisé comme promoteur le disulfure de dioctadécane. On a mené sur plusieurs jours des essais à une pression proche de l'atmosphère en utilisant une plaque après l'autre. On a obtenu des résultats valables. Les résultats pour les deux plaques ne diffèrent pas de facon significative et sont en bon accord avec des mesures antérieures pour des surfaces verticales en cuivre et le disulfure de dioctadécane.

TROPFENKONDENSATION—DER EINFLUSS DER THERMISCHEN STOFFWERTE DES KONDENSATORMATERIALS

Zusammenfassung—Über den Einfluss der thermischen Stoffwerte der Kondensatoroberfläche beim Wärmeübergang durch Tropfenkondensation bestehen widersprüchliche Aussagen. Um diese Widersprüche beizulegen, wurden weitere genaue Messungen angestellt, und zwar mit senkrechten Kondensatorplatten aus Kupfer und unlegiertem Stahl. Beide Platten waren verkupfert, um gleiche Oberflächenbedingungen zu haben. Die Dicke der aufgetragenen Kupferschicht betrug 0·012 mm bei beiden Platten. Als Promoter wurde Dioktadecyl–Disulfid verwendet. Mehrere Versuche wurden bei etwa Atmosphärendruck durchgeführt, und zwar an verschiedenen Tagen, wobei die Platten abwechselnd benutzt wurden. Die erzielten Ergebnisse waren konsistent. Die Ergebnisse für beide Platten wichen nicht wesentlich voneinander ab und stimmten gut mit früheren Messungen an senkrechten Kupferoberflächen, die mit Dioktadecyl-Disulfid aktiviert waren, überein.

КАПЕЛЬНАЯ КОНДЕНСАЦИЯ. ВЛИЯНИЕ ТЕПЛОВЫХ СВОЙСТВ МАТЕРИАЛА КОНДЕНСАТОРА

Аннотация—Существуют противоречивые данные по влиянию тепловых свойств конденсирующей поверхности на теплоперенос при капельной конденсации пара. Для выяснения этого вопроса проводились точные измерения с помощью вертикальных конденсирующих пластин из меди и малоуглеродистой стали. Обе пластины были омеднены для обеспечения одинаковых условий на поверхности. Толщина медного покрытия каждой пластины составляла 0,012 мм. В качестве активатора использовался двусернистый диоктадецил. Несколько экспериментов проводилось при около атмосферном давлении с использованием каждый день разных пластин поочередно. Результаты для двух пластин значительно не отличаются и хорошо согласуются с данными измерений для вертикальных медных поверхностей с двусернистым диоктадецилом, взятым в качестве активатора.