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HEAT-TRANSFER MEASUREMENTS DURING DROPWISE CONDENSATION OF MERCURY

S. NECMI and J. W. ROSE
Department of Mechanical Engineering, Queen Mary College, University of London, London E1 4NS, England

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Abstract—Measurements of vapour-to-condensing surface temperature difference and heat flux, for various vapour pressures, during dropwise condensation of mercury on a plane vertical surface are reported. The test condenser was a copper block of thickness 45 mm. A stainless steel plate was bonded (using a technique which gave low thermal interface resistance) to the vapour-side of the block and machined to a thickness of 0.25 mm. Thermocouples accurately located and spaced through the copper block served to measure, by extrapolation, the copper–steel interface temperature at the mid-height of the plate. The heat flux and hence the temperature of the stainless steel condensing surface were found from the temperature gradient in the block. Errors due to the presence of non-condensing gases were eliminated by vapour cross flow, vertically downwards over the condensing surface. The strong effect of non-condensing gases, resulting from 'outgassing' of the walls of the apparatus at the higher temperatures, in the absence of cross flow, was demonstrated. The vapour-side heat-transfer coefficient was found to increase with increasing vapour pressure but was essentially independent of heat flux at a given vapour pressure. The results are in fair agreement with those of the most recent earlier investigation.

NOMENCLATURE

A, cross-sectional area of test condenser chamber;
c_P, isobaric specific heat-capacity of coolant (secondary condenser);
h_{fg}, specific enthalpy of vapour–liquid phase change;
$\dot{m}$, coolant mass flow rate (secondary condenser);
Q, heat flux (test condenser);
T_v, vapour temperature;
v_g, specific volume of 'saturated' vapour;
α, vapour-to-surface (stainless steel) heat-transfer coefficient;
ΔT, vapour-to-surface (stainless steel) temperature difference;
ΔT_c, temperature increase of coolant (secondary condenser).

INTRODUCTION

FEW HEAT-TRANSFER measurements have so far been made for dropwise condensation of mercury. There are wide discrepancies between such data as exist. The present work was undertaken in order to resolve these differences and to provide reliable results for comparison with theories of dropwise condensation, which to date are based almost entirely on measurements for steam.

APPARATUS

The stainless steel test loop, comprising boiler, test condenser and secondary condenser, was basically as used in earlier film condensation measurements [1]. The vapour flowed downwards over the vertical plane stainless steel surface of the test condenser. Cross flow was generated by the secondary condenser situated below the test condenser. A vent tube, which passed via a liquid nitrogen 'cold trap' to a vacuum pump, was located near the base of the secondary condenser. The condensate from both test condenser and secondary condenser was returned by gravity to the boiler.

The copper test condenser block (thickness 45 mm, condensing surface 40 mm square) was constructed as described earlier [1], so that five thermocouple holes (0.3 mm square) passed through the block from side to side, parallel to and at different distances from, the condensing surface, in the mid-height horizontal plane. Butt-welded thermocouples were placed in the holes so that the junctions were located in the central vertical plane of the block.

In order to obtain dropwise condensation, a stainless steel plate was bonded to the condensing side of the copper block and machined to a thickness of 0.25 mm. A joint of low thermal resistance was achieved by the technique of 'silver–copper eutectic diffusion bonding'. The surfaces were made accurately flat. The copper surface was silver plated and the stainless steel surface was copper plated, each to a thickness of 0.025 mm, before being clamped together in a vacuum furnace at temperature of 800°C for 30 min.

The heat flux was found from the temperature gradient in the block. The temperature at the copper–steel interface was found by extrapolation and the condensing surface temperature obtained by adding the calculated temperature difference across the steel plate.

So as to reduce the velocity-induced temperature non-uniformities in the vapour (see [1]), the secondary condenser was modified and the cross section of the test condenser chamber was increased.

Full details of the apparatus are given in [2].

OBSERVATIONS

Unfortunately the block was incorrectly assembled so that the thermocouples were remote from the condensing surface, leading to increased uncertainty in the extrapolated surface temperature. However, owing to the smallness of the holes and of the precision with which they were located, this was less serious than would otherwise have been the case. The possible systematic error resulting from uncertainty of thermocouple position (estimated along the lines given by Wilcox and Rohsenow [3]) is proportional to the heat flux, and for the present results ranged from 0.02 to 0.65 K.

After out-gassing the apparatus and admitting mercury under vacuum as described in [1], it was discovered that the pressure had risen significantly overnight owing to a fault in the seat of the valve between the test loop and the vacuum pump. It was considered however that the vapour cross flow over the test condenser and venting from the secondary condenser would be adequate to eliminate the effects of out-gassing during operation. Tests were also carried out without cross flow so as to assess the effects of out-gassing on the results under these conditions.

Observations were made at vapour temperatures of 105, 139, 179, 219 and 258°C, using several different coolant flow rates at each vapour temperature. When the coolant flow rate was changed, the power input to the boiler was adjusted so as to maintain the desired vapour temperature. Sets of measurements were taken both with and without operation of the secondary condenser. When using the secondary condenser, its coolant mass flow rate and temperature increase were observed and the downstream (of the test condenser) vapour velocity estimated by $\dot{m}c_p\Delta T_c v_g/h_{fg}A$ (i.e. assuming the vapour to be 'saturated'). The values ranged from about 4 m/s at the highest vapour temperature to about 60 m/s at the lowest vapour temperature.

The appearance of the test condenser surface was that of ideal dropwise condensation throughout all tests.

RESULTS

The results obtained with and without operation of the secondary condenser are shown in Fig. 1. It is apparent that, in general, the graphs of ΔT vs Q are adequately represented by straight lines through the origin, indicating that the heat-transfer coefficient is essentially constant for a given vapour temperature.

Figure 2 shows the dependence of the mean heat-transfer coefficient on vapour temperature. It may be seen that, at the lower temperatures, vapour cross flow had little effect on the heat-transfer coefficient despite the fact that, at these temperatures, cross-flow velocities were the highest (due to the high values of vapour specific volume). At the highest vapour temperature the value of α with vapour cross flow exceeds that for zero cross flow by a factor of around 10. These results illustrate clearly the strong effect of non-condensing gases arising from out-gassing of the walls of the apparatus. At the lowest vapour temperatures where out-gassing is small, relatively high vapour velocities had little effect on the heat-transfer coefficient while at the higher temperatures where out-gassing is greater, relatively low cross-flow velocities had a strong effect on the heat-transfer coefficient.

These results may be compared with earlier filmwise condensation measurements [1] where, when using a well out-gassed apparatus, vapour velocity was found to have little or no effect on the heat-transfer coefficient.

In Fig. 3 the present results (with vapour cross flow) are compared with those of Ivanovskii *et al.* [4], who also found that the heat-transfer coefficient was, for a given vapour temperature, essentially independent of heat-flux. [It may be noted that Ivanovskii *et al.* reported that the values of α fell with decreasing Q, for values of ΔT below about 2 K. Evidence of a fall in α at low values of ΔT is also seen in the present results for the three highest temperatures (see Fig. 1b).]

It may be seen form Fig. 3 that, at the lowest vapour temperatures, the present heat-transfer coefficients are smaller than those reported by Ivanovskii *et al.*, whereas the reverse is true at the higher vapour temperatures. Even though the present values of α, at the high vapour temperatures exceed those of Ivanovskii by a factor of about 3, this might easily be attributable to systematic experimental error [resulting from (i) uncertainties in the thermocouple positions, (ii) uncertainty in the value of the thermal conductivity of the stainless steel or (iii) possible significant resistance at the copper–steel interface] in one or other or both investigations, since the vapour-to-surface temperature differences at the high vapour temperatures were very small (1–3 K). The discrepancies at the low vapour temperatures (where the present values of ΔT lay in the approximate range 6–60 K) are more significant. The above notwithstanding, it is apparent that the present results are in broad agreement with those of Ivanovskii *et al.*

The earlier data of Misra and Bonilla [5] and of Gelman [6] do not, in general, agree with the present results. Misra and Bonilla report that for temperatures less than 260°C, their values of α ranged from about 80 to about 450 kW/m^2 K. They do not report any systematic trend with variation of T_v. This range of values is broadly in line with the present results. For vapour temperatures exceeding 260°C, the heat-transfer coefficients reported by Misra and Bonilla varied in the approximate range of 20–25 kW/m^2 K, i.e. much lower than those found in the present work and suggesting that α decreased with increasing T_v rather than increased as found in the present work and [4]. Such a fall in α at high values of vapour temperature suggests that the results were affected by non-condensing gases arising from out-gassing of the walls of the apparatus.

Gelman [6] obtained heat-transfer coefficients ranging from values similar to those of [4] down to values lower by factors of 30 to 40. The strong dependence on vapour velocity and apparently weak dependence on

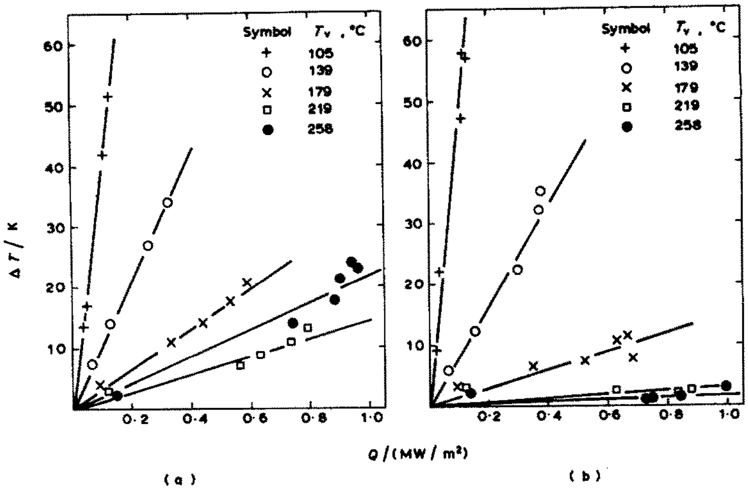

Fig. 1. Variation of vapour-to-surface temperature difference with heat flux; (a) without cross flow, (b) with cross flow.

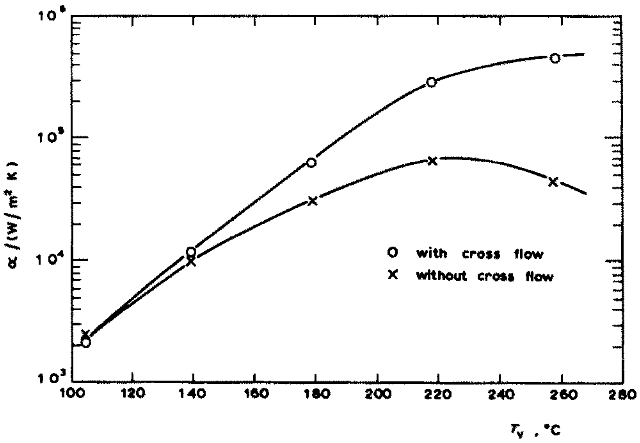

Fig. 2. Variation of mean heat-transfer coefficient with vapour temperature.

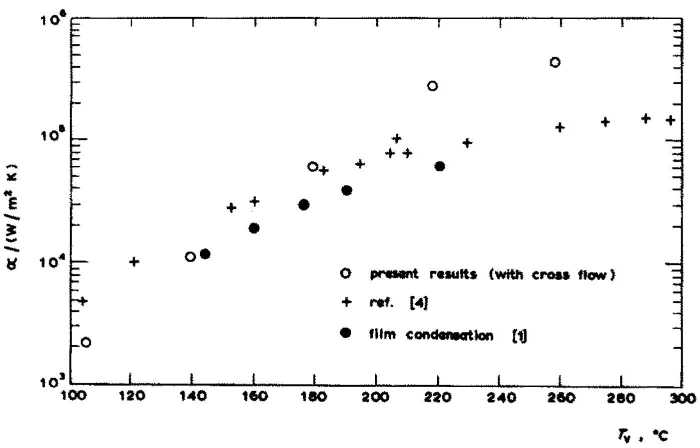

Fig. 3. Variation of mean heat-transfer coefficient with vapour temperature. Comparison of present results with those of [4] and with film condensation measurements [1].

non-condensing gas content, both suggest that significant amounts of non-condensing gas were present in the tests with supposedly pure vapour.

Film condensation measurements [1] are also shown in Fig. 3. It may be seen that at the lower vapour temperatures the dropwise and filmwise values of α are of similar magnitude. At the higher vapour temperatures the present dropwise values and those of Ivanovskii *et al.* [4] exceed the filmwise values by factors of about 5 and 2 respectively. The fact that the dropwise to filmwise heat-transfer coefficient ratio is much smaller for mercury than for water is due to the high thermal conductivity of the condensate which, in the case of mercury, gives high heat-transfer coefficients even for film condensation.

The fact that the heat-transfer coefficient increases with vapour temperature for dropwise and filmwise condensation is due to the significant role played by the vapour–liquid interface resistance in both cases.

CONCLUDING REMARKS

The results of Ivanovskii *et al.* [4], together with those of the present work, constitute the most reliable data at present available for dropwise condensation of mercury. It was shown earlier [7] that the measurements of Ivanovskii *et al.* were in fair agreement with theory. New and more accurate measurements, using a new test condenser block and a well-outgassed apparatus, are planned. Further detailed comparison with theory will be deferred until the new results are available.

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MESURE DE TRANSFERT THERMIQUE PENDANT LA CONDENSATION EN GOUTTES DU MERCURE

Résumé—On décrit les mesures de la différence de température entre vapeur et surface de condensation et de flux thermique, pour différentes pressions de vapeur, lors de la condensation en gouttes du mercure sur une surface plane et verticale. Le condenseur est un bloc de cuivre de 45 mm d'épaisseur. Une plaque d'acier inoxydable est liée au bloc (par une technique qui assure une résistance thermique très faible à l'interface) et usinée jusqu'à une épaisseur de 0,25 mm. Des thermocouples disposés avec précision dans l'épaisseur du bloc de cuivre servent à la mesure, par extrapolation, de la température de l'interface cuivre-acier, à mi-hauteur de la plaque. Le flux de chaleur et par suite la température de la surface de condensation sont déterminés à partir du gradient de température dans le bloc. On élimine des erreurs dues à la présence de gaz incondensables par balayage de la vapeur descendant verticalement sur la surface. On a démontré la forte influence des gaz incondensables résultant du dégazage des parois de l'appareil aux températures les plus élevées, en l'absence de balayage. Le coefficient de transfert de chaleur du côté de la vapeur augmente avec la pression de vapeur mais il est indépendant du flux thermique pour une pression de vapeur donnée. Les résultats s'accordent bien avec ceux des travaux les plus récents.

WÄRMEÜBERGANGSMESSUNGEN BEI DER TROPFENKONDENSATION VON QUECKSILBER

Zusammenfassung—Es wird über Messungen des Wärmestroms und der Temperaturdifferenz zwischen Dampf und Kondensationsoberfläche bei verschiedenen Dampfdrücken bei Tropfenkondensation von Quecksilber an einer ebenen vertikalen Wand berichtet. Der Versuchskondensator bestand aus einem Kupferblock mit 45 mm Dicke. Eine 0,25 mm dicke Plattierung aus rostfreiem Stahl wurde auf die dampfseitige Fläche dieses Blockes aufgebracht (mit einer, einen geringen Kontaktwiderstand hervorrufenden Technik). Mit genau plazierten Thermoelementen im Kupferblock wurde extrapolativ die Temperatur der Grenzfläche zwischen Stahl und Kupfer ermittelt. Der Wärmestrom und die Temperatur der Kondensationsoberfläche wurde über den Temperaturgradienten im Kupferblock bestimmt. Fehler infolge des Vorhandenseins nicht kondensierbarer Gase wurden durch eine vertikal nach unten gerichtete Kreuzstromführung des Dampfes eliminiert. Der starke Einfluß nicht kondensierbarer Gase, bedingt durch das Ausgasen der Apparatewände bei höherer Temperatur, ohne diese Kreuzstromführung wird aufgezeigt. Der dampfseitige Wärmeübergangskoeffizient nahm mit zunehmendem Dampfdruck zu, war jedoch bei gegebenem Dampfdruck im wesentlichen unabhängig vom Wärmestrom. Die Ergebnisse stimmen gut mit kürzlich veröffentlichten Untersuchungen überein.

ИЗМЕРЕНИЕ ХАРАКТЕРИСТИК ТЕПЛОПЕРЕНОСА ПРИ КАПЕЛЬНОЙ КОНДЕНСАЦИИ РТУТИ

Аннотация — Сообщается о результатах измерения разности температур пара и поверхности конденсации, а также теплового потока при различных давлениях пара в случае капельной конденсации ртути на плоской вертикальной поверхности. Экспериментальным конденсатором служил медный блок толщиной в 45 мм. Пластинка из нержавеющей стали присоединя-

лась к блоку со стороны пара (с использованием методики, обеспечивающей низкое тепловое сопротивление поверхности раздела) и заделывалась на глубину 0,25 мм. Термопары, вмонтированные в медный блок, позволяли определять путем экстраполяции температуру поверхности раздела медь-сталь посередине пластины. Тепловой поток, а следовательно, температура поверхности конденсации определялись из величины температурного градиента в блоке.

Ошибки, обусловленные наличием неконденсирующихся газов, исключались благодаря поперечному потоку пара. Показано значительное влияние неконденсирующихся газов, возникающих в результате «газовыделения» стенок экспериментального устройства при высоких тепмературах, в случае отсутствия поперечного потока. Найдено, что коэффициент теплообмена для пара увеличивается с ростом давления пара и не зависит от величины теплового потока при данном давлении пара. Полученные результаты хорошо согласуются с данными большинства более ранних исследований.