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EFFECT OF CONDENSER TUBE MATERIAL ON HEAT TRANSFER DURING DROPWISE CONDENSATION OF STEAM

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Abstract—Overall heat-transfer measurements were made while condensing steam on horizontal tubes of copper, brass, aluminium and stainless steel, promoted with dioctadecyl disulphide. A second set of measurements was made when the brass, aluminium and stainless steel tubes had been copper-plated to a thickness of 9 ± 1 μm. After tube-wall resistances (based on uniform radial conduction) had been subtracted, the overall heat-transfer coefficients for the copper, brass, copper-plated brass, copper-plated aluminium and copper-plated steel tubes were essentially the same. The overall coefficients for the unplated aluminium and steel tubes were markedly lower. Recently reported [1] differences in the results for different tube materials are considered to be due to differences in promoter effectiveness on the different surfaces rather than the thermal properties of the tube material. Visual observation indicated mixed or film condensation for the aluminium and stainless steel surfaces and ideal dropwise condensation on the copper, brass and copper-plated surfaces. In the case of the copper, brass and copper-plated tubes, the results were, within experimental error, consistant with established vapour-side heat-transfer coefficients for dropwise condensation.

All tests were conducted at pressures near to atmospheric. The non-condensing gas content of the steam was minimised by pre-boiling and possible effects of remaining traces of gas obviated by vapour cross flow over the condenser tube. In all cases measurements were repeated on different days with excellent reproducibility. The heat-transfer rate obtained from the mass flow rate and temperature rise of the coolant was in good agreement with that obtained by measuring the condensation rate.

NOMENCLATURE

c_P,	isobaric specific heat capacity of coolant;
d_o,	outside diameter of tube;
d_i,	inside diameter of tube;
k,	thermal conductivity of coolant;
k_t,	thermal conductivity of tube;
Nu,	$\alpha d_i/k$;
Pr,	$\mu c_P/k$;
Q_i,	heat flux at inside surface;
Q_o,	heat flux at outside surface;
R,	$\dfrac{T_v - T_c}{Q_o} - \dfrac{d_o}{2k_t}\ln\left(\dfrac{d_o}{d_i}\right)$;
Re,	$u\rho d_i/\mu$;
T_c,	$(T_{out} + T_{in})/2$;
T_i,	tube wall inside temperature;
T_{in},	coolant inlet temperature;
T_{out},	coolant outlet temperature;
T_v,	vapour temperature;
u,	coolant velocity;
α,	$Q_i/(T_i - T_c)$;
μ,	viscosity of coolant at T_c;
μ_i,	viscosity of coolant at T_i;
ρ,	density of coolant.

INTRODUCTION

This work was prompted by a recent report [1] that, for dropwise condensation of steam on tubes of different materials, the vapour-side heat-transfer coefficient (based on overall heat-transfer measurements) depended strongly on the tube material as well as on the wall thickness. It was suggested that this dependence was due to the thermal properties of the tube material along the lines of a theoretical treatment [2], which considered the heat-transfer resistance arising from the non-uniformity of heat flux near the condensing surface. In contrast, direct measurements, using copper and copper-plated (12 μm) steel surfaces [3], indicated that the vapour-side coefficients for the two materials were essentially the same. An important difference between these investigations is that in [3] the *surfaces* were both copper, whereas in [1] the tubes were not copper plated.

The present work was undertaken to test the hypothesis that the differences in results for different materials (as found in [1]) are due to differences in promoter effectiveness on the different surfaces rather than to differences in the thermal properties of the materials.

There have been earlier reports of significant dependence of heat-transfer coefficients on condenser material [4,5]. As suggested in [3], these may be attributable either to systematic error in measurement of the surface temperature or to promoter ineffectiveness on certain surfaces. Moreover, as pointed out in [3], the vapour-side coefficients for dropwise condensation of steam on teflon [6,7] were essentially the same as those for copper surfaces.

Very recently further theoretical [8] and experimental [9] work, indicating a dependence of heat-transfer coefficient on the thermal conductivity of the condensing surface material, have been reported. In

[9] it was found that the coefficient for stainless steel was lower than that for copper by a factor of about 2.4. Different surface temperature measurement techniques were used in [9] for the copper and stainless steel surfaces; that for the latter was extremely elaborate (a film resistance thermometer being separated from the base material and the gold vapour-side surface by very thin layers of insulating material).

APPARATUS AND PROCEDURE

Referring to Fig. 1, steam, generated from distilled water in a small electrically-heated boiler (maximum power 10 kW), flowed over the horizontal condenser tube (nominal outside diameter 13 mm, exposed length 108 mm) located in, and normal to the axis of, the horizontal cylindrical test section (inside diameter 120 mm). Water was passed through the condenser tube via a float-type flowmeter, calibrated by weighing water collected over measured time intervals. The condensate from the test condenser could be collected, for measuring, when required. Excess steam was condensed in a secondary condenser downstream of the test condenser. The proportion of the steam supplied which was condensed by the test condenser varied from about 10% at the lowest condensation rates to about 60% at the highest condensation rates. The pressure in the test section was always close to atmospheric.

The temperatures of the coolant at inlet and outlet of the test condenser and of the steam were measured by thermocouples located in narrow bore copper tubes. Care was taken to ensure adequate isothermal immersion of the leads. The calibration of the thermocouples, wiring of the leads and precautions taken to avoid errors in the thermo-electric measurements were the same as those described in [10]. The thermo-electric e.m.f.'s were measured by a digital voltmeter reading to 1 μV.

Copper, brass, aluminium and stainless steel condenser tubes were used. Each tube was thoroughly cleaned with metal polish followed by acetone before inserting, via O-ring seals, into the test section. The downstream end of the condenser section could be removed to permit the temporary insertion of a trough which encircled the condenser tube. The tube was promoted *in situ* by filling the trough with a 1% solution of dioctadecyl disulphide in carbon tetrachloride, so as to cover the tube, which was then rotated slowly for about 20 min.

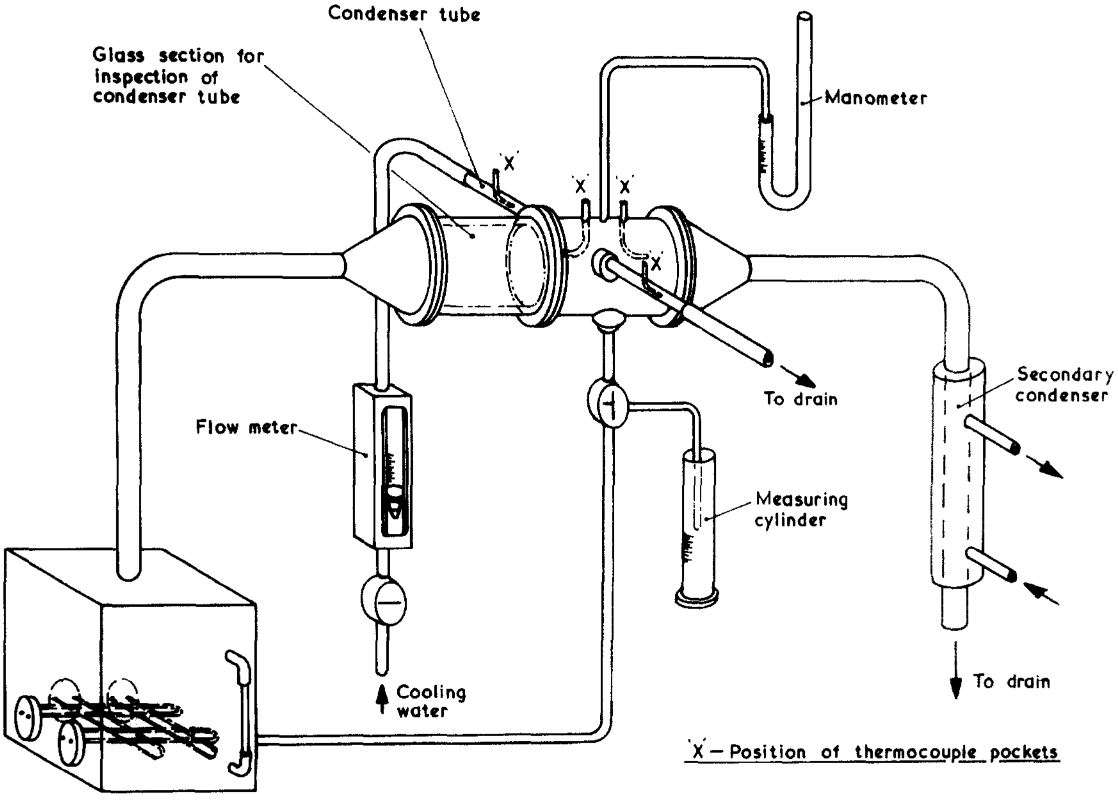

FIG. 1. Apparatus.

Tests were carried out for a range of coolant flow rates using each tube in turn. In all cases, measurements were repeated on different days. Finally the brass, aluminium and steel tubes were copper-plated to a thickness of 9 ± 1 μm and further sets of observations taken.

The heat-transfer rate to the condenser tube was determined from the mass flow rate and temperature rise of the coolant. On a few occasions a second estimate was obtained by collecting condensate over a measured time interval. The relatively small condensation rate on the test section walls was first observed (when the inside of the condenser tube was dry) and an appropriate correction made. The two values of the heat-transfer rate were found to be in good agreement, the largest discrepancy being about 5%.

RESULTS

Figure 2 shows the observed dependence of the heat flux on coolant velocity for the four different tubes. It may be seen that the results for the brass and copper-plated brass surfaces were essentially the same and close to those obtained for the copper tube. The observed heat fluxes for the aluminium and stainless-steel tubes were substantially higher when copper-plated than when unplated.

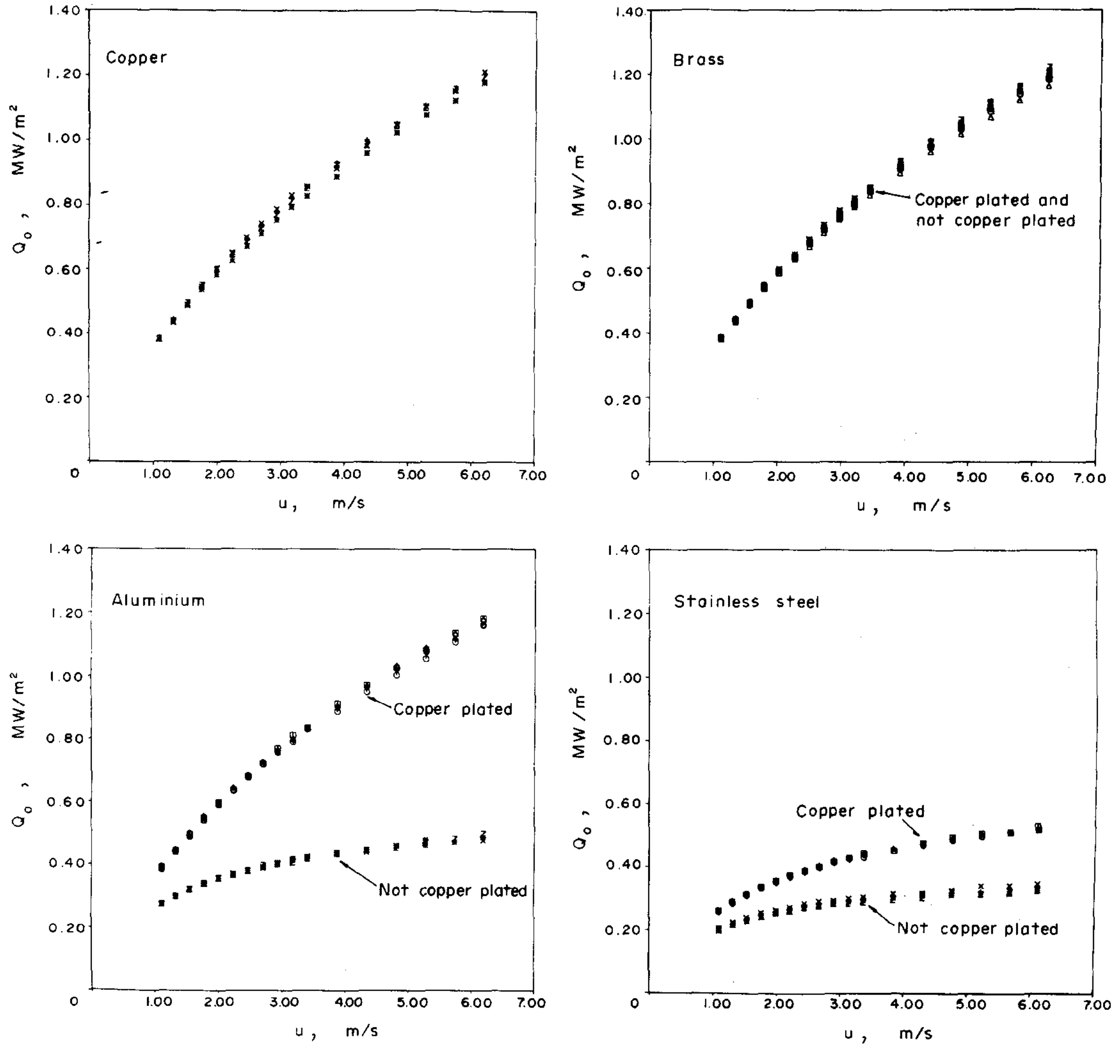

FIG. 2. Dependence of heat flux on coolant velocity. Different symbols denote different test runs. + × * z, unplated tubes; ○ □ △ ◇, copper-plated tubes.

For each of the seven cases, four separate runs were made on at least two different days. The repeatability of the observations is seen to be good. Part of the small difference in results between runs using the same tube and surface treatment is attributable to small differences in coolant inlet temperature and steam temperature. Visual observations indicated ideal dropwise condensation on the copper, brass and copper-plated tubes and either mixed or film condensation on the unplated aluminium and stainless steel tubes. The results for the aluminium and stainless steel clearly illustrate the advantage of dropwise over filmwise condensation. For aluminium, for which the tube-wall thermal resistance is relatively small, the *overall* heat-transfer coefficient with dropwise condensation exceeds that with filmwise condensation by a factor of about 3 at the highest flow rate.

In fig. 3 the effect of the tube wall resistance is removed by plotting R, the observed overall thermal resistance less that of the tube, the latter evaluated on the basis of uniform radial conduction, thus:

$$R = \frac{T_v - T_c}{Q_o} - \frac{d_o}{2k_t}\ln\left(\frac{d_o}{d_i}\right). \qquad (1)$$

The values of k_t used were 383, 129, 231 and 17 W/m K for the copper, brass, aluminium and stainless steel respectively. It may be seen that the values of R for the copper, brass and copper-plated tubes are essen-

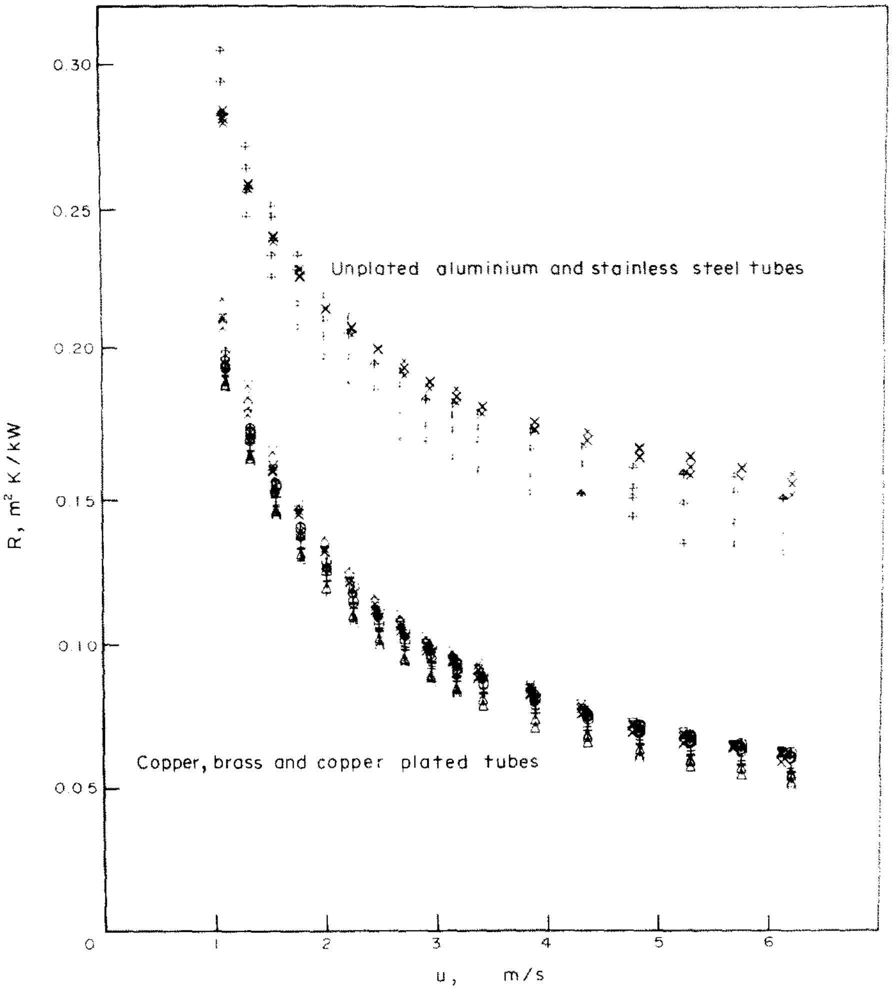

FIG. 3. Dependence of combined steam- and water-side resistance on coolant velocity. ○, copper; △, brass; +, copper-plated brass; ×, aluminium; ◇, copper-plated aluminium; ⍋, stainless steel; ⊼, copper-plated stainless steel.

tially the same. The relatively small differences are less than those arising from uncertainties in the values of k_t and may, to some extent, also be attributable to variations in coolant inlet temperature and to the effect of differences in coolant-side resistance resulting from differences in inside wall temperature.

In a separate investigation [11] using the same apparatus, but with thermocouples fitted in the tube wall, it was established that the coolant-side heat transfer could be very precisely represented by

$$Nu = 0.03Re^{0.8}Pr^{1/3}(\mu/\mu_i)^{0.14}. \qquad (2)$$

(The coefficient 0.03 in the above is greater than the usual value of 0.023 for "long" tubes owing to thermal entrance effects.) Equation (2) was used with the present overall heat-transfer data, and assuming uniform radial conduction in the tube wall, to estimate vapour-side coefficients. For the copper, brass and copper-plated tubes, values in the approximate range 100–200 kW/m² K were obtained, the higher values being found for the brass and stainless steel. These may be compared with established and more precisely determined values for dropwise condensation on vertical surfaces which, for the present range of heat flux, vary from about 150 kW/m² K to about 300 kW/m² K. For the unplated aluminium and stainless steel tubes values close to 10 kW/m² K were found.

As a check on the above estimates, the vapour-side coefficient for each data set was regarded as constant (i.e. independent of heat flux) and the coolant-side heat transfer represented by:

$$Nu = CRe^{0.8}Pr^{1/3}(\mu/\mu_i)^{0.14}. \qquad (3)$$

Then, for each data set, the vapour-side coefficient and C were determined by minimizing the sum of the squares of the differences between the observed and "predicted" overall temperature differences. In all cases C was found to be close to 0.03 and the vapour-side coefficients were close to those obtained previously.

CONCLUSION

The vapour-side heat-transfer coefficients for dropwise condensation on the surfaces listed below are essentially* the same as those for copper surfaces

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*Certainly this statement is considered valid for the purpose of calculating overall coefficients for water-cooled tubes.

($k_t \simeq 380$ W/m K):
brass ($k_t \simeq 130$ W/m K) [present work];
Teflon ($k_t \simeq 0.25$ W/m K) [6, 7];
copper-plated ($\simeq 9$ μm) aluminium ($k_t \simeq 230$ W/m K) [present work];
copper-plated ($\simeq 9$ μm) stainless-steel ($k_t \simeq 17$ W/m K) [present work];
copper-plated ($\simeq 12$ μm) mild steel ($k_t \simeq 46$ W/m K) [3].

As has been suggested earlier [3], it is possible that the extremely high rate of coalescence during dropwise condensation leads to space- and time-wise temperature fluctuations of such high frequency that the surface temperature is essentially uniform and steady, so that the material of the condensing surface plays a negligible part in determining the vapour-side heat-transfer coefficient.

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EFFET DE LA MATIERE DES TUBES DE CONDENSEUR SUR LE TRANSFERT THERMIQUE LORS DE LA CONDENSATION EN GOUTTES DE LA VAPEUR D'EAU

Résumé—Des mesures du transfert thermique global sont faites sur la condensation de vapeur d'eau sur des tubes horizontaux en cuivre, laiton, aluminium et acier inoxydable et en présence de disulfure dioctadécyl. Une deuxième série de mesures est faite avec des tubes de laiton, d'aluminium et d'acier inoxydable recouverts d'une couche de 9 ± 1 μm de cuivre. Après soustraction des résistances de paroi (basées sur la conduction radiale uniforme), les coefficients de transfert thermique pour tous les tubes sont pratiquement les mêmes mais beaucoup plus faibles pour ceux en aluminium et en acier inoxydable. Des différences récemment publiées [1] pour divers matériaux sont dues plus à des différences entre efficacités de promoteurs qu'à des différences entre propriétés thermiques des matériaux. Une visualisation révèle une condensation mixte ou en film pour l'aluminium et l'acier inoxydable et une condensation idéale en gouttes sur les surfaces de cuivre, de laiton ou recouverte par du cuivre. Dans le cas des tubes de cuivre, de laiton et recouverts de cuivre, les résultats sont, dans la marge des erreurs expérimentales, en accord avec les coefficients de transfert établis pour la condensation en gouttes. Tous les essais sont menés à des pressions proches de la pression atmosphérique. La présence de gaz incondensable est réduite par une ébullition préalable et des effets possibles de traces de gaz éliminés par une circulation forcée de vapeur sur les tubes du condenseur. Dans tous les cas, les mesures sont répétées à des jours différents avec une excellente reproductibilité. Les coefficients de transfert obtenus à partir du débit massique et de l'accroissement de la température du réfrigérant sont en bon accord avec ceux obtenus par la mesure du débit du condensat.

EINFLUSS DES ROHRMATERIALS IM KONDENSATOR AUF DEN WÄRMEÜBERGANG BEI DER TROPFENKONDENSATION VON DAMPF

Zusammenfassung—Es wurden Wärmedurchgangsmessungen mit kondensierendem Dampf an waagerechten Röhren aus Kupfer, Messing, Aluminium und rostfreiem Stahl durchgeführt. Als Arbeitsmittel wurde Dioktadecyl-Disulfid verwendet. Eine zweite Meßreihe wurde durchgeführt, nachdem die Rohre aus Messing, Aluminium und rostfreiem Stahl mit einer Kupferschicht von 9 ± 1 μm Dicke beschichtet wurden. Nachdem der Wärmewiderstand der Rohrwand, verursacht durch gleichmäßige, radiale Wärmeleitung, aus den Ergebnissen eliminiert war, ergaben sich nahezu gleiche Wärmedurchgangskoeffizienten für die Rohre aus Kupfer, Messing, kupferbeschichtetem Messing, kupferbeschichtetem Aluminium und kupferbeschichtetem Stahl. Die Wärmedurchgangskoeffizienten für die unbeschichteten Aluminium- und Stahlrohre waren bedeutend niedriger. Unterschiedliche Ergebnisse für verschiedent Rohrmaterialien, wie sie vor kurzem in [1] berichtet wurden, sind wahrscheinlich mehr auf die Verbesserung des Wärmeübergangs bei den verschiedenen Oberflächen zurückzuführen als auf die thermischen Eigenschaften des Rohrmaterials. Versuchsbeobachtungen zeigten Misch- oder Filmkondensation an der Oberfläche bei Aluminium und rostfreiem Stahl und ausgeprägte Tropfenkondensation bei Kupfer, Messing und kupferbeschichtetem

Material. Für die Rohre aus Kupfer, Messing und Kupferbeschichtungen gab es innerhalb der Meßgenauigkeit eine gute Übereinstimmung mit bekannten Wärmeübergangskoeffizienten für die Tropfenkondensation von Dampf. Alle Messungen wurden etwa bei Atmosphärendruck durchgeführt. Der nicht kondensierbare Fremdgasanteil des Dampfes wurde durch Vorsieden verringert und mögliche Effekte von verbleibenden Gasspuren durch einen Dampfstrom über das Kondensatorrohr ausgeschaltet. In allen Fällen wurden die Messungen an verschiedenen Tagen mit hervorragender Reproduzierbarkeit wiederholt. Der übertragene Wärmestrom, berechnet aus Massenstrom und Temperaturanstieg des Kühlmittels, war in guter Übereinstimmung mit dem Wärmestrom, den man durch Messung des Kondensatstroms bestimmen kann.

ВЛИЯНИЕ МАТЕРИАЛА КОНДЕНСАТОРНОЙ ТРУБКИ НА ТЕПЛОПЕРЕНОС ПРИ КАПЕЛЬНОЙ КОНДЕНСАЦИИ ПАРА

Аннотация — Измерялся теплообмен при конденсации пара на горизонтальных трубках, выполненных из меди, латуни, алюминия и нержавеющей стали, активированных диоктадецильным дисульфидом. Вторая серия измерений проводилась на медных, алюминиевых и из нержавеющей стали трубках с нанесенным на них слоем меди толщиной до 9 ± 1 м. Если вычесть сопротивление стенки трубки (в предположении равномерного радиального распределения), то полные коэффициенты теплообмена оказываются почти одинаковыми для медных, латунных, латунных с медным покрытием, алюминиевых с медным покрытием и из стали с медным покрытием трубок. Коэффициенты же теплообмена для алюминиевых и стальных трубок без покрытия были значительно ниже. Из последних сообщений [1] следует, что различие в результатах по теплообмену для различных материалов трубок объясняется скорее разной эффективностью активатора, чем теплофизическими свойствами материала, из которого сделаны трубки. Путём визуального наблюдения установлено наличие смешанной или пленочной конденсации на поверхностях алюминиевой и из нержавеющей стали трубок и идеальной капельной конденсации на медных, латунных и с медным покрытием поверхностях. Для последних результаты находятся в пределах экспериментальной погрешности и согласуются с коэффициентами теплопереноса для пара при капельной конденсации. Все эксперименты проводились при давлениях близких к атмосферному. Количество неконденсирующегося газа в паре было сведено до минимума путём предварительного нагрева, а возможное влияние остаточных следов газа устранялось поперечным потоком пара в конденсаторной трубке. Воспроизводимость экспериментов в разные дни была хорошей. Наблюдалось удовлетворительное соответствие между значениями скорости переноса тепла, определенными по массовому расходу газа и увеличению температуры охладителя, и определенными по скорости конденсации.