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LAMINAR FILM CONDENSATION OF STEAM CONTAINING SMALL CONCENTRATIONS OF AIR

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Abstract—Film condensation heat flux measurements have been made on a vertical surface at film Reynolds numbers below the critical values for ripple formation. These measurements have been made on air–steam mixtures with air mass fractions of 1×10^{-4}–1×10^{-2} and on pure steam at saturated vapor temperatures of 150, 115 and 80°F. The average heat flux values for air–steam mixtures have been divided by those computed from the Nusselt theory for pure vapor at the same difference between vapor and surface temperature. The ratios so obtained are found to be about 20 per cent above the theoretical predictions of Minkowycz and Sparrow.

NOMENCLATURE

C_p, specific heat [Btu/lb °F];
h, heat transfer coefficient [Btu/h ft^2 °F];
L, length of test surface [ft];
q, heat flux [Btu/h ft^2];
T, temperature [°F];
W_∞, volumetric free-stream mass fraction of air;
W_G, measured free-stream mass fraction of air.

Greek symbols
Γ, mass flow rate of condensate [lb/ft h];
λ, latent heat of vaporization [Btu/lb];
μ, viscosity [lb/h ft].

Subscripts
v, saturated vapor;
w, wall;
Nu, predicted by Nusselt equation.

INTRODUCTION

THE EFFECT of noncondensable gas on the film condensation of a pure substance has a considerable analytical history, culminating in the solution of Minkowycz and Sparrow [1] which, for the two-dimensional case, includes all the important aspects of the problem except that of ripples at the condensate–vapor interface. The numerical calculations of this solution have been made for air and steam and are presented for vapor pressures at atmospheric and below. As the pressure is reduced, there is a decrease in the condensation rate produced by a given temperature difference for a given concentration of air in the vapor.

There have been a number of experiments to examine this effect of the presence of a noncondensable gas in the vapor, but the interpretation of these results is always impeded by the fact that in these experiments the heat transfer coefficients as determined with pure vapor are usually higher than the values indicated by the Nusselt solution. Hampson [2] presents results for the film condensation of steam at atmospheric pressure in which the experimental average heat transfer coefficients are 20 per cent above those indicated by the Nusselt solution. In those experiments the final film Reynolds number $4\Gamma/\mu$ was about 200. When nitrogen was added to the steam, the resulting reduction in heat transfer coefficient was approximated as $h/h_{Nu} = 1{\cdot}2\,(1 - 16{\cdot}7\,W_\infty)$, for weight fractions of nitrogen up to 0·02. Meisenburg [3] found $h/h_{Nu} = 1{\cdot}17 \times (100\,W_\infty)^{-0{\cdot}11}$ for air in steam condensing on the outside of a vertical tube. To illustrate the difference between these frequently referenced older prediction methods [4] and the Minkowycz theory, a tabulation of heat transfer results at atmospheric pressure appears in Table 1.

Table 1.

	h/h_{Nu}			
W_∞	0·005	0·01	0·02	0·04
$1{\cdot}2\,(1 - 16{\cdot}7\,W_\infty)$	1·10	1·00	0·80	—
$1{\cdot}17\,(100\,W_\infty)^{-0{\cdot}11}$	1·26	1·17	1·085	1·005
Minkowycz ($T_v - T_w = 15$°F)	0·45	0·37	0·29	0·23

The values in the first two rows of Table 1 indicate far less reduction in heat transfer than shown by the theory. Minkowycz, however, showed that a few of the values obtained by Othmer on a horizontal tube agree more closely with the theory in terms of average heat flux. More recently, similar results have been obtained by Henderson [5] and an analogous empirical impression for the horizontal tube was proposed. This expression, as well as the ones in Table 1, suffer from over simplification since they are restricted to atmospheric pressure and do not include a dependence on $T_v - T_w$.

To provide additional experimental results for the appraisal of the effect of air on the condensation of steam, experiments were performed by Slegers [6] on condensation on a vertical surface with saturated mixtures of air and steam at sub-atmospheric pressure corresponding to temperatures of 150, 115 and 80°F and varying $T_v - T_w$.

APPARATUS

The apparatus used for the present experiments was essentially that which has been described by Mills [7] where the condensing surface was contained in a 24-in. high, 18-in dia. glass bell-jar mounted on a base plate. The condensing surface was a 2-in. wide, 5-in. high vertical face of high purity, oxygen free copper block, 4·5 in. thick, the back surface of which was cooled by a refrigerated coolant. Condensation was restricted to the front surface of the block through its installation in an inner chamber with only the front surface exposed to the vapor. A thermally insulating Teflon plate completed the enclosure of the inner chamber with the lateral sides of the block, enabling evacuation of the chamber to insure thermal insulation at the sides of the block. The temperature instrumentation described in [7] had been modified to columns of six thermocouples at 1 in. and 2 in. from the surface installed at 0·25-in. depth in one side of the block. In addition to these twelve, one more thermocouple was installed in the opposite side to verify at one point the existence of spanwise symmetry in the isothermal surfaces in the block. The average heat flux was calculated assuming unidimensional conduction by averaging the indicated temperatures in each column and using a thermal conductivity of 220 Btu/h ft °F. An average surface temperature was obtained by linear forward extrapolation of the measured temperatures to the test surface.

The apparatus was further modified by elimination of the condensate metering system and the addition of a baffle and steam distributor over the 5-in. dia. opening of the boiler in the bell-jar base. This baffle had the double function of suppressing vapor velocities near the test surface and to induce vapor mixing by directing the vapor generated in the boiler uniformly in all directions along the base plate. The entire bell-jar was enclosed in a Plexiglass cover with the air space between the bell-jar and the cover heated to reduce heat loss due to condensation on the glass.

The desired quantities of air were metered into the apparatus from an external cylinder of known volume. From a pressure and temperature measurement on the cylinder, and the known volume of the apparatus, the resulting average air concentration in the apparatus could be computed for any vapor pressure. As a verification, a local air concentration near the surface was measured by withdrawing a sample for analysis in a modified McLeod gauge as described in [6]. This measurement was made at 80°F vapor temperature only.

System operation was started with 1·5 l distilled water in the boiler with the system vented to an aspirating pump such that about 25 per cent of the generated vapor was continuously withdrawn. After about 4 h of running, all the air was removed from the apparatus as evidenced by the agreement in heat flux with previous pure vapor results. Then access to the aspirator was closed, and the absence of air leaks was verified by the maintenance of pure vapor heat flux under these conditions. Air was then metered into the apparatus with simultaneous adjustments to heat input to achieve the desired operating conditions. The maximum heat flux capability of the apparatus was about 30000 Btu/h ft^2.

Each data point indicates a constant operating condition corresponding to a particular heater setting. A new operating condition followed a 0·75 hour transient after heat input had been adjusted. At lower vapor pressures the available nucleation sites in the boiler did not suffice to insure stable boiling, and bumping occurred. Even stainless steel wire gauze would not stabilize boiling at the vapor pressure corresponding to 80°F. Teflon chips placed in the boiler stabilized the boiling but several days of running with pure vapor were required to remove all traces of noncondensable gas that resulted from outgasing of the Teflon. Such preliminary running periods were required each time the Teflon had been exposed to the atmosphere.

RESULTS FOR PURE STEAM

Condensation measurements of pure steam were made at 150, 115 and 80°F at saturated conditions as verified by a pressure measurement. The air–steam mixture data was also taken at these temperatures. The measured average heat flux for pure steam is shown in Fig. 1 as a function of the temperature difference $T_v - T_w$ and is shown to be about 15 per cent above the prediction of the Nusselt solution with properties evaluated at $T^* = T_w + 0{\cdot}31\,(T_v - T_w)$, and the latent heat of vaporization corrected as $\lambda^1 = \lambda + 0{\cdot}68C_p\,(T_v - T_w)$. Film instability or ripples could cause this increase in heat flux, but no ripples were observed, and the film Reynolds number $4\Gamma/\mu = 4qL/\mu\lambda$ never exceeded 39, or well below the values generally quoted for which ripples begin to occur.

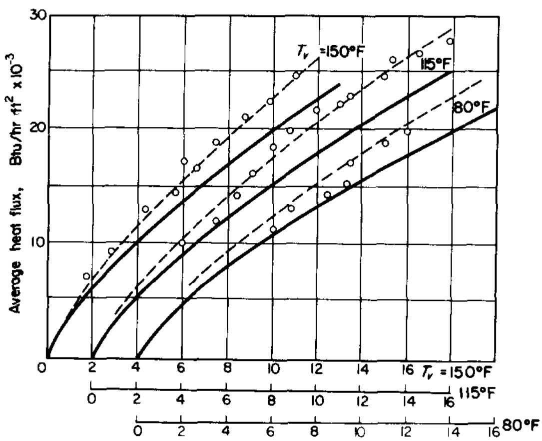

FIG. 1. Average Nusselt heat flux measurements on condensing pure steam at constant vapor temperature, —— q_{Nu}, – – – $1{\cdot}15q_{Nu}$.

This data discrepancy was not in evidence in the results of Mills obtained on this system, but the range of scatter in his data corresponds to the present departure from theory. It is suspected that this discrepancy is caused by an error in the experimental determination of heat flux due to spanwise nonuniformity or edge effect in the film thickness. Near both edges of the test surface the film surface assumes a curvature which meets with the sharp corners of the block leaving the corner essentially dry. Even though this edge effect is localized in a very narrow strip (about 0·05 in) along both edges, increased heat flux is indicated at the location of the temperature instrumentation. Evidence in this regard was obtained by a numerical solution for the temperature field in the block, on a two-dimensional basis which therefore did not account for edge effect, using as boundary conditions the observed temperatures from the column of thermocouples farthest from the surface, and the saturated temperature of the vapor temperature in conjunction with a developing Nusselt liquid film on the surface. The computed temperatures departed from the thermocouple measurements in the forward column in a manner to cause the measured heat flux to be about 8 per cent too high. Incorrect average surface temperature determination caused the Nusselt heat flux to be computed too low by a similar fraction thus explaining the discrepancy in the data. Further support for this interpretation was obtained from previous experiments on film condensation of *n*-butyl alcohol [8] where measured heat fluxes did agree with the Nusselt solution. For this case, the predicted temperatures for the forward column of thermocouples did agree with the measured values. Apparently the thicker alcohol film and greater wettability of this liquid reduced or eliminated the film imperfection that caused this discrepancy in the steam data.

On the basis of these findings, all heat flux measurements of air–steam mixtures have been reduced by 8 per cent. The error in determining T_w has been neglected since with air–steam mixtures the value of $T_v - T_w$ is much larger than for pure vapor, and according to the theory the quantity q/q_{Nu} is only weakly dependent on $T_v - T_w$.

RESULTS FOR AIR–STEAM MIXTURES

The measured average heat fluxes for air–steam mixtures reduced by the 8 per cent correction are compared with the pure vapor heat flux for the same value of $T_v - T_w$. Figures 2–4 give the results as q/q_{Nu} (which is equal to h/h_{Nu}) as a function of $T_v - T_w$, parametrically in terms of weight concentration of air W_∞, at the three different vapor temperatures. The quantity q_{Nu} was compared from the Nusselt equation based on $T_v - T_w$ with property values evaluated

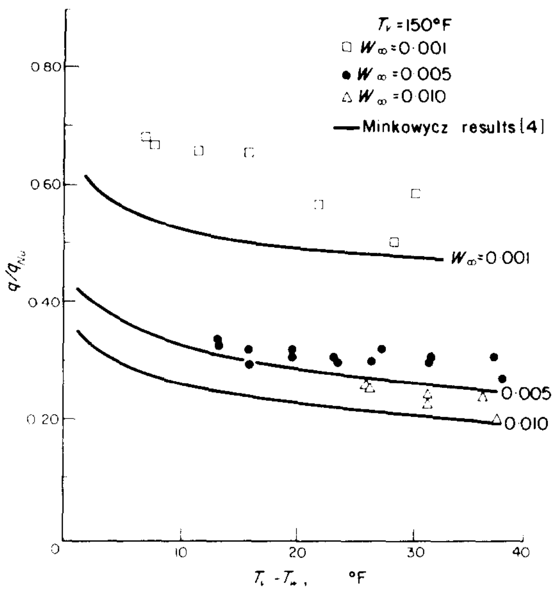

FIG. 2. Average heat flux measurements on condensing air–steam mixtures at constant vapor temperature.

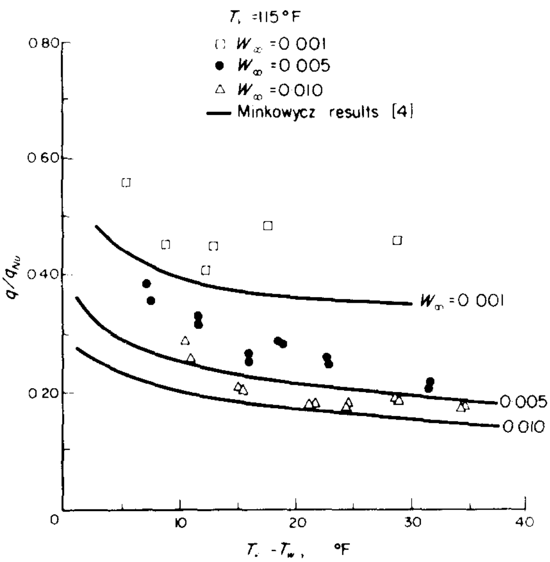

FIG. 3. Average heat flux measurements on condensing air–steam mixtures at constant vapor temperature.

at the reference temperature since in most cases q_{Nu} was not within the heat flux capability of the apparatus.

Measurements were made at $T_v = 80°F$ for air concentrations below the range for which analytical results have been presented in [1].

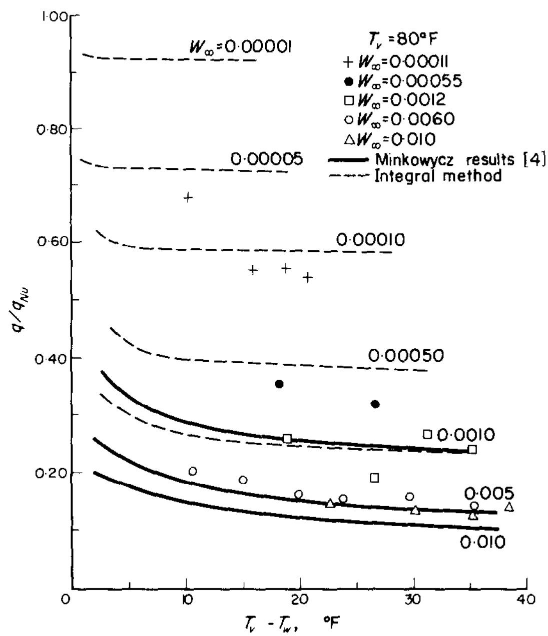

FIG. 4. Average heat flux measurements on condensing air–steam mixtures at constant vapor temperature.

To provide a theoretical prediction at values of $W_\infty < 0{\cdot}001$ an integral solution method was employed as described in [6]. This method of solution was essentially similar to one derived by Rose [9] except that modified Kármán–Pohlhausen expressions were used for the velocity and temperature profiles. The integral solution is entered as dashed lines on Fig. 4 and shows reasonable to good agreement with the exact solution of Minkowycz at $W_\infty = 0{\cdot}001$. The solution method of Rose also underpredicts the exact solution but in contrast to the present integral method, shows better agreement at small than at larger values of $T_v - T_w$. This difference in the approximate solutions is probably due to the vapor properties evaluation. Both approximations are quite satisfactory but their applicability to very low air concentrations is more questionable since neither analysis adequately accounts for the strong suction at the liquid–vapor interface.

The theoretical trend of decreasing q/q_{Nu} for increasing $T_v - T_w$ is confirmed by the experiments for all values of W_∞. The data is scattered in a range of slightly below to 30 per cent above the theory with a tendency toward higher scatter at lower concentrations. On the average, the experimental results in each of the Figs. 2–4 are about 20 per cent above the theory.

When it is considered that perfect film conditions were at all times visually verified, two possible departures from ideal mode to cause the data discrepancy are:

1. Forced flow in the vapor.
2. Nonuniform air concentration the ball-jar.

It was noticed in the early phases of the experimentation that measured heat flux on air–steam mixtures greatly increased under conditions of forced flow, The present data was taken when the incoming steam was directed away from the test surface by installing a baffle over the boiler, but perfect stagnant conditions may still not have been achieved causing the data to be high. The second effect may be visualized as imperfect mixture conditions in the vapor as caused by the increased air concentration layer flowing down the test surface and collecting near the bottom of the bell-jar. Such local air enrichment in the base of the apparatus would cause W_∞ near the test surface to decrease below the average computed value. To verify this condition a separate determination of local air concentration was made at 4 in. distance and 3 in. from the top of the test surface for the 80°F vapor temperature data. These measurements are summarized in Table 2 where the average concentration W_∞ computed over the bell-jar volume is compared with W_G measured locally.

The values of W_G confirm or even exceed the volumetric average, indicating a trend opposite

Table 2.

W_∞	0·0050	0·0010	0·00050	0·00010
W_G	0·0060	0·0012	0·00055	0·00011

to that of the stratification argument. The effect of forced flow thus is the more acceptable explanation for the difference between theory and experiment.

CONCLUDING REMARKS

The results tend to be on the average 20 per cent above the prediction of Minkowycz and the difference is ascribed to forced flow in the vapor since it is assumed that, for the low film Reynolds numbers at which these experiments were performed, the theoretical predictions are essentially correct. The atmospheric pressure data of Hampson indicates for less reduction in heat transfer, but his experiments were performed with substantial magnitudes of forced flow as judged from the apparatus. It is thus concluded that the effect of air in condensing stagnant vapor is far greater than previously reported, and is properly predicted for stagnant vapor at stable film conditions by the Minkowycz theory as shown by the present experiments to within 20 per cent. Better agreement with the theory might have been obtained in the present results if stagnant vapor conditions had been more nearly achieved.

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FILM LAMINAIRE DE CONDENSATION D'UNE VAPEUR CONTENANT DE L'EAU EN FAIBLE CONCENTRATION

Résumé—Des mesures de flux thermique dans un film de condensation sont faites sur une surface verticale pour des nombres de Reynolds inférieurs aux valeurs critiques de formation de rides. Les mesures sont faites sur des mélanges avec des concentrations massiques d'air variant de $1 . 10^{-4}$ à $1 . 10^{-2}$ et sur de la vapeur pure à des températures de saturation de vapeur de 150, 115 et 90°F. Les valeurs moyennes de flux thermique pour les mélanges air-vapeur sont divisées par celles calculées à partir de la théorie de Nusselt pour de la vapeur pure à la même différence de température entre la vapeur et la surface. Les rapports ainsi obtenus ont une valeur supérieure d'à peu près 20 pour cent à celles prédites théoriquement par Minkowycz et Sparrow.

LAMINARE FILM-KONDENSATION VON DAMPF MIT GERINGEM LUFTGEHALT

Zusammenfassung—Wärmeübergangsmessungen bei Filmkondensation an einer senkrechten Oberfläche wurden durchgeführt. Die Reynoldszahlen des Films lagen unter den kritischen Werten für den Beginn der Wellenbildung. Die Messungen wurden mit 10^{-4} bis 10^{-2} Massenanteilen Luft im Dampf und mit reinem Dampf bei Sättigungstemperaturen von 66°C, 46°C und 32°C durchgeführt. Die mittleren Wärmestromdichten für die Dampf-Luft-Gemische wurden dividiert durch die nach der Nusseltschen Theorie errechneten Werte für reinen Wasserdanpf bei gleichen Temperaturdifferenzen zwischen Dampf und Kondensationswand. Die erhaltenen Quotienten liegen ungefähr 20 Prozent über den theoretischen Voraussagen von Minkowycz undSparrow.

ЛАМИНАРНАЯ ПЛЕНОЧНАЯ КОНДЕНСАЦИЯ ВОДЯНОГО ПАРА ПРИ НЕБОЛЬШОМ СОДЕРЖАНИИ ВОЗДУХА

Аннотация—Проведены измерения теплового потока при пленочной конденсации на вертикальной поверхности при пленочных числах Рейнольдса ниже критических (образование ряби). Измерения проводились со смесями воздух-водяной пар при весовых концентрациях воздуха от 1×10^{-4} до 1×10^{-2}, а также с чистым паром при температуре насыщенного пара 150, 115 и 90°F. Средние значения теплового потока для паро-воздушных смесей отнесены к значениям, рассчитанным по теории Нуссельта для чистого пара при одинаковой разности температур пара и поверхности. Найдено, что полученные таким образом отнощения на 20% превышают теоретические расчеты Минковича и Спэрроу.