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FREE CONVECTION FILM CONDENSATION OF STEAM IN THE PRESENCE OF NON-CONDENSING GASES

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Abstract—Heat-transfer measurements for film condensation of steam on a vertical plane surface in the presence of air, argon, neon and helium, under free-convection conditions are reported. The results indicate greater reductions in heat transfer, for given non-condensing gas concentrations, than suggested by earlier reports. The present measurements agree satisfactorily with recent boundary-layer analyses.

NOMENCLATURE

M_g,	relative molecular mass ("molecular weight") of non-condensing gas;
M_v,	relative molecular mass ("molecular weight") of vapour, i.e. water;
P,	pressure of gas–vapour mixture;
$P_{\mathrm{sat}}(T)$,	liquid–vapour equilibrium ("saturation") pressure for water at temperature T;
Q,	heat flux;
Q_{Nu},	heat flux given by simple Nusselt theory in the absence of a non-condensing gas;
T_w,	temperature of condensing surface;
T_∞	temperature in gas–vapour mixture outside boundary layer at mid-height of plate;
W_{mean},	mean mass concentration of non-condensing gas;
W_∞,	$\dfrac{P - P_{\mathrm{sat}}(T_\infty)}{P - [1 - (M_v/M_g)]\,P_{\mathrm{sat}}(T_\infty)}$;
ΔT,	$T_\infty - T_w$.

1. INTRODUCTION

THE EFFECT of non-condensing gases in reducing the heat flux during condensation of vapours is well known. Considerable progress has been made in recent years towards the theoretical understanding of the problem for the case of film condensation on plane surfaces under laminar flow conditions with free convection [1–5], forced convection [6, 7] and combined forced and free convection [8]. Much of the experimental work however has been directed towards the practically more relevant case of the tube.

Prior to the commencement of the present work, such limited data as was available for plane surfaces related to free convection conditions [9, 10]. These measurements were compared by the present authors with the theoretical solutions [3, 4]. It was found that the theory predicted substantially smaller heat-transfer coefficients than those found experimentally. It was felt that before progress towards satisfactory solutions for more complex cases (different geometries, mode of condensation and flow regime) could be made, it was necessary to establish the validity or otherwise of the theoretical solutions so far obtained.

2. APPARATUS

Referring to Fig. 1, steam was generated from de-ionized water in the cylindrical glass boiler. Using the graduated glass cylinder, measured

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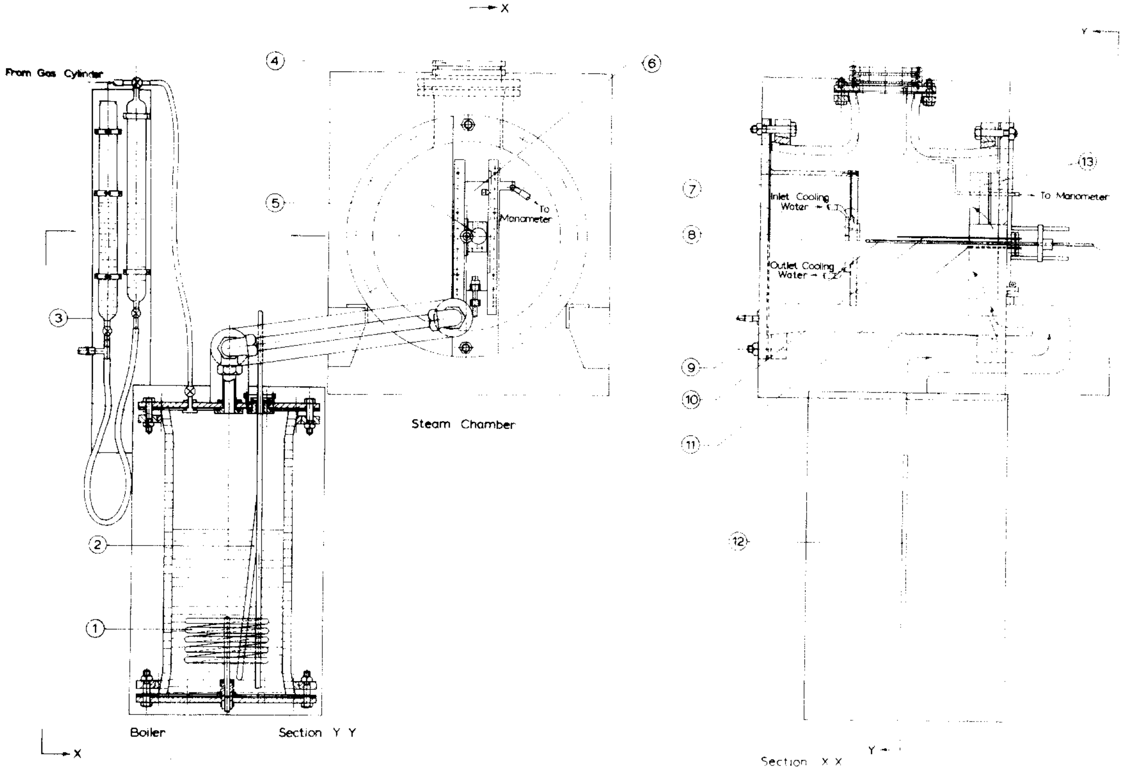


FIG. 1. General assembly of the apparatus.

1. electric heater; 2. electric heater; 3. gas measuring cylinders; 4. electrically heated window; 5. electrically heated window; 6. vertically sliding plate; 7. condensing plate; 8. cooling box; 9. horizontally moveable thermocouple (see also Fig. 3) mounted on vertically sliding plate; 10. thermocouple mounted on vertically sliding plate; 11. thermocouple mounted on vertically sliding plate; 12. water level inspection slit; 13. flow straightener.

quantities of non-condensing gas could be introduced to the boiler. The vapour–gas mixture passed into the cylindrical glass steam chamber of diameter 0·46 m, via the flow straightening section. The steam condensed on the vertical copper test plate which was cooled on the reverse side by water. The condensate ran back to the boiler via the vapour supply pipe. The steam chamber was fitted with two electrically heated glass windows to allow visual observation from above and directly onto the condensing plate. The boiler and the steam chamber were well lagged.

The function of the flow straightening section was to provide uniform flow of the mixture towards the condensing surface and thus to obviate forced convection effects. The section contained three equi-spaced vertical screens of fine stainless steel mesh, parallel to the condensing surface. This arrangement was established by preliminary tests using air, the uniformity of flow along the steam chamber being studied using a quartz fibre anemometer (for details see [11]).

The thickness of the test plate was 12·5 mm and the condensing surface was a square of side

97 mm. Six butt-welded nichrome–constantan thermocouples of diameter 0·21 mm, were cast in an "Araldite" strip which fitted tightly into a slot, of width 0·5 mm, machined from the rear face of the plate in a horizontal diametral plane to a depth of 10·7 mm, i.e. the bottom of the slot was 1·8 mm from the condensing surface. The positions of the thermocouples in the strip, and hence their distances from the condensing surface when installed, were accurately determined using a travelling microscope. Figure 2 shows a section through the plate with the "Araldite" strip in position.

This technique for precisely locating thermocouples at different depths below the condensing surface, in order to obtain high-accuracy surface temperatures by extrapolation, has been successfully used earlier in work on dropwise condensation [12]. That the results were not vitiated by the presence in the plate of the "Araldite" strip is shown by the excellent linear temperature distributions invariably found in the plate. (Individual points did not generally deviate from the "least-squares" straight lines by more than 0·1 K or 0·1 mm.) Also, as will be seen, the results for "gas-free" steam were found to be in good agreement with the well-established Nusselt theory.

The pressure of the vapour–gas mixture was measured by a water manometer, giving the gauge pressure, together with a barometer in the laboratory. Temperatures in the steam chamber were determined by three thermocouples, mounted on a vertically traversable plate, fitted to the front end of the steam chamber. Two of the thermocouples were fixed in position with respect to the sliding plate so that they measured temperatures in the vertical plane through the centre of the condensing surface at distances of 130 mm and 290 mm

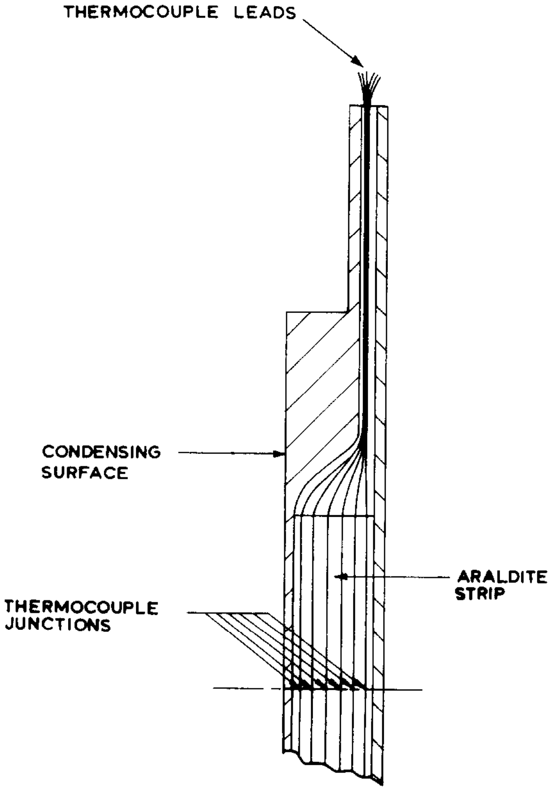


FIG. 2. Section through the condensing plate.

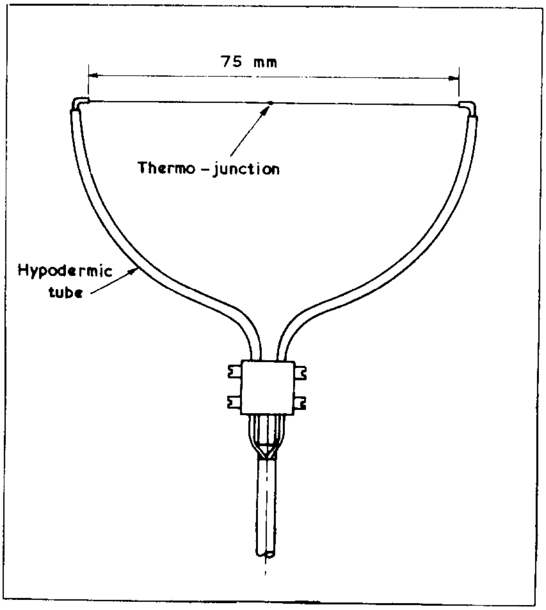


FIG. 3. The horizontally and vertically traversable thermocouple.

from the latter. The third thermocouple, shown in Fig. 3, could also be traversed in the direction normal to the condensing surface. The leads, in the vicinity of the junction, ran horizontally and parallel to the condensing surface (i.e. along isotherms) to avoid error due to conduction along the leads. Vernier scales on the vertically moveable plate facilitated measurement of temperature profiles in the vicinity of the condensing surface at different heights as well as vertical temperature distributions in the steam chamber at distances of 130 mm and 290 mm from the condensing surface.

The mean gas concentration was found using the measured quantity of injected gas, the known dimensions of the apparatus and the observed water level in the boiler. The local gas concentration, W_∞, remote from the condensing surface was calculated from the pressure and local temperature using the ideal gas mixture laws and assuming saturation conditions.

That the apparatus was satisfactorily leak-proof could be checked by operating with gas-free steam, for time intervals longer than those used in tests. If the temperature and pressure corresponded to the saturation values within the precision of the measurements then inward leakage of air was either absent or insignificant.

The procedure for measuring thermoelectric emfs and calibration of the thermocouples was the same as that described earlier [13], giving an accuracy of temperature measurement better than $\pm 0{\cdot}05$ K.

3. PROCEDURE

Before a test run, the condensing surface was first rinsed with tap water then rubbed with fine emery paper wetted with dilute sodium hydroxide solution. It was then rinsed thoroughly with tap water and finally with de-ionized water. The test plate and the cooling box were then assembled with the steam chamber. The boiler heaters were switched on to maximum power. The water was allowed to boil for at least two hours while purging the system with steam to atmosphere. The system was then closed and the coolant turned on.

A pre-determined volume of the non-condensing gas (measured at atmospheric temperature and pressure) was then injected. The boiler heaters were adjusted so as to maintain a steady pressure slightly above atmospheric. When steady conditions had become established, the readings of plate and steam chamber thermocouples, water manometer and barometer were observed.

Variation of temperature with height in the steam chamber could be observed when required by traversing the sliding plate on which the thermocouples were mounted, as could temperature profiles near the condensing surface (at different heights) by traversing the moveable thermocouple normal to the condensing surface. Different heat fluxes were obtained by varying the coolant flow rate and temperature. All tests were carried out at near-atmospheric pressure.

4. PRELIMINARY TESTS

Before filling with distilled water, the boiler and steam chamber were evacuated, when small leaks were detected and cured.

Pure steam

After de-gasing by boiling for two hours, while purging the apparatus with steam to atmosphere, the system was closed. The pressure and temperature in the steam chamber were found to correspond to saturation values to within the precision of the measurements and to remain so for the duration of the measurements. This indicated that the non-condensing gas concentration (assumed to be air) was less than 0·004.

The results of tests carried out with pure steam are shown in Fig. 4. The agreement with the simple Nusselt theory is somewhat closer than found in many earlier investigations. This may well be fortuitous. On the other hand, such factors as: the presence of significant amounts of non-condensing gases, "mixed" condensation, film rippling and turbulence, which would cause deviations from the Nusselt theory, were

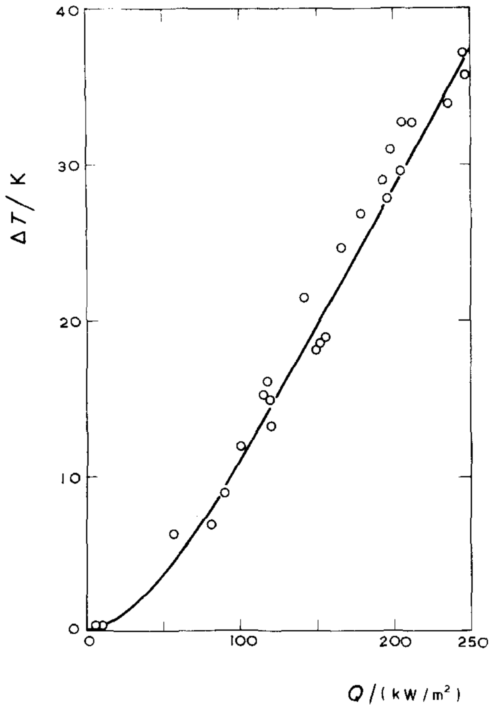


FIG. 4. Comparison of pure steam results with the simple Nusselt theory.

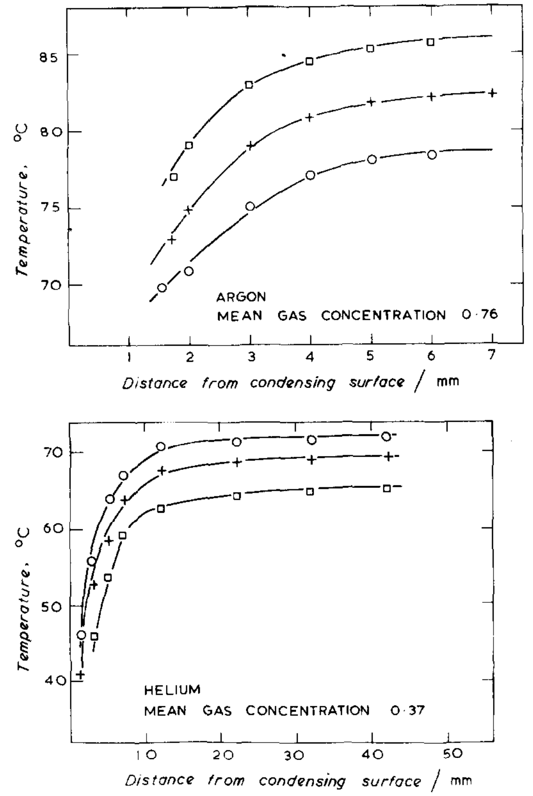


FIG. 5. Temperature profiles near the condensing surface. Distance from top edge of plate: □ 29 mm; + 49 mm; ○ 69 mm.

not present in this work. It had been intended to use the results of the experiments with pure steam as a basis for estimating the temperature drop in the condensate film for the tests with non-condensing gases. However, in view of the close agreement seen in Fig. 4, the simple Nusselt theory was used for this purpose.

Variation of temperature and gas concentration in the steam chamber

Apart from the expected temperature drop in the gas–vapour mixture near to the condensing surface, a variation of temperature with height was observed in the steam chamber. This may be seen from the typical temperature profiles shown in Fig. 5. It may be seen that in the case of argon, the temperature increases with height, whereas the reverse is true for the case of helium.

This temperature variation results from the finite dimensions of the closed steam chamber.

Condensation on the plate and, to a lesser extent, on the walls of the steam chamber, results in higher gas concentration in these regions. In the case of helium, the mean density of the mixture near the plate and walls is smaller than in the bulk, consequently there is an upward convective motion resulting in a higher gas concentration at the top of the steam chamber. The small amount of condensation on the walls of the apparatus ensures that near-saturation conditions prevail at least in the neighbourhood of the walls, and the temperature of the mixture is consequently lower in the regions where the gas concentration is higher. In the case of gases having a molecular weight greater than that of steam the mean density near the walls is larger causing a downward motion resulting in a higher gas concentration and consequently a lower temperature at the bottom of the chamber.

For the purpose of comparing the present results with theory, wherein temperature and gas concentration remote from the condensing surface were taken to be independent of height, the temperature outside the boundary layer at the mid-height of the plate was used to calculate the remote gas concentration W_∞. (It may be noted that the vertical temperature variation outside the boundary layer, between the levels of the upper and lower edges of the plate, was much smaller than the temperature drop normal to the condensing surface across the boundary layer.) The remote gas concentration calculated as described above did not differ greatly from the average gas concentration for the whole steam chamber as may be seen in Fig. 6. The increased gas concentration near the condensing surface leads to a mean concentration for the whole apparatus somewhat higher than the local value outside the boundary layer.

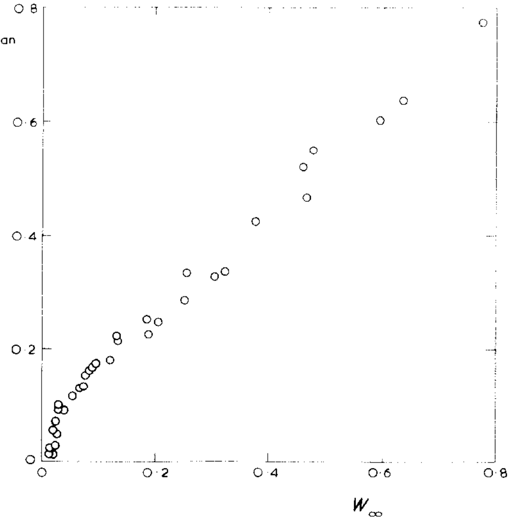


FIG. 6. Relationship between the mean gas concentration and the calculated local gas concentration outside the boundary layer at the mid-height of the condensing plate.

5. RESULTS

In Fig. 7 the fractional reduction in heat flux Q/Q_{Nu}, caused by the presence of the non-condensing gas, is plotted against the temperature difference $(T_\infty - T_w)$ between the remote gas–vapour mixture and the surface of the condensing plate, for different values of the remote gas concentration W_∞. The results given in Fig. 7 are for air, neon and argon (i.e. the gases having molecular weights exceeding that of water for which the theoretical solutions [3, 4] are relevant).

The experimental results are compared with free-convection boundary layer solutions. Numerical results for the exact solution [3] are available only for the case of air. (For air–steam mixtures, the exact [3] and approximate [4] solutions agree closely except at very small gas concentrations.) The exact solution is shown in Fig. 7 for the lowest air concentration (the theoretical line was obtained by interpolating between the results given [3] for W_∞ equal to 0·01 and 0·02). In all other cases the theoretical lines are based on the approximate solution [4]. The methods used for obtaining the relevant thermophysical properties are given in [11].

Overall comparison of the measurements and theory shows that agreement is generally satisfactory. The only significant discrepancies, for all three gases, occur at the lowest gas concentrations. These discrepancies may be due to experimental errors, since at the lowest gas concentrations Q/Q_{Nu} is very sensitive to variations in gas concentration (see Fig. 8). The variation of W_∞ with height may also have contributed to the discrepancies. It is notable that, for the case of the lowest air concentration, the exact solution [3] agrees more closely with the measurements. Thus, the discrepancies at low gas concentrations may in part result from inadequacies in the approximate solution.

In Fig. 8, Q/Q_{Nu} is plotted against W_∞ for the gases having molecular weights higher than that of steam. Fig. 8 contains results additional to those given in Fig. 7. The values of $(T_\infty - T_w)$ varied from about 5 K to about 80 K. Included

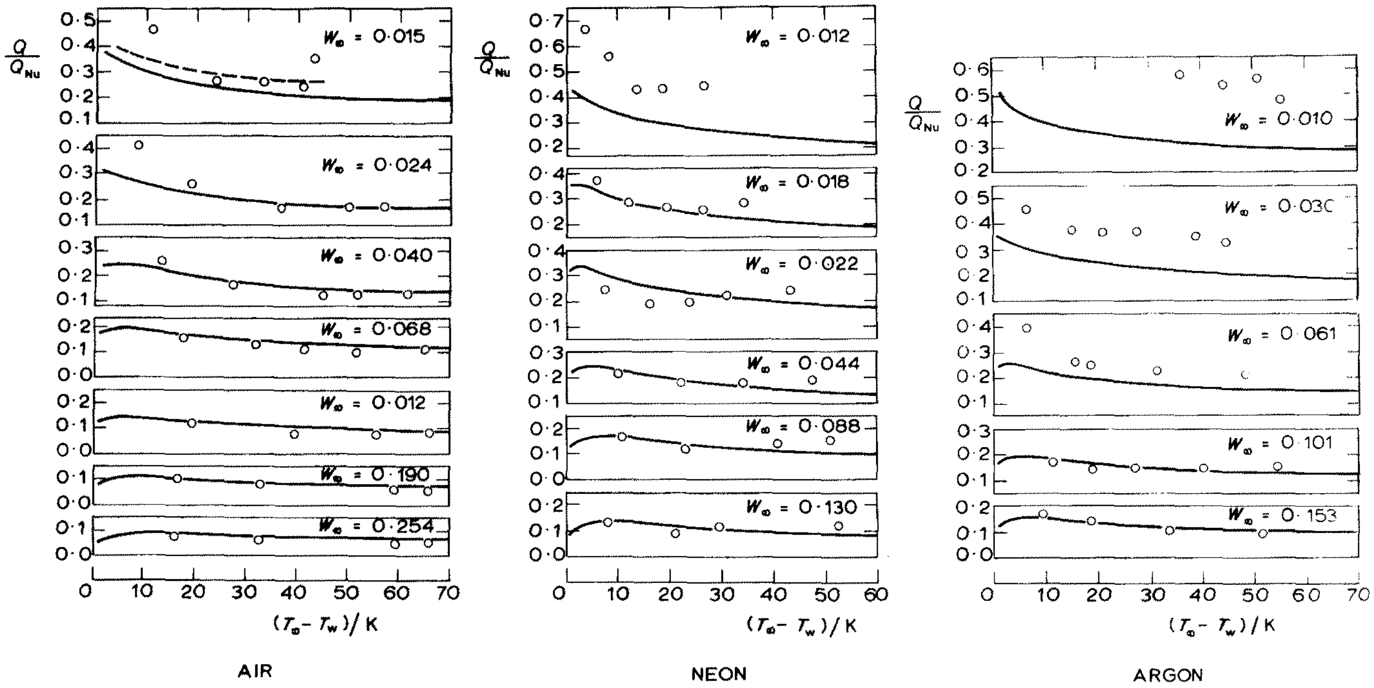


FIG. 7. Reduction in heat transfer vs vapour-to-surface temperature difference for gases with molecular weights greater than that of water.

------ exact numerical solution [3]
——— approximate integral solution [4]

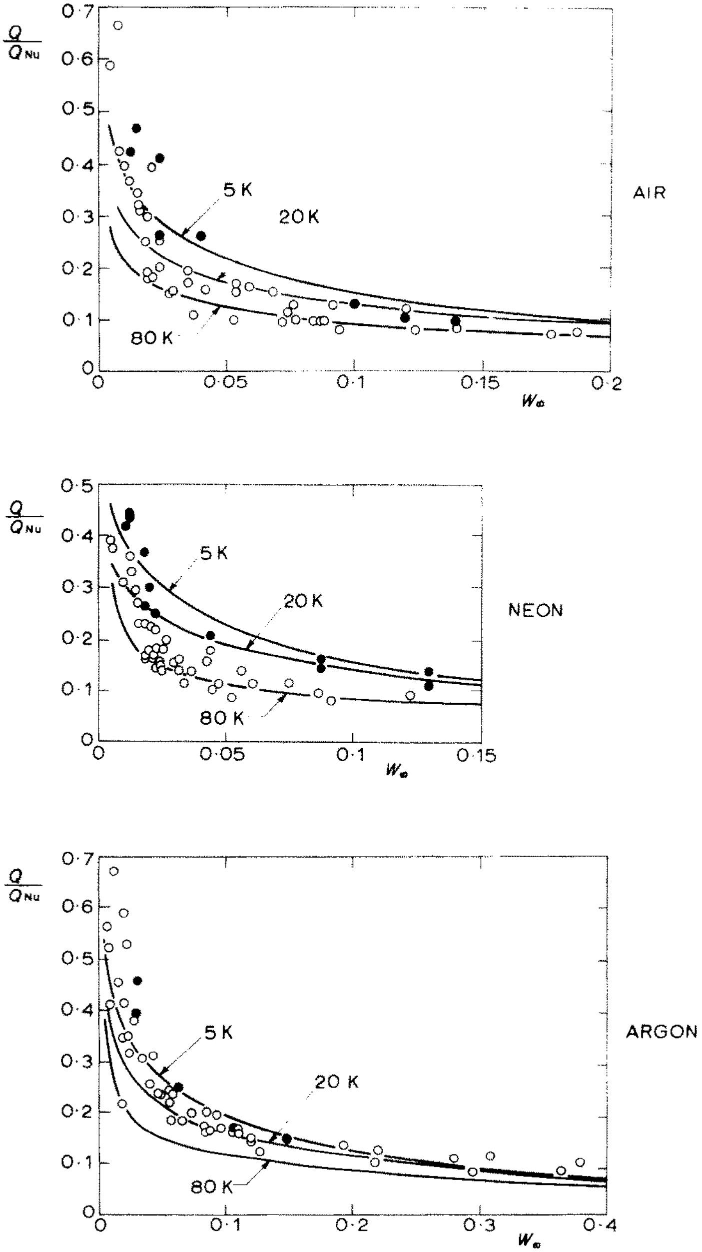
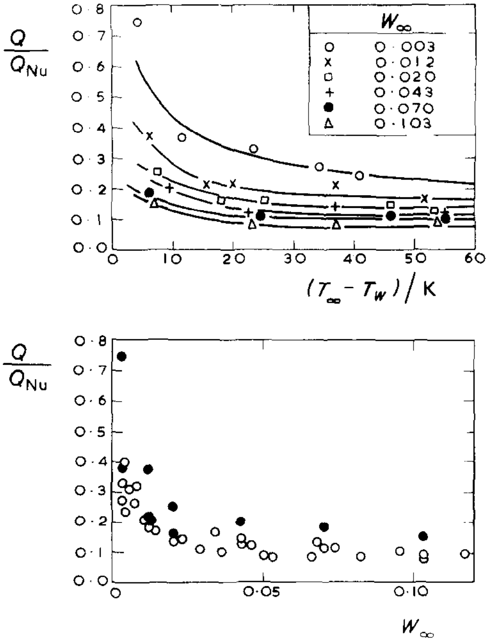


FIG. 8. Reduction in heat transfer vs non-condensing gas concentration for gases with molecular weights greater than that of water.

● $T_\infty - T_w < 20$ K
○ $T_\infty - T_w > 20$ K
—— approximate integral solution [4]

on Fig. 8 are lines given by the approximate theory [4] for three values of $(T_\infty - T_w)$. That Q/Q_{Nu} is not strongly dependent on $(T_\infty - T_w)$ is shown both by the measurements and the theoretical results. In the case of the measurements, the dependence on $(T_\infty - T_w)$ is largely masked by scatter and different symbols have been used to differentiate only between results for which $(T_\infty - T_w)$ was less than or greater than 20 K. Again, it may be seen that agreement between experiment and theory is generally satisfactory.

Figure 9 shows the results for the case of helium. The trends are the same as those found with air, neon, and argon. It may be seen that the value of Q/Q_{Nu} for a given W_∞ is somewhat smaller for the case of helium than for the gases with higher molecular weight.



● $T_\infty - T_w < 20$ K
○ $T_\infty - T_w > 20$ K

FIG. 9. Reduction in heat transfer for helium.

6. CONCLUDING REMARKS

In contrast to the earlier work on condensation of steam in the presence of nitrogen [9], and of ethanol and carbon tetrachloride in the presence of nitrogen and carbon dioxide [10], the present measurements in general lend support to the boundary layer analyses. It is thought that the substantially higher heat-transfer coefficients found in the earlier work may be due to significant forced convection.* In the case of [9] nitrogen was fed continuously to the apparatus and vented, along with excess steam, near to the bottom of the condensing plate. In the case of [10], the condensing plate was situated directly above the boiling liquid. Although a baffle, in the form of a disc, was fitted at the bottom of the test plate, this may not have been adequate to prevent significant disturbance of the flow near the plate. In the present work the steam entered the condenser chamber via the flow straightening section ensuring that the flow at entry was uniform and normal to the condensing surface.

The results of a more recent experimental investigation [5, 14], published during the course of present work, also support the boundary layer theory. These observations for air–steam mixtures were made at sub-atmospheric pressures and the results cannot directly be compared with the present work. On average the measured heat-transfer rates [5, 14] were about 20 per cent higher than predicted by the exact solution [3], and the authors [5, 14] suggest that this might have been due to forced convection effects.

To summarize, recent measurements (present and [5, 14]) where special care was taken to avoid forced convection effects, indicate that the effect of non-condensing gases in reducing condensation heat transfer is much greater than previously reported. Moreover, these measurements agree quite closely with free convection boundary layer theory.

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* Theory [7] indicates that forced convection greatly increases the vapour-side heat-transfer coefficient for condensation in the presence of a non-condensing gas.

From a practical viewpoint it is clear that the theory should provide accurate, or at least conservative, estimates of the heat-transfer. If significant forced flow is present, heat-transfer rates may be substantially higher than predicted by the free convection theory.

Finally, for the case where the molecular weight of the non-condensing gas is smaller than that of the vapour, no theoretical results are available. Since, in this case, the free convective motion in the gas–vapour mixture near to the condensing surface is upwards whereas that of the condensate is downwards, one would expect that the distances from both upper and lower edges of the plate would play a part in determining the local heat-transfer rate. Thus, in order to obtain a satisfactory correlation of such data, local measurements are needed at different distances down the plate and for various plate heights. The present results for helium–steam mixtures, as well as contributing to the data available for correlation, might be used in future investigations to check that forced convection effects were not significant.

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CONDENSATION DE VAPEUR EN FILM PAR CONVECTION NATURELLE EN PRESENCE DE GAZ NON CONDENSABLE

Résumé—On traite de mesures de transfert thermique pour la condensation de vapeur en film sur une surface plane verticale en présence d'air, d'argon, de néon et d'hélium dans les conditions de convection naturelle. Pour des concentrations données de gaz non condensables les résultats montrent de plus grandes réductions dans le transfert thermique que celles suggerées par de précédents mémoires. Les mesures présentées sont en accord satisfaisant avec les récentes analyses de couche limite.

FILMKONDENSATION VON DAMPF BEI FREIER KONVEKTION IN GEGENWART NICHT KONDENSIERBARER GASE.

Zusammenfassung—Es wird berichtet über Wärmeübergangsmessungen bei Filmkondensation von Dampf an einer vertikalen ebenen Oberfläche mit Anwesenheit von Luft, Argon, Neon und Helium bei freier Konvektion.

Die Ergebnisse deuten an, dass die Verminderungen des Wärmeübergangs bei einer vorgegebenen Gaskonzentration grösser sind, als in früheren Arbeiten berichtet wurde. Die vorliegenden Messungen stimmen zufriedenstellend überein mit neuen Grenzschichtbetrachtungen.

ПЛЕНОЧНАЯ КОНДЕНСАЦИЯ ПАРА В ПРИСУТСТВИИ НЕКОНДЕНСИРУЮЩИХСЯ ГАЗОВ

Аннотация—Приводятся сведения об измерениях теплообмена при пленочной конденсации пара на вертикальной плоской пластине для воздуха, аргона, неона и гелия в условиях свободной конвекции. Результаты указывают на более заметное снижение теплообмена при принятых концентрациях неконденсирующихся газов, чем это предполагалось ранее. Данные измерений удовлетворительно согласуются с результатами современных теоретических исследований пограничного слоя.