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EFFECT OF REGULARLY SPACED SURFACE RIDGES ON FILM CONDENSATION HEAT TRANSFER COEFFICIENTS FOR CONDENSATION IN THE PRESENCE OF NONCONDENSABLE GAS

KI. I. CHANG and DONALD L. SPENCER
University of Iowa, Iowa City, Iowa, U.S.A.

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NOMENCLATURE

$\bar{h}$, mean heat-transfer coefficient;
k, thermal conductivity;
μ, viscosity;
ρ, density;
g, acceleration of gravity;
N_{Re}, Reynolds number.

INTRODUCTION

A NUMBER of analytical and experimental condensation heat-transfer studies dealing with the influence of condensables have been reported in the literature. For example, Sparrow and Eckert [1], Sparrow and Lin [2] and Minkowycz and Sparrow [3] transformed governing equations in partial differential form into ordinary differential equations by using similarity parameters and solved them numerically. Othmer [4] and Meisenburg *et al.* [5] have showed experimentally the reduction of condensation heat-transfer coefficients for condensing steam in the presence of air.

None of the above-mentioned works, however, give information about possible instability of the flow due to the presence of noncondensables and possible secondary flow associated with the transport of noncondensables.

Spencer *et al.* [6] have reported the existence of instability phenomena, the occurrence of ridge waves and the effect of molecular weight of noncondensables on the condensation heat-transfer process. In this work, Freon 12 was used as a condensable vapor and N_2, He and CO_2 as noncondensable gases. It was reported that the condensation heat transfer coefficients are dependent on the molecular species of the noncondensable gas and also that a liquid film wave phenomenon exists peculiar to condensation in the presence of noncondensables. These waves were called "ridge waves", since wave crests were vertical rather than horizontal.

They interpreted the occurrence of ridge waves as being evidence that steady state diffusion does not take place under the condition of the experiment at sufficiently high Reynolds number, but rather that cellular motion occurs in which condensable vapor is transported in and noncondensables transported out essentially in eddy motion.

In addition, extremely low heat-transfer coefficients obtained in [6] was interpreted as an evidence of an interfacial resistance effect due to or enhanced by noncondensables.

In order to further clarify the interaction between the condensable vapor and the noncondensables and the formation of ridge waves due to noncondensables, some changes were made to the apparatus used in the above reference work. A $\frac{1}{2}$ in. wide annular brass plate was attached to the

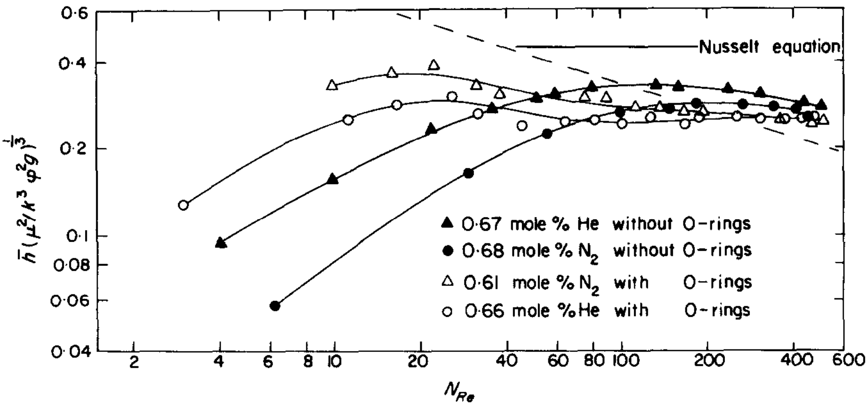

FIG. 1. Effect of O-rings on condensation heat-transfer coefficients in the presence of noncondensables.

top of the condensing cylinder and the O-rings, which were used on the condensing surface to help identify the onset of ridge waves in the previous experiment, were removed. Besides these changes, a small tangential component of feed vapor drift was eliminated by adjusting the vapor ducts inside the condensing chamber. Except for these changes, the apparatus was the same as described in [6].

DISCUSSION

Experimental heat-transfer coefficients measured without the O-ring obstruction to the flow of condensate and in the presence of N_2 and He in a dimensionless form, $\bar{h}(\mu^2/k^3\rho^2 g)^{1/3}$, are plotted vs. Reynolds number in Fig. 1. Also shown in the figure are the results by Spencer *et al.* [6] and the analytical work by Nusselt [7].

The results show the same general trend for both N_2 and He and indicate that O-rings have a considerable effect on the condensation process when noncondensables are present. Heat-transfer coefficients measured without O-rings show higher values when Reynolds number is larger than a certain limit and lower values in moderately small Reynolds number ranges as compared with the data taken with O-rings for both He and N_2 as noncondensables. In other words, data curves with different surface geometries in the presence of each noncondensable intersect each other. The two curves with He intersect around Reynolds number of 35 and those with N_2 around 150. It is very interesting to note that the above results have the same tendency as those in Fig. 2 for pure Freon 12 vapor, which is also reported in [6]. It can be seen in the figure that with 1 in. spaced O-rings up to 5 or 10 per cent higher heat-transfer coefficients for pure Freon 12 vapor are obtained when Reynolds number is above 50 and 5 or 10 per cent lower coefficients when Reynolds number is smaller than the above value. The tendency indicates that O-rings have only slight effect on the condensation heat transfer for a pure vapor and this effect is greatly magnified when noncondensables are present.

Another surprising phenomenon which can be recognized in Fig. 1 is that with O-rings the experimental data with He show higher heat-transfer coefficients than those with N_2 for same mole fraction. This is an entirely opposite trend compared with Fig. 3, which is reproduced from [6]. The results in Fig. 3 show that helium caused the most significant reduction in heat transfer and carbon dioxide the least and the nitrogen curve lies in between. The discrepancy between

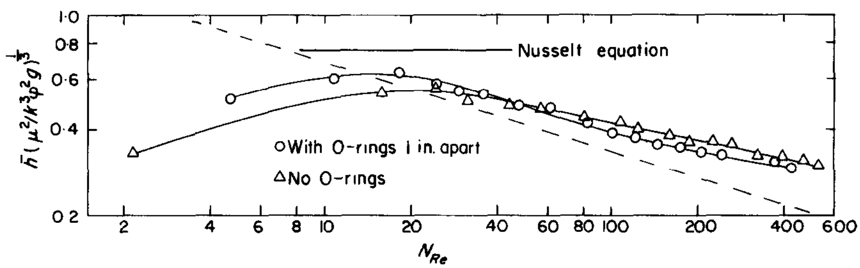

FIG. 2. Effect of O-rings on pure Freon 12 condensation heat transfer.

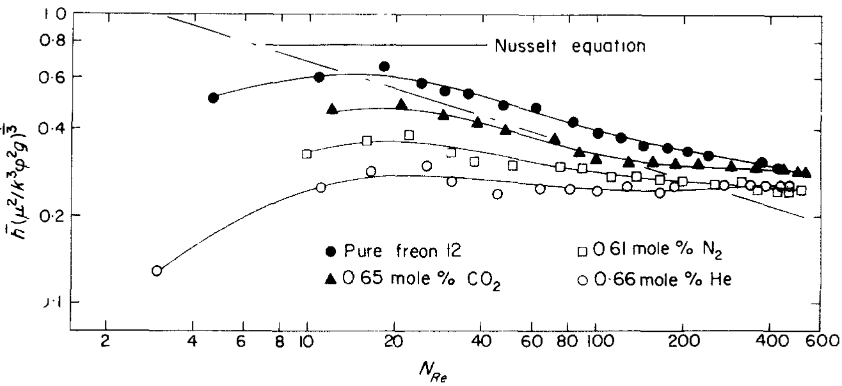

FIG. 3. Effect of molecular weights of noncondensables on heat transfer coefficients with O-rings.

two experimental results implies that condensation heat transfer depends on the condensing cylinder surface geometry as well as on the molecular weights of noncondensables. It is evident that the drastic differences in surface roughness can change the nature of the transport of noncondensables to and from the liquid–vapor interface.

Schlieren technique was used in the present condensation study. Figure 4, which was taken with about 25°F temperature difference between the condensing vapor and the condenser in the presence of He, shows that when the condensation rate is high enough, a thin layer of strikingly uniform concentration of noncondensables exists along the condensing surface rather than a diffusion boundary layer. The layer cannot be seen when Reynolds number is smaller than 50 or when no noncondensable gas is present in the condensing chamber. This indicates that a density jump occurs next to the condensate film surface when noncondensables are present and the condensation rate is fairly high. The helium moves upward within the layer due to the buoyancy effect and transported outward in eddy motion. This can be clearly seen in Fig. 5, which was taken with 1 in. spaced O-rings. This may indicate that eddy motions and perhaps vortices exist along the liquid film condensate as postulated by Spencer *et al.* [6] A small component of vapor feed velocity tangential to the condensing cylinder produced ridge waves with a uniform direction of drift velocity, while removal of this directed bulk velocity produced random directions of ridge wave drift.

The above postulation may be verified to a certain extent by the fact that generally weaker ridge waves could be observed with the top brass plate mentioned earlier. A possible explanation to this phenomenon may be as the followings: the top plate has a tendency to induce outward or "source" flow near the top where ridge waves are easily observed (no interaction with roll waves). Vortex formation is thus attenuated at the point where they can most easily be detected. However, Schlieren photographs with and without the top plate were identical except very near the top plate, i.e. the mode of transport of non-condensables was not significantly changed by the plate. Figure 6 shows the effect of the top plate on the dispersion of vertically flowing noncondensables near the top.

CONCLUSIONS

It may be inferred by various observable phenomena that the O-rings have a small effect on the condensation heat transfer for a pure vapor and this is magnified in the presence of noncondensables. At low Reynolds numbers, O-rings enhance heat transfer, while at high Reynolds numbers, resistance to heat transfer is increased. The above conclusion, however, still requires more careful analyses.

When noncondensables are present and Reynolds number is above 50, a strong, uniformly concentrated layer of noncondensable exists next to the condensate film. In addition to that, it can be assumed by Schlieren photographs that tiny vortices or eddy motions stem from an interaction between the light noncondensable layer and the heavy oncoming condensable vapor, Freon 12 and give rise to ridge waves. This can be partly verified by placing O-rings on the condensing cylinder and by attaching an annular brass plate to the top of the cylinder. The O-rings also reverses the effect of molecular weights of noncondensables on the condensation heat transfer, i.e. helium, which has lower molecular weights than N_2, causes more reduction in condensation heat-transfer coefficients than N_2 when O-rings are placed on the condensing cylinder, while the reverse is true when the O-rings are removed. This may be because of the change in significance of eddy diffusion relative to upward convection in the transport process.

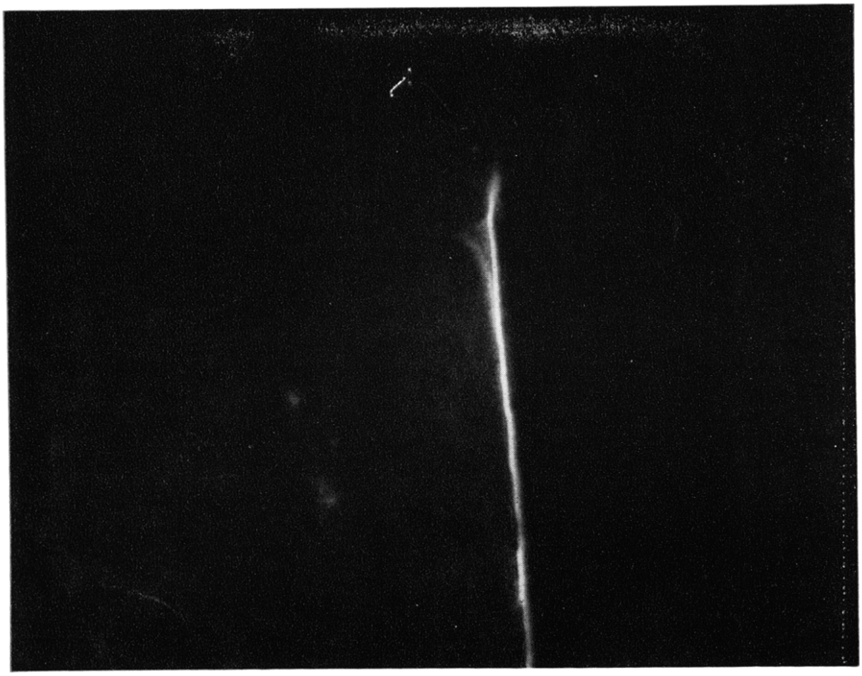

FIG. 4. Concentration layer of He next to the liquid condensate film with 25°F temperature difference.

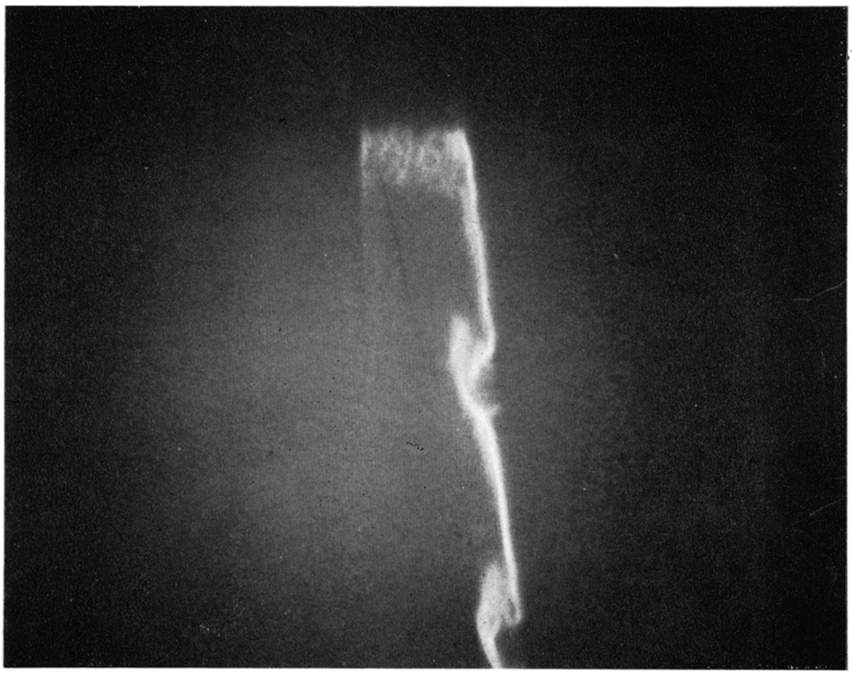

FIG. 5. Effect of O-rings on the concentration layer of noncondensables.

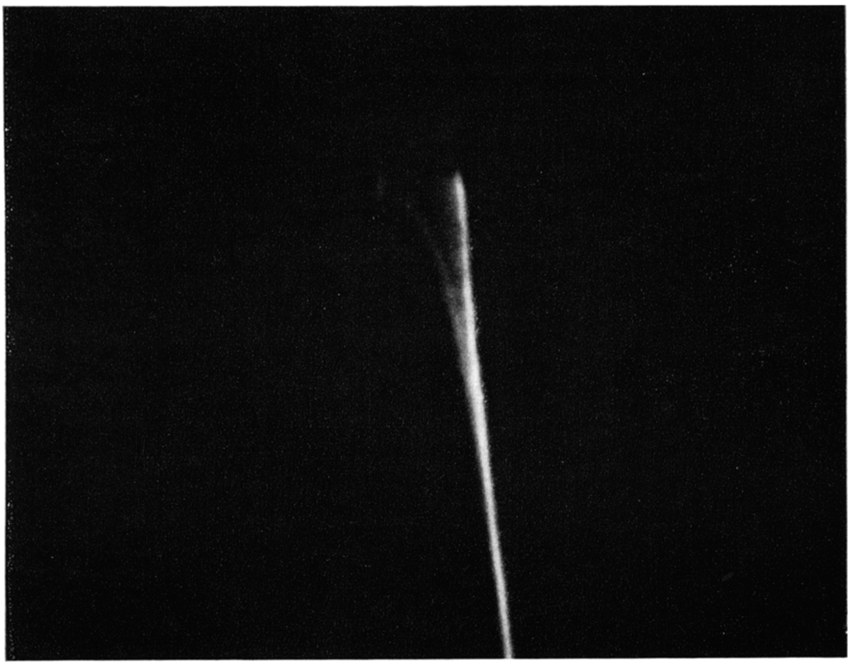

FIG. 6. Effect of the top plate on the concentration layer of noncondensables.

ACKNOWLEDGEMENT

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FREE CONVECTION HEAT TRANSFER OF A LAYER OF LIQUID HEATED FROM BELOW—THE EFFECT OF MAXIMUM DENSITY

ZU-SHUNG SUN* and CHI TIEN

Department of Chemical Engineering and Metallurgy, Syracuse University, Syracuse, New York, U.S.A.

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NOMENCLATURE

- a, dimensionless wave number in linear stability analysis;
- A, temperature difference ratio defined as $(T_1 - T_{max})/(T_1 - T_2)$;
- B, amplitude, see equations (15) and (16);
- d, depth of liquid layer;
- D, operator defined as d/dz^+;
- f, function associated with w and θ, see equations (15) and (16);
- g, gravitational acceleration;
- H, quantity associated with temperature disturbance, see equation (16);
- N_{Nu}, Nusselt number defined by equation (21);
- N_{Ra}, Rayleigh number defined as
$$\frac{2\gamma_1 A\,\Delta Tg\,\Delta Td^3}{\nu\kappa}\left(1 + \frac{3}{2}\frac{\gamma_2}{\gamma_1}A\Delta T\right);$$
- $N_{Ra_{cr}}$, critical Rayleigh number;
- P, pressure;
- $P_0(z)$, average pressure over x–y plane;
- δp, pressure variation, equation (8);
- T, temperature;
- T_{max}, temperature at which the density of the liquid is maximum;
- $T_0(z)$, average temperature over x–y plane;
- T_1, T_2, lower and upper surface temperature of liquid layer;
- ΔT, temperature difference, $T_1 - T_2$;
- u_i, velocity vector;
- W, velocity component x_3 (or z) coordinate;
- W, quantity associated with velocity disturbance, equation (15);
- x_i, coordinates.

Greek letters

- κ, thermal diffusivity;
- λ_1, λ_2, constants defined as
$$-\frac{1}{A}\,\frac{1 + 3\frac{\gamma_2}{\gamma_1}A\Delta T}{1 + \frac{3}{2}\frac{\gamma_2}{\gamma_1}A\Delta T} \text{ and } \frac{1}{A^2}\,\frac{\frac{3}{2}\frac{\gamma_2}{\gamma_1}A\Delta T}{1 + \frac{3}{2}\frac{\gamma_2}{\gamma_1}A\Delta T};$$

*Present Address: Dept. of Chemical Engineering, University of Delaware.