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CONDENSING SURFACE THICKNESS EFFECTS IN DROPWISE CONDENSATION

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NOMENCLATURE

a, droplet radius;
b, adiabatic cylinder radius;
h_c, dropwise condensation constriction conductance;
J_i, Bessel function of order i;
k, surface thermal conductivity;
k_l, condensate thermal conductivity;
q, heat flux;
r, radial coordinate;
$\hat{r}$, departing drop size;
R_c, constriction resistance, h_c^{-1};
$R_{c,\infty}$, constriction resistance for infinitely thick surface;
T, temperature;
w, surface thickness;
z, axial coordinate.

Greek symbols

α_n, eigenvalue, solution of $J_1(\alpha_n) = 0$;
ψ, approximation for infinite series of equation (1).

INTRODUCTION

RECENT theoretical and experimental work on dropwise condensation heat transfer has produced a coherent picture of the process and the various thermal resistances involved [1–4]. The existence of a finite thermal resistance associated with the nonuniformity of surface heat flux and dependent upon the thermal properties of the condensing surface has been predicted and experimentally verified [5, 6].

The purpose of the present work is twofold: (1) to present an approximate analysis for the effect of condensing surface thickness on the constriction resistance in dropwise condensation (and to modify the correlation of [5] accordingly), and (2) to examine various dropwise condensation thermal resistances as to their importance for design considerations.

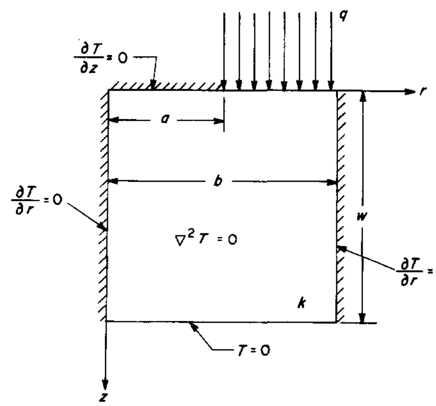

FIG. 1. Prototypical constriction resistance problem.

ESTIMATE OF THE EFFECT OF SURFACE THICKNESS ON THE CONSTRICTION RESISTANCE

Realization of the basis of the mechanism underlying the surface thermal property effect in dropwise condensation—namely, the constriction of the heat flow lines near the surface due to nonuniformity of the surface temperature—leads to the conclusion that the resulting thermal resistance depends also upon the condensing surface thickness (and possibly, the coolant-side boundary condition).

A precise general expression for the thickness dependence would be difficult to formulate. Consideration of the elemental problem shown in Fig. 1 is useful in gaining insight into the phenomenon and will allow an estimate of the thickness effect to be made. In this problem, the constriction resistance associated with a single large droplet and its accompanying active condensation area is modeled as indicated, on a cylindrical element of condensing surface of finite thickness and conductivity.

An analytical expression for the temperature field of this problem is obtainable [7]. Interpreted as a constriction conductance in series with the direct droplet conductance and the substrate conductance due to pure conduction, the result is

$$h_c^{-1} = \frac{4a^2b^3}{k(b^2-a^2)^2} \sum_{n=1}^{\infty} \frac{\tanh(\alpha_n w/b) J_1^2(\alpha_n a/b)}{\alpha_n^3 J_0^2(\alpha_n)} \qquad (1)$$

in which the eigenvalues α_n are the zeros of $J_1(x)$.

For calculation purposes, it was found that the infinite series in (1) above could be adequately approximated by the expression

$$\psi = 0.023 \frac{a}{b}\left(1 - \frac{a}{b}\right)^{1.5} \tanh(4\,w/b), \qquad (2)$$

which agrees with the result of Mikic [8] for the case $w/b \to \infty$.

There remains the task of interpreting these results in the context of dropwise condensation. The model of [5]. presents a correlation for the constriction conductance in dropwise condensation on an infinitely thick surface, for which the equations (1) and (2) can provide a modifying term to account approximately for the effect of finite thickness. It is assumed that the ratio of constriction conductances for the finite- and infinite-thickness cases will be similar for both the fundamental problem discussed above and the more complicated aggregate of adiabatic cylinder subproblems which more realistically describes the effect for dropwise condensation. Further, the departing drop size is taken as an appropriate characteristic length for constriction for the droplet distribution, a somewhat arguable but conservative assumption. The constriction conductance correlation thus obtained is

$$\frac{h_c \hat{r}}{k} = 11.2\left(\frac{k}{k_l}\right)^{-0.07} [\tanh(4w/\hat{r})]^{-1}. \qquad (3)$$

A comparison of the present estimate of the thickness effect with a prior independently derived approximation [4] is shown in Fig. 2.

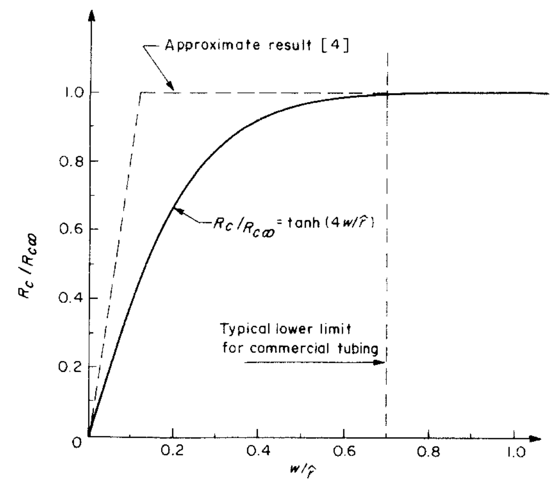

FIG. 2. Comparison of thickness effect estimates.

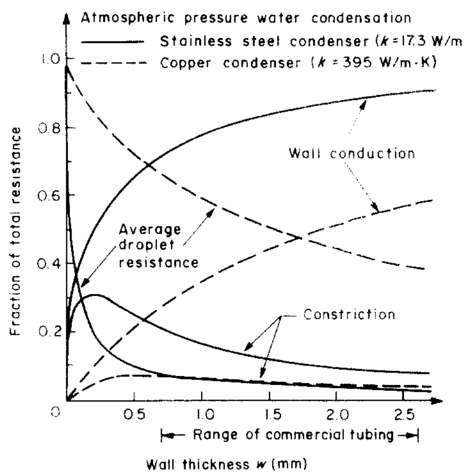

FIG. 3. Comparison of resistances in dropwise condensation.

THE MAGNITUDE OF VARIOUS THERMAL RESISTANCE IN DROPWISE CONDENSATION

The ultimate goal of heat-transfer analysis and experimentation is the facilitation of the design of useful equipment. To this end, it is appropriate to consider a comparison of the magnitude of various resistances in dropwise condensation—specifically, the distribution-averaged droplet resistance, the constriction resistance, and the wall conduction resistance. These resistances are in series with each other and with the coolant-side resistance, which will not be explicitly considered here.

The discussion is framed in terms of Fig. 3, which presents a calculation of the contribution of each of the thermal resistances versus condenser wall thickness for two materials (stainless steel and copper, which bracket the expected range of wall thermal conductivities) in atmospheric pressure dropwise condensation of steam. Here the wall conduction resistance was taken as the ratio of wall thickness to thermal conductivity (thereby ignoring curvature effects); the droplet resistance was taken as $0.441 \times 10^{-5}\ m^2\,K/W$, a suitable value for steam condensation; and the constriction resistance was calculated using equation (3) with parameters appropriate for atmospheric pressure dropwise condensation of steam.

Over the range of wall thicknesses characteristic of commercially-available condenser tubing [9], it can be seen that for copper, the wall conduction and droplet resistances are of similar magnitude, with the constriction resistance being of lesser import. For stainless steel surfaces, wall conduction alone is the predominant resistance, with the constriction resistance being substantially larger than the droplet conduction resistance.

For design purposes, then, in the light of the existence of a finite coolant-side conductance and the possible importance of ancillary resistances (such as those due to noncondensable gases and promoter layer conduction), both the constriction resistance and the droplet resistance can be ignored for standard stainless steel surfaces, while for copper surfaces in the same thickness range the wall conduction resistance and the droplet resistance must both be considered.

While it thus appears that the constriction effect will always be of minor importance in the overall heat-transfer resistance (even though it is the major component of the steamside resistance for low-conductivity surfaces), it cannot be neglected for thin condensing surfaces of low conductivity material (possible for geometries other than the standard condensing tube) and perhaps for dropwise condensation of fluids other than water (e.g. liquid metals, for which the constriction resistance may be limiting).

CLOSURE

In the present work, an estimate for the effect of condensing surface thickness on the dropwise condensation heat-transfer coefficient was developed utilizing an analytical solution for a prototypical heat conduction problem. This estimate was incorporated into a previously developed correlation for the dropwise condensation constriction conductance.

The relative importance of various dropwise condensation resistances was assayed from the design standpoint. Designers of advanced, high performance heat transfer surfaces should be particularly cognizant of the possible importance of the constriction resistance in dropwise condensation for thin, low conductivity surfaces.

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