paratus function. The arc plasma jet is a versatile ground device to simulate re-entry plasma over large temperature ranges with high velocities. The rotational temperature has been measured in the plasma jet wind tunnel and by changing the electric power in the arc, the possibility to tune the temperatures is demonstrated.

Acknowledgments

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Analytical Investigation of the Rewetting of Grooved Surfaces

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Nomenclature

c = specific heat of the plate
G = mass flux
h_f = liquid latent heat
k = conductivity of the plate
Q = total heat input
q'' = heat flux
R = groove radius
T = temperature
U = average velocity of the liquid
α = thermal diffusivity
δ = thickness of the plate
ρ = density

Subscripts

l = liquid
max = maximum
w = wetting

Introduction

RECENT developments in high-density electronic components and two-phase heat rejection systems for spacecraft thermal control have focused attention on the problems associated with heat transfer in the thin film region. Of particular interest are the rewetting characteristics of heated plates, determination of the maximum heat flux a plate with a given film thickness can sustain, and the rate at which a liquid will rewet a surface once all of the liquid has evaporated. Several investigations have been conducted to determine the rewetting characteristics of liquid films on heated surfaces. Shires et al.[1] experimentally investigated the rewetting characteristics of liquid on the outer surfaces of heated rods. Elliot and Rose[2] confirmed the experimental results of Shires et al., but found that the wetting front velocity U_w to be independent of the liquid flow rate. Several other researchers[3,4] investigated the effects of mass flux, flow quality, thermal properties of both the cooling liquid and the heated surface, and surface characteristics of heated surface on the rewetting rates for both the inside and outside of circular tubes. In two separate investigations, Ueda et al.[5,6] studied the rewetting characteristics of a falling liquid film on the surface of a hot stainless steel tube, both theoretically and experimentally.

In addition to the investigations into the rewetting characteristics of heated rods and tubes, several investigations have been conducted to evaluate the rewetting of liquid flowing over a flat plate. Bankoff[7] and Orell and Bankoff[8] conducted analytical investigations of dryout and rewetting of thin liquid films flowing on flat heated plates and Stroes et al.[9] experimentally investigated the heat-flux-induced dryout and rewetting in thin films, focusing on the effects of film thickness, flow rate, and inclination angle.

Although these investigations have provided substantial experimental data and considerable insight into the behavior of thin films on both circular tubes and flat plates, no general physical model exists that is capable of describing the governing phenomena or the behavior of the liquid in this region. In order to understand better the rewetting characteristics of liquid flowing over a heated plate with parallel grooves, a physical model was developed and an analytical expression for the rewetting velocity as a function of the fluid properties, the physical geometry, and the applied heat flux was derived.

Development of the Physical Model

Although liquid flow and heat transfer on rough surfaces is considerably more complex than flow on smooth surfaces, one of the principal areas of interest to the designers of high-capacity heat pipes for spacecraft applications is the rewetting behavior of thin liquid films on heated grooved surfaces. For this type of flow, the rewetting may be assisted or hindered by gravity, depending upon the gravitational vector. It has been previously shown[10] that the liquid film thickness has a significant effect on the rewetting and heat transfer characteristics, however in the application of interest here—the evaporator section of high-capacity heat pipes—the liquid film only fills the grooves; that is, for a wetting fluid, the level of liquid is never higher than the surface of the grooved plate,

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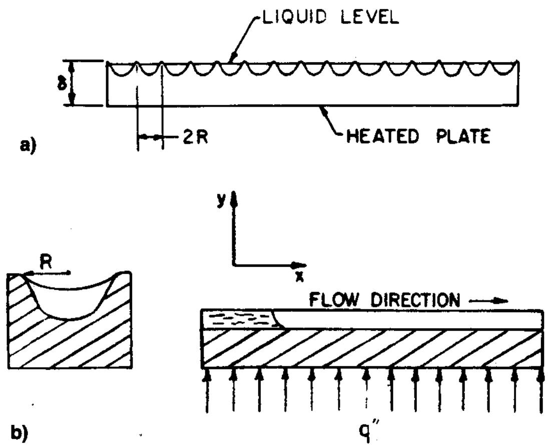

Fig. 1 Analytical model.

as shown in Fig. 1a. This allows each parallel groove to be evaluated independently.

In the current investigation, the rewetting liquid front is assumed to advance along the surface of a plate to which a heat flux q'' has been applied. The advancing liquid film cools and wets the heated surface of the grooved plate. At the leading edge of the advancing wetting front, some of the liquid is vaporized and the remaining liquid advances with a velocity U_w, known as the wetting front velocity. The heat required to vaporize the liquid is supplied by conduction from the dry, hot zone of the plate. Two things are intuitively apparent: first the wetting velocity for an unheated plate U is higher than for a heated plate, because in the latter case, some of the liquid is vaporized; second, when dryout occurs, not all of the heat supplied to the plate is absorbed by the vaporization of the liquid.

The analytical model utilized in this investigation is illustrated in Fig. 1b. To solve this problem, the liquid was assumed to be supplied to the edge of the plate at a constant velocity and the conduction equation for the plate was transformed to a coordinate system moving with the wetting front at a velocity U_w. In addition, several other fundamental assumptions were made. These can be summarized as follows:

1) Conduction heat transfer through the plate is one-dimensional.

2) The heat flux supplied to the bottom of the plate is uniform.

3) The thermophysical properties of liquid and plate are assumed to be constant.

4) The grooves on the plate are located immediately adjacent to one another and the groove radius is much smaller than the plate thickness ($R/\delta < 0.1$).

5) The liquid temperature at the rewetting front is different from the rewetting temperature, which is assumed to be constant and equal to the saturation temperature of the liquid. As a result, the sensible heat absorbed by the liquid can be neglected.

6) The convective heat transfer between the plate and air (or vapor) along with the radiation between the hot surface and the surroundings is neglected.

Utilizing these assumptions, the conduction equation for the plate, yields

$$k\frac{\partial^2 T}{\partial x^2} + \frac{q''}{\delta} = +\rho c\frac{\partial T}{\partial t} \tag{1}$$

or

$$k\frac{\mathrm{d}^2 T}{\mathrm{d}x^2} + \frac{q''}{\delta} = \rho c U_w\frac{\mathrm{d}T}{\mathrm{d}x} \tag{2}$$

The general solution of Eq. (2) is

$$T = C_1 + C_2\exp\left[\frac{\rho C U_w x}{k}\right] + \frac{q''x}{\rho C U_w \delta} \tag{3}$$

$$\frac{\mathrm{d}T}{\mathrm{d}x} = C_2\left(\frac{\rho C U_w}{k}\right)\exp\left[\frac{\rho C U_w}{k}x\right] + \frac{q''}{\rho C U_w \delta} \tag{4}$$

When $x \to \infty$, $\mathrm{d}T/\mathrm{d}x \to \infty$, this is physically impossible which implies that $C_2 = 0$. At the rewetting front, however, the plate temperature can be assumed to be equal to the Leidenfrost or wetting temperature; that is, $x = 0$, $T = T_w$, and using this condition, a solution can be derived as

$$T(x) = T_w + \frac{q''}{\rho C U_w \delta}x \tag{5}$$

From this, the total heat conduction at $x = 0$ can be found as

$$Q = \left(2R\delta - \frac{1}{2}\pi R^2\right)k\left.\frac{\mathrm{d}T}{\mathrm{d}x}\right|_{x-0}$$

$$\approx 2R\delta k\left.\frac{\mathrm{d}T}{\mathrm{d}x}\right|_{x-0} = \frac{2Rq''\alpha}{U_w} \tag{6}$$

Because the total heat conduction in the region of the wetting front is equal to the energy absorbed by the vaporization of the liquid

$$Q = \tfrac{1}{2}(U - U_w)\rho_L \pi R^2 h_f \tag{7}$$

Combining Eqs. (4) and (5) and rearranging yields

$$U_w^2 - UU_w + \frac{4q''\alpha}{\pi R\rho_l h_f} = 0 \tag{8}$$

Solving this expression for the rewetting velocity yields

$$U_w = \frac{1}{2}\left[U \pm \sqrt{U^2 - \frac{16q''\alpha}{\pi R\rho_l h_f}}\right] \tag{9}$$

To satisfy the physical constraints, the correct solution occurs when the second term of Eq. (9) is positive. Hence, the rewetting velocity is

$$U_w = \frac{1}{2}\left[U + \sqrt{U^2 - \frac{16q''\alpha}{\pi R\rho_l h_f}}\right] \tag{10}$$

Analysis and Discussion

When the surface temperature of a grooved plate is higher than the rewetting temperature T_w and the heat flux is below the maximum value, the rewetting velocity is given by Eq. (8). It is clear from this expression that the rewetting velocity is closely related to the heat flux, the groove radius, and the thermal properties of both the liquid and the plate. Equation (8) provides theoretical evidence to support the conclusions presented by several previous experimental investigations. Furthermore, the wetting conditions of a grooved plate, or the existing real roots of Eq. (6), should be

$$U^2 - \frac{16q''\alpha}{\pi R\rho_l h_f} \geq 0 \tag{11}$$

Hence, the limiting condition or maximum heat flux under which rewetting can occur is

$$q_{\max} = \frac{\pi R\rho_l h_f}{16\alpha}U^2 \tag{12}$$

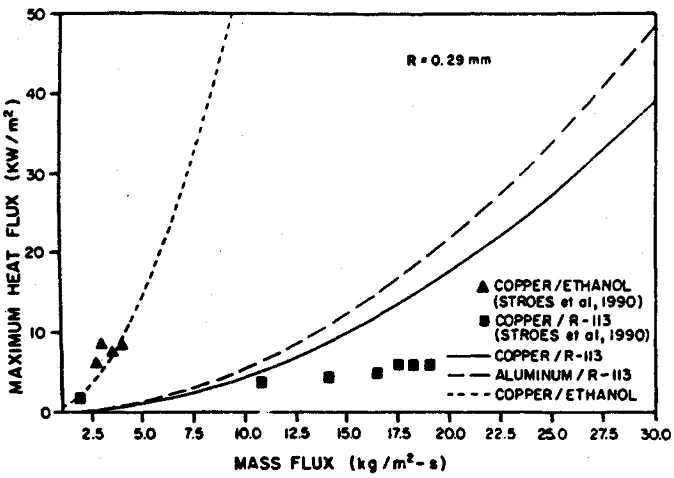

Fig. 2 Comparison of experimental and predicted values for a grooved plate, R = 0.29 mm.

Writing the liquid velocity U in terms of the mass flux G, Eqs. (8) and (10) can be rewritten as

$$U_w = \frac{1}{2}\left[\left(\frac{G}{\rho_l}\right) + \sqrt{\left(\frac{G}{\rho_l}\right)^2 - \frac{16q''\alpha}{\pi R \rho_l h_f}}\right] \qquad (13)$$

$$q_{\max} = \frac{\pi R \rho_l h_f}{16\alpha\rho_l} G^2 \qquad (14)$$

Therefore, for a given mass flux and groove radius, the rewetting heat flux can not exceed the value described by Eq. (10), otherwise the liquid supplied will be unable to provide sufficient cooling to allow the surface to rewet. It is also apparent from Eq. (10) that $q''_{\max}$ is a function of the thermal properties of both the liquid and the heated plate and also of the mass flux, proposed but not verified by Iloeje et al.[4]

It is worthy to note that Eqs. (8) and (10) are for a given mass flux. If the liquid flowing in the grooves is driven only by capillary pressure or surface tension, as is the case in heat pipes and capillary pumped loops, the liquid mass flux or velocity can be found from the transport equations and determined as a function of the capillary pressure difference caused by the groove radius. In this type of situation, the rewetting velocity will be somewhat more complicated.

The relationship between the maximum heat flux and the mass flux is illustrated in Fig. 2 for several different liquid/material combinations. To determine the accuracy of this analytical solution, experimental data from the investigation of Stroes et al.[9] are also illustrated. Although these data were obtained for thin liquid films on flat copper plates, the thickness of the thin film and the radius of the grooves utilized in this solution are comparable, making it acceptable for comparison. As illustrated, the experimentally obtained rewetting heat flux values for R-113 and denatured alcohol films on copper plates are in reasonably good agreement with the theoretical values obtained using Eq. (12). However, as the mass flux becomes larger, the difference between the measured and predicted values diverge significantly.

Conclusion

A physical model has been developed and a theoretical investigation conducted to determine the rewetting characteristics of thin liquid films flowing over a flat grooved plate. An expression for the rewetting velocity as a function of the thermal properties of the liquid and the plate, the input heat flux to the plate, and the groove radius has been derived analytically. The analytically predicted maximum heat flux as a function of the mass flux has been compared with the experimental data of other investigators and shown to agree reasonably well at low mass flux levels. The theoretical analyses presented here also demonstrates the effects of variations in the geometry and structure on rewetting, and supports the conclusions proposed by several other investigators who have studied the effect of wick structures on rewetting in high capacity heat pipes.

The resulting expressions for predicting the rewetting conditions and limits will aid in the design of many types of heat exchangers, and also in the design of the evaporator portion of heat pipes designed for use on future spacecraft. Finally, additional experimental investigations are required to evaluate further the validity of the theoretical analyses presented here.

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Flowfield Analysis for High-Enthalpy Arc Heaters

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Introduction

FOR more than two decades, electric arc jets have provided heat-transfer simulations of hypersonic flight en-

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