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# EVAPORATION ON/IN CAPILLARY STRUCTURES OF HIGH HEAT FLUX TWO-PHASE DEVICES

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## ABSTRACT

Two-phase devices (heat pipes, capillary pumped loops, loop heat pipes, and evaporators) have become recognized as key elements in thermal control systems of space platforms (ref. 1). Capillary and porous structures are necessary and widely used in these devices, especially in high heat flux and zero-g applications, to provide fluid transport and enhanced heat transfer during vaporization and condensation. However, some unexpected critical phenomena, such as dryout in long heat pipe evaporators and high thermal resistance of loop heat pipe evaporators with high heat fluxes, are possible and have been encountered in the use of two-phase devices in the low gravity environment. Therefore, a detailed fundamental investigation is proposed to better understand the fluid behavior in capillary-porous structures during vaporization at high heat fluxes. The present paper addresses some theoretical aspects of this investigation.

## INTRODUCTION

Miniature flat heat pipes with axial micro grooves, shown in figure 1, are intended for the cooling systems of electronic components (ref. 2). Both capillary and boiling limitations are found to be important for flat miniature copper-water heat pipes with external dimensions of  $2 \times 7 \times 120$  mm and plain axial micro grooves on the inner surface which can have width of only 0.1 mm. Flat miniature heat pipes are capable of withstanding heat fluxes on the order of  $40 \text{ W/cm}^2$  applied to the evaporator wall (refs. 3 and 4). Higher heat fluxes are possible with the use of porous materials in addition to grooved structures as shown in figure 1(c). The enhanced copper-water flat heat pipe with axial grooves and a porous coating on the lands between the grooves can operate at a maximum heat flux in the evaporator of  $80 \text{ W/cm}^2$  in the horizontal orientation (ref. 5). Heat fluxes of up to  $200 \text{ W/cm}^2$  on evaporator walls of miniature heat pipes are achievable with the "inverted meniscus"-type evaporators (refs. 6 and 7).

While heat transfer during evaporation of liquid from capillary-grooved surfaces was considered by many investigators (refs. 8 to 11), their analyses were done for comparatively small heat fluxes. In all above mentioned papers, the variation of temperature of the liquid free surface along the microfilm in modeling of evaporative heat transfer on capillary-grooved surfaces was emphasized. Khrustalev and Faghri (ref. 11) took into consideration the existence of surface roughness and its influence on evaporative heat transfer. The film surface curvature,  $K$ , was expressed in terms of the solid surface curvature,  $K_w$ , and film thickness and formation of the thin liquid evaporating film was considered. Accounting for the roughness of the solid surface in the thin evaporating film region resulted in a decrease of the heat transfer coefficient by up to about 30% in comparison to

that obtained for a smooth surface for the case when the accommodation coefficient was set equal to unity. For  $\alpha \ll 1$  the influence of surface roughness on the evaporative heat transfer coefficient was insignificant. The simplified model of evaporative heat transfer, where it was assumed that the free film surface curvature in the microfilm region was equal to that in the meniscus region, predicted values of the heat transfer coefficient only up to 5% smaller in comparison to the case where the curvature variation along the film was taken into account (for  $\alpha = 1$ ). The value of the local evaporative heat transfer coefficient (for a fixed meniscus contact angle) was practically independent of the heat flux on the evaporator external wall. It should also be noted that Khrustalev and Faghri (refs. 4 and 11) found that their predictions of the effective evaporative heat transfer coefficient matched the existing experimental data only for very small values of the accommodation coefficients, for example,  $\alpha = 0.05$ . With small accommodation coefficients, the role of the thin-film region of the evaporating meniscus is smaller than with  $\alpha = 1$  because of the interfacial thermal resistance.

### HIGH FLUX EVAPORATION FROM LIQUID-VAPOR MENISCI

The main objective of the proposed theoretical effort is to identify the importance of various physical phenomena in initiating critical mechanisms in capillary structures with high heat fluxes. With high heat fluxes, some additional physical phenomena can be important in evaporative heat transfer from liquid-vapor menisci. Some examples include:

1. Fluid flow effects, neglected in the previous evaluations of the effective evaporative heat transfer coefficient, can significantly alter its value.
2. Shear stresses induced on the liquid-vapor interface by thermocapillarity and complex two- or three-dimensional vapor flow can cause the recession of the evaporating liquid meniscus in a groove (or pore) and lead to an unstable mode of operation in the axially-grooved evaporator.
3. The existence of thick liquid films attached to the extended evaporating meniscus in a capillary tube, recently observed in the experiments by Belonogov and Kiseev (ref. 12), can significantly change the existing methods in the prediction of dryout in capillary-driven devices.

In the zero-gravity environment, these phenomena can be more important than in the gravity field.

### Fluid flow in evaporating films and liquid-vapor menisci

A cross section of the liquid-vapor evaporating meniscus is given in figure 2(a). In the previous attempts, the liquid flow in the meniscus region and the vapor flow were neglected. The evaporation of liquid from the meniscus liquid-vapor interface mainly takes place in the thin-film region. This means that the corresponding injection of mass into the vapor space can induce recirculation of vapor over the interface due to strong asymmetry of the hydrodynamical problem in consideration, as shown in figure 3. The vapor flow along the liquid-vapor interface causes a shear stress in the liquid which can be as important as that produced by thermocapillarity.

For an incompressible fluid with constant vapor and liquid viscosities and densities depending on temperature, two-dimensional continuity and momentum equations for both vapor and liquid should be solved along with the energy equation. The mass, energy, and momentum energy balances should be satisfied at the liquid-vapor interface. Such two-dimensional problems, describing the evaporating meniscus in a narrow slot between two parallel walls, should include the evaporating microfilm model by Khrustalev and Faghri (ref. 11). A special control volume should be developed

in the numerical model containing the liquid evaporating microfilm. The liquid flow in this microfilm is driven mainly by the surface tension and the disjoining pressure.

$$\frac{dp_\ell}{ds} = -\sigma \frac{dK}{ds} + \frac{dp_d}{ds} - K \frac{d\sigma}{dT_\delta} \frac{dT_\delta}{ds} + \frac{d}{ds} (\rho_v^2 u_{v,\delta}^2) \left( \frac{1}{\rho_v} - \frac{1}{\rho_\ell} \right) \quad (1)$$

where  $K$  is the local interface curvature,  $p_d$  is the disjoining pressure and the last term is the kinetic reaction of the evaporating fluid pressure.

The temperature of the interface,  $T_\delta$ , is affected by the disjoining and capillary pressures, and also depends on the value of the interfacial resistance. The relation between the vapor pressure over the thin evaporating film,  $(p_{\text{sat}})_\delta$ , affected by the disjoining pressure, and the saturation pressure corresponding to  $T_\delta$ ,  $p_{\text{sat}}(T_\delta)$ , is given by the extended Kelvin equation (ref. 1). The liquid free surface saturation pressure,  $(p_{\text{sat}})_\delta$ , is different from the normal saturation pressure,  $p_{\text{sat}}(T_\delta)$ , and varies along the thin film (or  $s$ -coordinate). This is also due to the fact that  $T_\delta$  changes along  $s$ .

### Formation of thick liquid evaporating films

In the recent experiment by Belonogov and Kiseev (ref. 12), thick evaporating films ( $\delta > 1 \mu\text{m}$ ) attached to the evaporating menisci of various liquids in a glass capillary tube were observed using a microcamera (figure 2(b)). The length of these thick films were several diameters of the capillary tube. This discovery can have a significant influence on the understanding of the evaporation of liquid from capillary tubes or porous structures. Explanation of the thick films existence by Belonogov and Kiseev (ref. 12) was consistent with that by Volintine and Wayner (ref. 13) where a mixture of two liquids was investigated with a surface tension gradient along the evaporating thick liquid film. Present efforts, however, are focused on evaporation of a pure liquid in a circular microchannel in the vicinity of a hemispherical liquid-vapor meniscus as shown in figure 2(b). It is assumed that thick liquid films can exist due to frictional vapor-liquid interaction at high rates of evaporation. A steady state mathematical model developed includes coupled vapor and liquid flows. The momentum conservation for viscous flow in a liquid film is expressed by the Stokes approximation.

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w_\ell}{\partial r} \right) = \frac{1}{\mu_\ell} \frac{dp_\ell}{dz} \quad (2)$$

The boundary conditions are a no-slip condition at  $r = R$  and shear stresses at the liquid-vapor interface due to the frictional liquid-vapor interaction and surface tension gradient related to the interfacial temperature gradient along the channel.

$$w_\ell|_{r=R} = 0 \quad \frac{\partial w_\ell}{\partial r}|_{r=R-\delta} = \frac{1}{\mu_\ell} \left( -\frac{d\sigma}{dT} \frac{dT_\delta}{dz} - \mu_v \frac{\partial w_v}{\partial r}|_{r=R-\delta} \right) \quad (3)$$

Note that thick films inevitably end with the microfilm, therefore the microfilm model should be included in the thick-film problem. One essential feature of the thick film model should be mentioned here: due to the cylindrical geometry, the equation for the local curvature of the liquid-vapor interface contains the term directly related to the thickness of the liquid film. The pressure difference between the vapor and liquid phases is due to capillary and disjoining pressure effects.

$$p_v - p_\ell = \sigma \left\{ \frac{d^2 \delta}{dz^2} \left[ 1 + \left( \frac{d\delta}{dz} \right)^2 \right]^{-3/2} + \frac{1}{R - \delta} \cos(\text{atan} \frac{d\delta}{dz}) \right\} - p_d \quad (4)$$

The cosine term in the right-hand side of this equation is due to the second principal radius of the interfacial curvature for a cylindrical film. Therefore, the film surface curvature  $K$  increases with the liquid film thickness while the local heat flux through the liquid film decreases, which can make thick liquid films stable. It is possible that the existence of these thick films can directly affect thermal resistance of high heat flux evaporators in the zero-gravity environment. This problem is also important because it is closely related to the concept of the available capillary pressure developed by a porous structure and supporting fluid circulation in capillary-driven devices.

## CONCLUSION

High flux evaporation from liquid-vapor menisci can result in some additional effects compared to the low flux case such as recirculation zones in vapor, changes in effective heat transfer coefficients, and thick liquid films attached to the evaporating meniscus. Investigation of these effects is needed to better understand critical mechanisms in high heat flux capillary-driven devices.

## Nomenclature

$K$	curvature [1/m]
$p$	pressure [Pa]
$p_d$	disjoining pressure [Pa]
$s$	coordinate along the liquid-solid interface [m]
$T$	temperature [K]
$T_w$	temperature of the solid-liquid interface [K]
$u_{v,s}$	vapor blowing velocity [m/s]
$v$	velocity along the $y$ -coordinate [m/s]
$w$	velocity along the $z$ -coordinate [m/s]
$x, y, z$	coordinates [m]

### Greek symbols

$\delta$	film thickness [m]
$\mu$	dynamic viscosity [Pa-s]
$\rho$	density [kg/m <sup>3</sup> ]
$\sigma$	surface tension [N/m]

### Subscripts

$\ell$	liquid
$v$	vapor
$w$	wall
$\delta$	liquid film free surface

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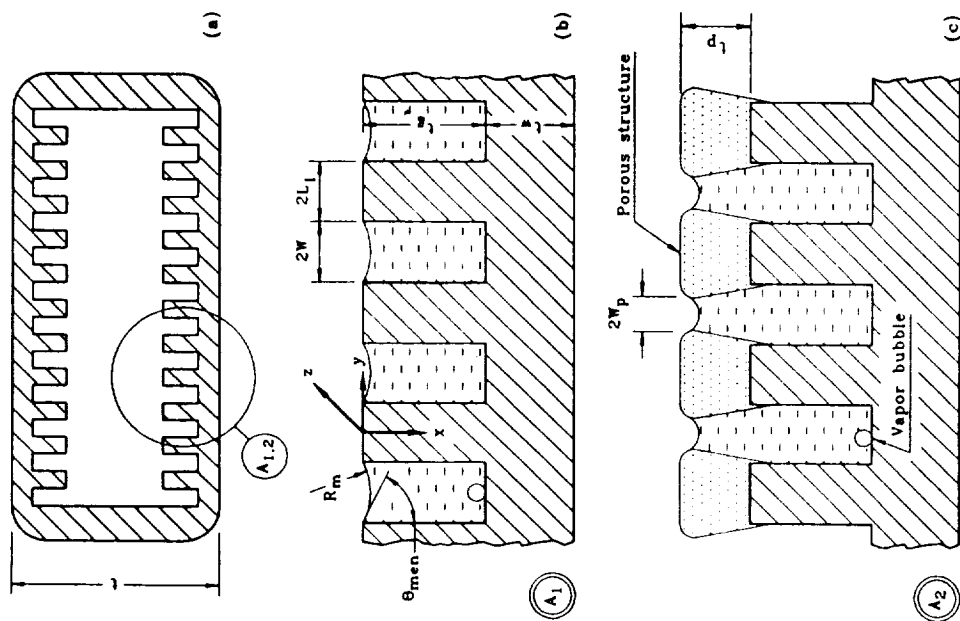


Fig. 1: Cross sections of high heat flux heat pipes: (a) flat miniature heat pipe, (b) plain capillary grooves, and (c) grooves with porous coating

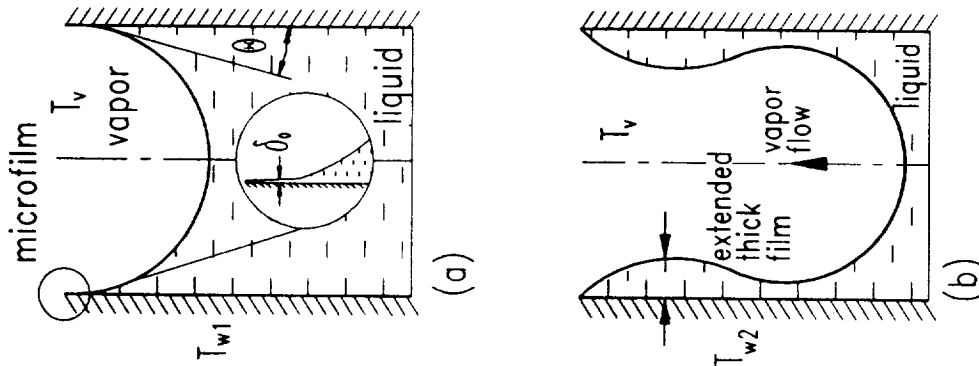


Fig. 2: Evaporation of liquid from cylindrical pores: (a) at low evaporation rates, and (b) at high evaporation rates

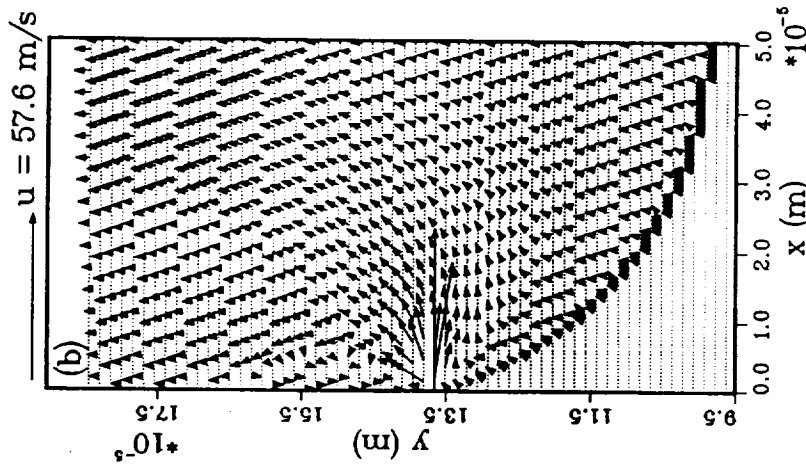


Fig. 3: Vapor flow over evaporating liquid-vapor meniscus (water,  $T_w - T_v = 10$  K)