Acceleration-Induced Depriming of External Artery Heat Pipes

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Nomenclature

A = channel area
a = acceleration
b = thickness of liquid film
H = length of liquid column
h = length of liquid film
L = length of heat pipe
m = mass
R = radius
U = average velocity
u = velocity of the liquid film
V = volume of liquid
$\dot{V}$ = volumetric flow rate
v_x = velocity through the slot
δ = width of the slot
μ = absolute viscosity
σ = surface tension
τ = time

Subscripts
1 = liquid flow channel
2 = slot
3 = vapor flow channel

Analysis

TWO external artery heat pipes are currently under consideration for use as radiator elements on Space Station Freedom.[1,2] Both of these utilize a liquid and vapor channel connected by a longitudinal slot to provide axial pumping, Fig. 1. Although previous analytical[3] and experimental[4] investigations have demonstrated that these heat pipes will prime properly in a zero-g environment, little is known about the effect of accelerations caused by orbital attitude adjustments or docking maneuvers. These accelerations, particularly longitudinal accelerations, could result in redistribution of the working fluid and dryout of the evaporator. This would require a reduction in the evaporator heat flux to allow rewetting. In the present work, an analytical investigation was conducted to determine what reduction in heat flux would be required and the effect of short-term longitudinal accelerations on the liquid/vapor interface. Assuming the heat pipe is properly primed and operating normally in a zero-g environment, the most damaging accelerations will be those occurring along the longitudinal axis because these are most likely to deprime the liquid channel. When the magnitude and/or duration of the acceleration is sufficient, liquid will flow out of the liquid channel through the connecting slot and accumulate in the end of the liquid and vapor channels, opposite the direction of acceleration. Because this flow may occur quite rapidly, some of the liquid may remain in the slot or adhere to the surface of the liquid and vapor channels forming a thin liquid film flowing along the length of the heat pipe. Although the flow of liquid out of the liquid channel and into the vapor channel is the most significant, the flow

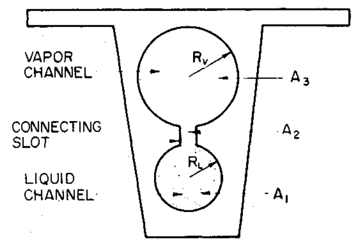

Fig. 1 Typical external artery heat pipe configuration.

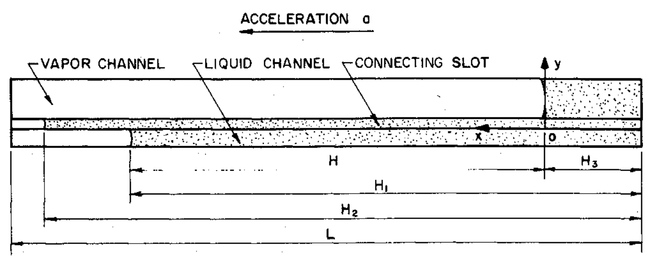

Fig. 2 Location of the liquid level in the liquid channel, vapor channel and connecting slot.

of liquid in the slot and the flow of the thin film on the surface of the liquid and vapor channels must also be evaluated.

The inertial force resulting from the longitudinal acceleration along with the surface tension forces induced by the capillary radius existing in the liquid channel and the slot separating the two channels, will determine the location and movement of the majority of the working fluid. The liquid configuration at some time τ after the onset of the acceleration is illustrated in Fig. 2, where H_1 and H_3 are the length of the liquid column in the liquid and vapor channels, respectively. Although when properly charged and primed, H_3 would be zero, there may be some liquid located at the far end of the condenser region due to overcharging. In order to evaluate how the liquid configuration varies with time, a coordinate system was selected with origin at the location of the liquid level in the vapor channel. At any position x, an energy balance of the form

$$\rho_l a(H - x) - \frac{2\sigma}{R_1} - \frac{2\sigma}{R_2} = \frac{1}{2}\rho_l v_x^2 \tag{1}$$

can be written where v_x is the velocity of the liquid flowing out of the liquid channel and into the vapor channel. This velocity distribution for the flow can be written as

$$v_x = \left[2a(H - x) - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{1/2} \tag{2}$$

Because of surface tension, there exists a position H' such that when $x \geq H'$, the velocity v_x, is equal to 0. From Eq. (2), it is apparent that this occurs when

$$H' = H - \frac{2\sigma}{\rho_l a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{3}$$

The volumetric flow rate at any time τ can be written as

$$\dot{V}(\tau) = \int_0^{H'} \delta v_x \, dx$$
$$= \delta \int_0^{H'} \left[2a(H - x) - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{1/2} dx \tag{4}$$

where δ is the width of the slot connecting the liquid and vapor channels. Integrating and rearranging yields

$$\dot{V}(\tau) = \frac{\delta}{3a}\left[2aH - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{3/2} \tag{5}$$

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Clearly, the change in volume of the liquid in the liquid channel can be expressed by continuity as

$$\mathrm{d}V(\tau) = -A_1\,\mathrm{d}H_1 = \dot{V}(\tau)\,\mathrm{d}\tau \qquad (6)$$

and also, by conservation of mass

$$A_1\,\mathrm{d}H_1 = -A_3\,\mathrm{d}H_3 \qquad (7)$$

Defining H as the difference in the length of the liquid column in the liquid and vapor channel yields

$$H = H_1 - H_3 \quad \text{or} \quad \mathrm{d}H = \mathrm{d}H_1 - \mathrm{d}H_3 \qquad (8)$$

and combining Eqs. (7) and (8) yields

$$\mathrm{d}H = \left(1 + \frac{A_1}{A_3}\right)\mathrm{d}H_1 \qquad (9)$$

Substituting Eqs. (6) and (9) into Eq. (5), results in an expression for H as a function of time:

$$\frac{-A_1A_3}{A_1 + A_3}\,\mathrm{d}H = \frac{\delta}{3a}\left[2aH - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{3/2}\mathrm{d}\tau \qquad (10)$$

If the heat pipe is properly charged; that is, no overcharge, $H = L$ at $\tau = 0$ and Eq. (10) becomes

$$H(\tau) = \frac{1}{2a}\left[\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau + \left[2aL - \frac{4\sigma}{\rho_l}\cdot\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{-1/2}\right]^{-2} + \frac{2\sigma}{\rho_l a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (11)$$

Differentiating yields

$$\mathrm{d}H = -\frac{1}{a}\left\{\frac{\delta(A_1 + A_2)}{3A_1A_3}\tau + \left[2aL - \frac{4\sigma}{\rho_l}\cdot\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{-1/2}\right\}^{-3}\mathrm{d}\left[\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau\right] \qquad (12)$$

and substituting Eq. (13) into Eq. (9) yields an expression for the change in the length of the liquid column in the liquid channel:

$$\mathrm{d}H_1 = \frac{-A_3}{a(A_1 + A_3)}\left\{\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau + \left[2aL - \frac{4\sigma}{\rho_l}\cdot\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{-1/2}\right\}^{-3}\mathrm{d}\left[\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau\right] \qquad (13)$$

Integrating yields an expression for the liquid column length as a function of time:

$$H_1 = L + \frac{A_3}{2a(A_1 + A_3)}\left\{\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau + \left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{-1/2}\right\}^{-2} - \frac{A_3}{2a(A_1 + A_3)}\cdot\left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right] \qquad (14)$$

Similarly, the length of the liquid column in the vapor channel can be expressed as

$$H_3 = L - \frac{A_1}{2a(A_1 + A_3)}\left\{\frac{\delta(A_1 + A_3)}{3A_1A_3}\tau + \left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]^{-1/2}\right\}^{-2} - \frac{A_3}{2a(A_1 + A_3)}\left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right] - \frac{2\sigma}{\rho_l a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (15)$$

As discussed previously, flow also occurs in the slot separating the liquid and vapor channels, and in the thin film on the surface of the liquid and vapor channels. The liquid flow in the slot was assumed to behave as one-dimensional laminar flow between two parallel plates, hence the momentum equation can be written as

$$\mu_l\frac{\mathrm{d}^2u}{\mathrm{d}a^2} = a\rho_l \qquad (16)$$

where $u = 0$ at $z = 0$ and $u = 0$ at $z = \delta$.

Integrating yields an expression for the local velocity in the x-direction in the slot; that is

$$u = -\frac{\delta^2}{2\mu_l}(a\rho_l)\left[\frac{z}{\delta} - \left(\frac{z}{\delta}\right)^2\right] \qquad (17)$$

The average velocity in the slot can then be found by integrating with respect to z

$$U_2 = \frac{1}{\delta}\int_0^\delta u\,\mathrm{d}z = -\frac{\delta}{2\mu_l}(a\rho_l)\int_0^\delta\left[\frac{z}{\delta} - \left(\frac{z}{\delta}\right)^2\right]\mathrm{d}z = -\frac{\delta^2}{12\mu_l}(a\rho_l) \qquad (18)$$

and the length of the liquid column in the slot h_2 can be written as

$$h_2 = L + U_2\tau = L - \frac{\delta^2}{12\mu_l}(a\rho_l)\tau \qquad (19)$$

Because the liquid film on the surface of the liquid channel is thin compared to the liquid channel radius, the film may be assumed to behave as flow over a flat plate. The resulting force balance yields

$$\mu_l\frac{\mathrm{d}^2u}{\mathrm{d}y^2} = a\rho_l \qquad (20)$$

where $u = 0$ at $y = 0$ and $\mathrm{d}u/\mathrm{d}y = 0$ at $y = b$. Combining and integrating yields an expression for the velocity of the liquid film in the x-direction of

$$u = \frac{b^2}{2\mu_l}(a\rho_l)\left[\left(\frac{y}{b}\right)^2 - 2\left(\frac{y}{b}\right)\right] \qquad (21)$$

When the liquid film initially forms, the film region is stationary and only inertial and capillary forces act upon it. The thickness of this liquid film can be approximated by R_l. Integrating yields an expression for the average film velocity in

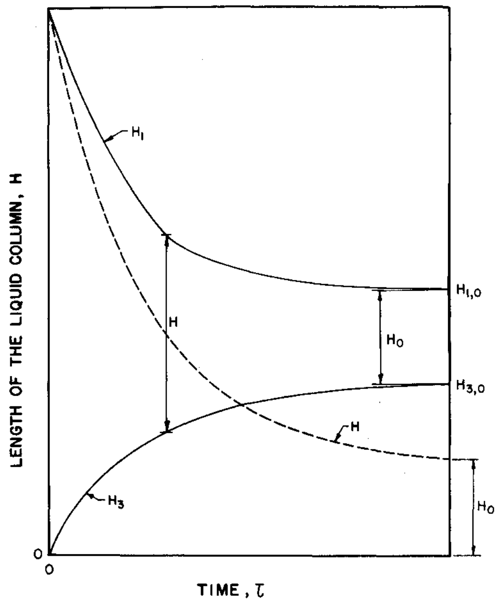

Fig. 3 Liquid position as a function of time for the liquid channel, the vapor channel, and the connecting slot.

the liquid channel of

$$U_1 = \frac{1}{2\pi R_l b}\int_0^b u 2\pi R_l\,dy = \frac{1}{b}\int_0^b \frac{b^2}{2\mu_l}(a\rho_l)\left[\left(\frac{y}{b}\right)^2 - 2\frac{y}{b}\right]dy = -\frac{b^2}{3\mu_l}(a\rho_l) \tag{22}$$

Substituting, as before, results in expressions for the length of the liquid film in the liquid and vapor channels of

$$h_1 = L + U_1\tau = L - \frac{R_l^2}{3\mu_l}(a\rho_l)\tau \tag{23}$$

and

$$h_3 = L + U_3\tau = L - \frac{R_3^2}{3\mu_l}(a\rho_l)\tau \tag{24}$$

respectively. Using Eqs. (14), (15), (19), (23), and (24) the location of the liquid vapor interface in the liquid channel, vapor channel, and connecting slot, along with the interface for the wall films in both the liquid and vapor channels can all be determined for a constant acceleration applied over some time interval.

Conclusion

Figure 3 illustrates the change of the liquid column lengths in the liquid and vapor channels H_1 and H_3, respectively, along with the difference between the two all as a function of time, τ. As illustrated, when H_1 decreases, H_3 experiences a corresponding increase. This results in the accumulation of the liquid in the end of the heat pipe opposite the direction of acceleration. If a constant acceleration is maintained for a sufficient period of time, both H_1 and H_3 will approach a constant value. If Eqs. (11), (14), and (15) are evaluated as the time over which the acceleration is applied approaches infinity; i.e., $\tau \rightarrow \infty$, the following relationships result:

$$H_{1,0} = L - \frac{A_3}{2a(A_1 + A_2)}\left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right] \tag{25}$$

$$H_{3,0} = L - \frac{A_3}{2a(A_1 + A_2)}\left[2aL - \frac{4\sigma}{\rho_l}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right] - \frac{2\sigma}{\rho_l a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{26}$$

and

$$H_0 = \frac{2\sigma}{\rho_l a}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{27}$$

Equations (25) and (26) illustrate that the final length of the liquid column in both the vapor and liquid channels depends not only upon the time and magnitude of the acceleration and properties of the working fluid, but also on the geometric parameters of the heat pipe.

Obviously, the distribution of the working fluid in an operating heat pipe during periods of acceleration is of critical importance in determining the operational limits and performance characteristics. For the case of longitudinal accelerations, one of two situations will occur: either the evaporator will be completely flooded (i.e., when the evaporator region of heat pipe is opposite the direction of acceleration) or the evaporator will dryout (i.e., when the evaporator end is toward the acceleration). For the latter case, dryout of the circumferential wall grooves may result in a need for significant reductions in evaporator heat fluxes to permit rewetting of the circumferential grooves.

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Combined Conjugated Heat Transfer from a Scattering Medium

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Introduction

IN this paper conjugated heat transfer from a convecting and radiating fluid in a reflecting rectangular channel is investigated. The model is representative of many high-temperature engineering problems commonly encountered in fur-

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