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Theoretical model for fast bubble growth in small channels with reference to startup of capillary pumped loops used in spacecraft thermal management systems

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A B S T R A C T

A capillary pumped loop (CPL) is a closed two-phase loop in which capillary forces developed in a wicked evaporator passively pump the working fluid over long distances to dissipate heat from electronic and power sources. Because it has no moving parts and requires minimal power to sustain operation, the CPL is considered an enabling technology for thermal management of spacecraft. While the steady-state operation of a CPL is fairly well understood, its thermal response during startup remains very illusive. During the startup, initial vapor bubble growth in the evaporator is responsible for liquid acceleration that results in a differential pressure spike. A large pressure spike can deprime the evaporator by forcing vapor into the evaporator's liquid-saturated wick, which is the only failure mode of a CPL other than fluid loss or physical damage to the loop. In this study, a numerical transient 3D model is constructed to predict the initial bubble growth. This model is used to examine the influence of initial system superheat, evaporator groove shape and size, and wick material. A simplified model is also presented which facilitates the assessment of parametric influences by analytic means. It is shown how these design parameters may be optimized to greatly reduce the bubble growth rate and therefore help prevent a deprime.

1. Introduction

1.1. Thermal management challenges of spacecraft

Two-phase cooling systems have been widely examined for thermal management of electronic devices in terrestrial applications. By capitalizing upon the merits of latent heat exchange, the performance of these systems is far superior to those of their single-phase counterparts. Another key advantage of a two-phase cooling system is the ability to tackle appreciable variations in the dissipated heat flux corresponding to only mild changes in the device temperature [1].

Spacecraft pose very unique challenges that are mostly the result of operating environment, which influences every aspect of the heat acquisition, transport and rejection. Waste heat from the electronic assemblies is transported to radiator panels that reject the heat by radiation to deep space. Long distances between the electronic assemblies and radiator panels preclude the use of conventional heat pipes. Mechanical pumps, which are essential to most two-phase cooling loops, are also undesirable in spacecraft because they can consume a significant fraction of a spacecraft's limited "power budget." Furthermore, spacecraft are designed for 10 years or more of maintenance-free operation, precluding the use of moving parts that are prone to mechanical failure.

1.2. Spacecraft thermal management using capillary pumped loops

Capillary pumped loops (CPLs) are two-phase systems designed to transport heat over a length of up to tens of meters for heat rejection from one or multiple heat sources. A CPL is a closed fluid loop in which capillary forces developed in a wicked evaporator passively pump the working fluid through the rest of the loop with no energy required other than the heat that the loop acquires and rejects. Fig. 1 shows a schematic of a basic CPL. Heat from the electronic sources is conducted through a metal flange to the outer wall of the CPL's evaporator. During normal operation, the working fluid enters the evaporator in liquid state, where it extracts the waste heat by evaporation. The fluid exits the evaporator in vapor state and flows to the condenser (which is attached to radiator panels) where it is converted back to liquid state. A reservoir is used to maintain excess fluid inventory for the CPL and may be thermally controlled to set the loop's saturation temperature and pressure.

The evaporator is by far the most critical component of the CPL because it provides the pressure rise necessary to pump the fluid throughout the loop. In its most basic form, the evaporator consists of a grooved cylindrical metal shell that encases a porous, annular wick as illustrated in Fig. 2. The incoming liquid fills the center of

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Nomenclature

A area
A_{gr} cross-sectional area of groove
c parameter defined in Eq. (13b)
c_p specific heat
D_h hydraulic diameter of groove
$f_i(\vec{r})$ initial temperature distribution function
h_{fg} latent heat of vaporization
k thermal conductivity
k_G geometric mean thermal conductivity
L_0 initial vapor length in groove
P pressure
P_{gr} perimeter of groove's cross-section
P_w wetted perimeter of groove in contact with liquid-saturated wick
$q''(z,t)$ heat flux into vapor-filled portion of groove in analytical model
$q''_{gr}(\vec{r},t)$ heat flux into vapor-filled portion of groove
$q''_s(t)$ surface heat flux for conduction from semi-infinite medium
$\vec{r}$ position vector
t time
T temperature
T_{sat} saturation temperature
ΔT_{sh} initial evaporator superheat
$\dot{V}_g(t)$ volumetric growth rate of vapor in groove
z axial coordinate
$z_g(t)$ vapor length in 3D model
$\dot{z}_g(t)$ axial vapor growth rate in 3D model
$Z_g(t)$ vapor length in simplified analytical model
$\dot{Z}_g(t)$ axial vapor growth rate in simplified analytical model
$Z_g^{-1}(z)$ inverse function of $Z_g(t)$

Greek symbols
α thermal diffusivity
Γ_1 interface between metal wall and vapor-filled portion of groove
Γ_2 interface between wick and vapor-filled portion of groove
ρ density
ρ_g density of saturated vapor
φ wick porosity

Subscripts
f liquid in wick voids
i evaporator subdomains defined in Fig. 5 (i = 1–4)
s solid material of wick
sat saturation

the evaporator, and is drawn radially outwards through the wick. The liquid evaporates at the wick's boundary in the grooves of the metal wall, where menisci are formed. The capillary pressure rise across these menisci is responsible for circulating the fluid throughout the CPL. The metal wall's grooves serve as vapor flow passages for the evaporator.

Several attributes render the CPL an enabling technology for thermal management of spacecraft [2,3]. These include requiring minimal external power to sustain operation, ability to passively transfer the heat over long distances while incurring negligible temperature changes, very low vibration levels, general simplicity, and, in the absence of moving parts, the potential for long life [2–5]. While some terrestrial applications may someday utilize CPLs, the presence of a gravity field can adversely affect thermal performance; hence, CPLs are better suited for space operation.

1.3. CPL startup concerns

Reliable operation of a CPL in the manner described in the previous section requires that only liquid be present in the liquid transport line and reservoir line, and in the evaporator core and wick. This ensures continuous liquid supply to the wick–groove boundary where evaporation takes place. Any vapor or gas bubbles in the "liquid side" of a CPL may eventually result in a *deprime*, which is ultimately the only failure mode of a CPL other than fluid loss or physical damage to the loop. The presence of non-condensible gases poses serious startup challenges [5–7]. Here, evaporation into a bubble containing non-condensible gases can occur at a temperature below the pure fluid's saturation temperature corresponding to the system pressure [8]. These non-condensible gas issues are beyond the scope of the present study.

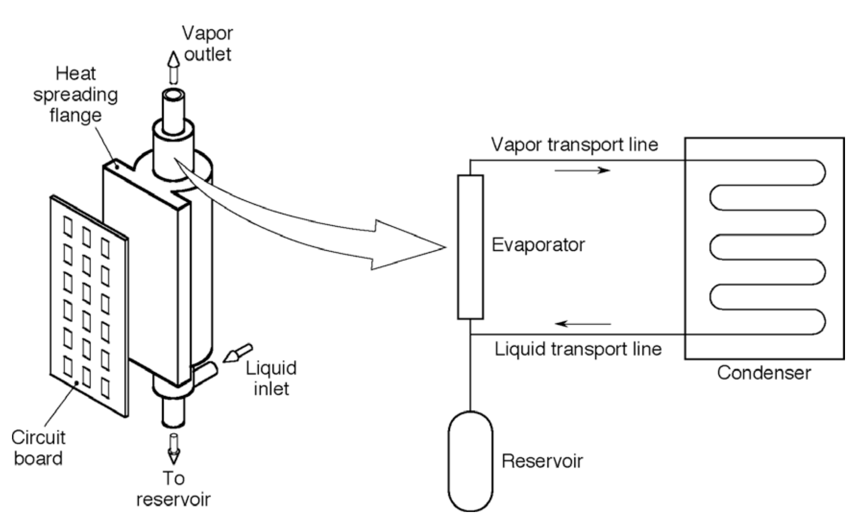

Fig. 1. Basic CPL configuration and circuit board attachment to tubular CPL evaporator.