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Transient characteristics of flow boiling in large micro-channel heat exchangers

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ABSTRACT

This study investigates both time-averaged and transient characteristics of large area micro-channel evaporators incorporated into an R-134a vapor compression loop that simulates thermal control for future space vehicles. The loop contains two separate micro-channel evaporators, one to simulate heat acquisition from the spacecraft crew and the other from the avionics. Both evaporators feature parallel $1 \times 1\text{-mm}^2$ micro-channels, with the smaller crew evaporator yielding relatively low qualities, and the larger avionics evaporator both low and high qualities. Heat transfer measurement and high speed video are used to investigate variations of heat transfer coefficient with quality for different mass velocities and heat fluxes, as well as transient fluid flow and heat transfer behavior. Relatively low qualities in the crew evaporator are dominated by slug flow and the nucleate boiling mechanism. On the other hand, the avionics evaporator produces different flow regimes and heat transfer mechanisms depending on quality range, with low qualities associated with slug flow and dominated by nucleate boiling, and high qualities by annular flow and convective boiling. Further increases in quality trigger incipient dryout of the annular film and transition to mist flow. An important transient phenomenon that influences both fluid flow and heat transfer is a liquid wave composed of remnants of liquid slugs from the slug flow regime. The liquid wave serves to replenish dry wall patches in the slug flow regime and to a lesser extent the annular regime. Two-phase flow in the two evaporators shows clear signs of parallel-channel instability.

1. Introduction

1.1. Implementation of vapor compression loop in spacecraft Thermal Control Systems (TCSs)

Managing heat dissipation in future manned space missions is complicated by anticipated increases in power consumption and waste heat dissipation [1]. The heat dissipation onboard spacecraft is managed with the aid of a Thermal Control System (TCS), which is tasked with heat acquisition from crew and avionics, heat transport to a condenser/radiator, and heat rejection from the radiator. And while past spacecraft have relied on single-phase liquid TCS, there is now serious interest in using two-phase TCS to capitalize on weight reductions made possible by greatly improved heat transfer performance realized with flow boiling and condensation.

Aside from the need to manage greatly increased amounts of heat, future spacecraft are expected to tackle different types of missions (e.g., missions to near Earth objects, Lunar surface, Martian surface, and deep space), with vastly different gravitational as well as temperature environments [2]. The latter can be classified into ‘cold’ environments, associated with heat sink temperatures that are lower than that of the TCS working fluid, and ‘warm’ environments, where the heat sink temperature exceeds that of the working fluid. While cold environments allow heat rejection from the TCS condenser/radiator using a pumped two-phase loop, warm environments necessitate the use of a vapor compression heat pump to reject the heat. Two specific mission stages that require vapor compression are Low Lunar Orbit (LLO) and Low Mars Orbit (LMO), with heat sink temperatures as high as 17 and 22 °C, respectively, both exceeding the lowest coolant temperature in the TCS evaporators of about 5 °C [2].

To tackle both cold and warm environments, Singh and Hasan [3] proposed the concept of a reconfigurable TCS that could operate as a pumped two-phase loop in cold environments, or a vapor compression loop in warm environments. Lee et al. [2] investigated the thermodynamic performance of this Hybrid Thermal Control System (H-TCS) for different space missions and identified R134a as optimum working fluid. The present study concerns the heat pump configuration of a H-TCS. Addressed in this study are dominant

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Nomenclature

A_{base}	total base area of heat sink
C_n	complex Fourier coefficient
C_n^*	complex conjugate Fourier coefficient
D_h	hydraulic diameter
F	frequency
$\hat{f}$	discrete Fourier transform
$\hat{f}^*$	complex conjugate of discrete Fourier transform
f_k	complex form of Fourier series
G	mass velocity
h	enthalpy
H_{ch}	micro-channel height
h_{fg}	latent heat of vaporization
H_{tc}	distance between thermocouple and bottom of micro-channel
h_{tp}	local two-phase heat transfer coefficient
j	superficial velocity
k	thermal conductivity
L	length of micro-channel
m	fin parameter
$\dot{m}$	total mass flow rate of heat sink
N	total number of measurement points
P	pressure
P	average power spectrum
q''	heat flux based on total base area of heat sink
Re	Reynolds number
Su	Suratman number
T	temperature
ΔT_{sat}	wall superheat, $\Delta T_{sat} = T_{w,b} - T_{sat}$
u	fluid velocity
$\bar{u}$	average fluid velocity
W_{ch}	micro-channel channel width
We^*	modified Weber number
W_w	half-width of copper sidewall separating micro-channels
x_e	thermodynamic equilibrium quality
x_k	sampling point in time
X_{tt}	turbulent–turbulent Lockhart–Martinelli parameter
z	axial coordinate

Greek symbols

δ	film thickness
η	fin efficiency
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

air	air
avionics	avionics HX
b	bottom of micro-channel
ch	micro-channel
cor	corrected
crew	crew HX
f	liquid
g	vapor
in	micro-channel inlet
lf	liquid film
Nyq	Nyquist frequency
ONB	onset of nucleate boiling
out	micro-channel outlet
s	solid (copper); sampling
sat	saturation
tc	thermocouple
tp	two-phase flow
w	micro-channel wall

flow patterns and heat transfer mechanisms associated with flow boiling in H-TCS evaporators.

Several schemes are available to dissipate heat by boiling [4], and while these schemes offer competing advantages and disadvantages, micro-channel boiling is ideally suited for spacecraft applications because of such factors as ability to achieve very high heat transfer coefficients, greatly decrease system weight and volume, reduce fluid inventory, tackle heat input from multiple heat sources, and minimize impact of reduced gravity on flow boiling compared to macro channels.

1.2. Nucleate boiling in micro-channels

Two mechanisms commonly associated with flow boiling in micro-channels are *nucleate boiling* and *convective boiling* [5,6]. Nucleate boiling is encountered in low quality bubbly and slug flow regimes in the upstream region of the channel and dominated by bubble nucleation. On the other hand, convective boiling is associated with downstream annular flow, dominated by heat transfer to the annular film, coupled with evaporation along the film's interface. Much of the difficulty predicting the magnitude of local heat transfer coefficient in a micro-channel stems from the inability to determine which of the two mechanisms is most prevalent, and the axial location associated with transition from nucleate boiling to convective boiling.

A key mechanism that governs the transition from nucleate to convective boiling is *suppression of nucleate boiling*. According to [7], nucleation in saturated flow boiling will commence on a wall cavity when the wall heat flux exceeds the heat flux corresponding to the onset of nucleate boiling (ONB), given by

$$q''_{ONB} = \frac{k_f h_{fg} \rho_g}{8 \sigma T_{sat}} \Delta T_{sat}^2, \tag{1}$$

where ΔT_{sat} is the wall superheat. For saturated flow boiling, $q'' = h \Delta T_{sat}$, where h is the heat transfer coefficient, which reduces Eq. (1) to

$$q''_{ONB} = \frac{8 \sigma T_{sat} h^2}{k_f h_{fg} \rho_g}. \tag{2}$$

For a uniformly heated micro-channel, nucleation is abundant in the upstream low quality region associated with mostly bubbly and slug flow regimes as discussed above. However, as quality increases downstream, annular flow is gradually established, where the heat is transferred mostly across the annular film and to a much lesser extent by nucleation along the wall. Gradual increases in quality and vapor shear cause simultaneous thinning and acceleration of the annular film, which enhances the heat transfer coefficient. Eq. (2) proves this increase in h in the annular region decreases the ability to sustain nucleation downstream; this is the basis for the aforementioned suppression phenomenon.

Thermodynamic equilibrium quality, x_e, is one of the key parameters investigators rely upon when identifying dominant heat transfer mechanisms in micro-channels. The magnitude of