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Investigation of flow boiling in large micro-channel heat exchangers in a refrigeration loop for space applications

S.H. Lee, I. Mudawar *

Boiling and Two-Phase Flow Laboratory (PU-BTPFL), School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA

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ABSTRACT

Future manned space endeavors will require a new class of vehicles, capable of conducting different types of missions and enduring varying gravitational and temperature environments. Thermal management will play a vital role in these new vehicles, and is complicated by the need to tackle both low and high heat sink temperatures. The present study concerns the development of a thermal management system operating in vapor compression mode to tackle high heat sink temperatures. The specific goal of the study is to investigate the two-phase heat transfer characteristics of two large micro-channel heat exchangers that serve as evaporators in the vapor compression loop using R134a as refrigerant. Both heat exchangers feature parallel micro-channels with identical 1×1-mm^2 cross-sections. The evaporators are connected in series, with the smaller 152.4-mm long heat exchanger situated upstream of the larger 609.6-mm long heat exchanger. This layout, along with broad ranges of mass velocity (152.90–530.72 kg/m^2 s) and base heat flux (8072.93–48,437.60 W/m^2) produced a wide range of qualities, which facilitated systematic assessment of dominant heat transfer mechanisms using both heat transfer measurements and high-speed video. Overall, it is shown low qualities are associated with slug flow and dominated by nucleate boiling, and high qualities with annular flow and convective boiling. Important transition points between the different heat transfer regimes are identified as (1) intermittent dryout, resulting from vapor blanket formation in liquid slugs and/or partial dryout in the liquid film surrounding elongated bubbles, (2) incipient dryout, resulting from dry patch formation in the annular film, and (3) complete dryout, following which the wall has to rely entirely on the mild cooling provided by droplets deposited from the vapor core. Finally, the study provides an assessment of the accuracy of eight previous correlations in predicting the measured two-phase heat transfer coefficient for both evaporators. Only one correlation is found to provide acceptable predictions in both accuracy and trend, evidenced by a mean absolute error of 21.19%, with 69.92% and 95.12% of the predictions falling within ±30% and ±50% of the data, respectively.

1. Introduction

1.1. Thermal Control System (TCS) for future space missions

Increased scope, complexity and duration of future space missions are expected to increase both power consumption and rate of waste heat rejection from future space vehicles, which will have a profound adverse impact on the vehicle's size and weight [1]. Additionally, future space endeavors will require a new class of vehicles, capable of conducting different types of missions and enduring varying gravitational and temperature environments. These include missions to near Earth objects, Lunar surface, Martian surface, and deep space, as well as Lunar and Martian habitats.

One method for decreasing a space vehicle's size and weight is to replace current single-phase Thermal Control Systems (TCSs) with two-phase counterparts. The TCS maintains acceptable temperature and humidity levels for both crew and avionics, and consists of components that tackle heat acquisition, transport, and rejection. The size and weight reductions are achieved by capitalizing upon the latent heat of the working fluid, through evaporation and condensation, rather on sensible heat alone. With a two-phase TCS, the heat is acquired via evaporators and rejected by radiation via a condenser/radiator. The evaporators acquire heat from two main sources, crew and avionics, with a total thermal load for space vehicles ranging from 1.0 to 6.25 kW, depending on space mission [2]. On the other hand, thermal loads for Lunar and Martian habitats are estimated at 50 and 25 kW [3], respectively.

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* Corresponding author. Tel.: +1 (765) 494 5705; fax: +1 (765) 494 0539.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://engineering.purdue.edu/BTPFL (I. Mudawar).

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Nomenclature

A_{base}	total base area of heat sink
Co	confinement number
D_b	bubble departure diameter
d_h	hydraulic diameter
G	mass velocity
g	gravitational acceleration
h	enthalpy
H_{ch}	micro-channel height
h_{fg}	latent heat of vaporization
H_{tc}	distance between thermocouple and base of micro-channel
h_{tp}	local two-phase heat transfer coefficient
$\bar{h}_{tp}$	average heat transfer coefficient
k	thermal conductivity
L	micro-channel length
m	fin parameter
$\dot{m}$	mass flow rate
Nu	Nusselt number
p	Pressure
Q	heat input
q''	heat flux based on total base area of heat sink
q_h''	heat flux based heated perimeter
T	temperature
t	time
W_{ch}	micro-channel channel width
W_w	half-width of copper sidewall separating micro-channels
x_{di}	quality corresponding to dryout incipience
x_e	thermodynamic equilibrium quality
z	coordinate along micro-channel

Greek symbols

β	ratio of micro-channel depth to width, $\beta = H_{ch}/W_{ch}$
η	fin efficiency
ρ	density
σ	surface tension
θ	percentage predicted within ±30%
ζ	percentage predicted within ±50%

Subscripts

3	three-sided heating
4	four-sided heating
avionics	avionics H/X
b	base of micro-channel
ch	micro-channel
cor	correlation
crew	crew H/X
di	dryout incipience
exp	experimental
f	liquid
fo	liquid only
g	vapor
in	micro-channel inlet
out	micro-channel outlet
pred	predicted
s	solid (copper)
sat	saturation
tc	thermocouple
tp	two-phase flow
w	micro-channel wall

Aside from increased size and weight, future space vehicles must endure broad variations in heat sink temperature. Space missions include (1) ‘cold’ environments, where the temperature of the working fluid exceeds the heat sink temperature, and (2) ‘warm’ environments, where the temperature of the working fluid is lower than the heat sink temperature. Cold environments enable heat rejection from the condenser/radiator using a pumped two-phase loop, while warm environments require a vapor compression heat pump to reject the heat. Most space missions provide cold environments. Two exceptions with environments are Low Lunar Orbit (LLO) and Low Mars Orbit (LMO), with heat sink temperatures as high as 17 and 22 °C, respectively [2], which exceed the lowest coolant temperature in the evaporators of 5 °C.

In recent years, researchers at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) have developed several options for design of two-phase thermal managements systems [4]. They include such schemes as pool boiling [5], falling liquid films [6–8], channel flow boiling [9], spray cooling [10,11], and mini/micro-channel cooling [12–15], as well as cooling systems combining jet impingement and mini/micro-channel cooling [16]. However, factors such as reduced gravity, and the need to reduce TCS weight and size, tackle heat loads from multiple heat sources, and enhance system efficiency largely favor the use of mini/micro-channel cooling for space vehicles.

Clearly, a space vehicle must be able to tackle both cold and warm environments. To achieve this goal, Singh and Hasan [17] proposed a reconfigurable TCS that uses a single working fluid. This TCS would operate as a mechanically pumped two-phase loop (or even single-phase loop at low thermal loads) for cold environments, and a heat pump for warm environments. Lee et al. [2] recently explored the design and thermodynamic performance of this type of Hybrid Thermal Control System (H-TCS) that satisfies the diverse thermal requirements of different space missions, endure both cold and hot environments, reduce size and weight, and enhance thermodynamic performance. R134a was deemed the most suitable working fluid based on its ability to provide a balanced compromise between reducing flow rate and maintaining low system pressure, and a moderate coefficient of performance (COP), let alone its favorable environmental attributes. The present study will address the thermal performance of mini/micro-channel evaporators that are used in conjunction with the heat pump configuration of a H-TCS.

1.2. Two-phase heat transfer in single mini/micro-channels

Two-phase flow and heat transfer characteristics of mini/micro-channels have been investigated experimentally in both single tubes and parallel multi-channel arrangements. References [18–22] are recent examples of studies addressing the heat transfer characteristics of single circular tubes. Lin et al. [18] investigated the effect of heat flux on the heat transfer coefficient for R141b in a vertical 1-mm diameter, 500-mm long tube over a mass velocity range of 300–2000 kg/m^2 and heat fluxes from 18 to 72 kW/m^2. Heat transfer at lower thermodynamic equilibrium qualities of $x_e < 0.4$ for 59,000 W/m^2 and $x_e < 0.03$ for 18,000 W/m^2 was dominated by nucleate boiling over the entire range of heat fluxes tested, evidenced by the heat transfer coefficient increasing with increasing heat flux and decreasing quality. On the other hand, the heat transfer coefficient was virtually independent of quality for $0.3 < x_e < 0.7$ in the intermediate heat flux range of