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Experimental and theoretical investigation of annular flow condensation in microgravity

Hyoungsoon Lee[a], Issam Mudawar[a,*], Mohammad M. Hasan[b]

[a] Boiling and Two-Phase Flow Laboratory (BTPFL), School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA
[b] NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA

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ABSTRACT

Vehicles for future manned space missions will demand unprecedented increases in power requirements and heat dissipation. Achieving these goals while maintaining acceptable size and weight limits will require replacing present single-phase thermal management components with far more efficient two-phase counterparts. This study discusses the development of an experimental facility for the study of annular condensation of FC-72 in microgravity, which was tested in parabolic flight as a prelude to the development of NASA's Flow Boiling and Condensation Experiment (FBCE) for the International Space Station (ISS). The flow behavior of the condensate film is shown to be sensitive mostly to the mass velocity of FC-72, with low mass velocities yielding laminar flow with a smooth interface, and high mass velocities turbulent flow with appreciable interfacial waviness. A select number of tests repeated in microgravity, Lunar gravity and Martian gravity prove that the influence of gravity is very pronounced at low mass velocities, manifest by circumferential uniformity for microgravity versus appreciable thickening along one side of the condensation tube for Lunar and Martian conditions. However, the thickening is nonexistent for Lunar and Martian conditions at high mass velocities due to increased vapor shear on the film interface, proving high mass velocity is an effective means to negating the influence of gravity in space missions. For microgravity, the condensation heat transfer coefficient is highest near the inlet, where the film is both thin and laminar, and decreases along the condensation length, but increases again downstream for high mass velocities due to turbulence and increased waviness. A model is proposed to predict the condensation heat transfer which accounts for dampening of turbulent fluctuations near the film interface. The model shows good agreement with the heat transfer coefficient data in both trend and magnitude.

1. Introduction

1.1. Importance of two-phase thermal management to future space missions

Future space missions to Mars and beyond are challenging all present practices in the design of space vehicles. These missions are expected to greatly increase in scope, size, complexity and duration. They will also bring about unprecedented increases in both power requirements and heat dissipation demands. However, it is highly unlikely that these increases can be accomplished with a commensurate increase in the size and weight of vehicle sub-systems, given the enormous impact of these two parameters on vehicle cost. Space vehicle developers are therefore exploring more efficient designs with greater power-to-weight ratio, including the use of fission power and replacing present single-phase thermal management systems with two-phase counterparts [1–6].

The effectiveness of two-phase thermal management systems is derived mostly from the orders-of-magnitude enhancement in evaporation and condensation heat transfer coefficients compared to single-phase counterparts. Thermal management is achieved via a Thermal Control System (TCS) that is tasked with heat acquisition, transport and rejection in the space vehicle. In a two-phase TCS, heat acquisition from a variety of heat-dissipating sources is achieved by evaporation or flow boiling of a working fluid. The heat is ultimately rejected to deep space to condense the working fluid back to liquid state. The heat acquisition can be achieved in a variety of boiling schemes including pool boiling [7,8], channel flow boiling [9–11], jet [12–14], and spray [15,16], especially when implemented with surface enhancement [17–19]. However, the configuration most suitable to a space vehicle's TCS is flow boiling in tubes. Similarly, the most suitable condensation configuration is flow condensation in tubes.

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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	area
$A_{f,*}$	cross-section area of liquid control volume
A^+	parameter in eddy diffusivity model
c_p	specific heat at constant pressure
D_i	inner diameter of condensation tube
D_o	outer diameter of condensation tube
f_i	interfacial friction factor
G	mass velocity of FC-72
g_e	Earth's gravitational acceleration
G_w	mass velocity of water
h	local condensation heat transfer coefficient
h_{fg}	latent heat of vaporization
K	Von-Karman constant
k	thermal conductivity
$\dot{m}$	mass flow rate
$\dot{m}_w$	mass flow rate for water
P	pressure
P_f	perimeter
Pr	Prandtl number
Pr_T	turbulent Prandtl number
q	heat transfer rate
q''	heat flux
Re	Reynolds number
T	temperature
t	time
u	axial velocity
u^+	dimensionless axial velocity
u^*	friction velocity
W	outer channel width of condensation module CM-FV
x_e	thermodynamic equilibrium quality
y	distance perpendicular to wall
y^+	dimensionless distance perpendicular to wall
z	stream-wise coordinate
Greek symbols	
Γ_{fg}	condensation mass transfer rate per unit axial distance
δ	liquid film thickness
δ^+	dimensionless liquid film thickness
ε_m	eddy momentum diffusivity
μ	dynamic viscosity
v	kinematic viscosity
ρ	density
τ	shear stress
Subscripts	
exp	experimental
f	saturated liquid
FC	FC-72
film	liquid film
g	saturated vapor
i	interfacial; inner surface of condensation tube
in	inlet of condensation length
o	outer surface of condensation tube
pred	predicted
sat	saturation
ss	stainless steel
w	water
wall	wall

A major challenge to designing a fission power system or phase-change TCS for a space vehicle is poor understanding of flow boiling and condensation in reduced gravity. Two-phase transport behavior can be highly susceptible to the influence of buoyancy, which is proportional to the product of gravity and density difference between liquid and vapor. Unfortunately, existing flow boiling and condensation pressure drop and heat transfer correlations and models are derived almost entirely from experiments that have been conducted in Earth's gravity. Therefore, it is impossible to ascertain the validity of these predictive tools for reduced gravity operation, especially microgravity, without conducting validation experiments over the appropriate gravity range. This fact is evident in a 2011 report by the National Research Council (NRC) [20] that was submitted to the U.S. Congress, which includes a detailed agenda for critical research needs in both life and physical sciences for future space exploration. The NRC places heavy emphasis on reduced-gravity two-phase flow and heat transfer, including the need for databases, correlations, theoretical models, and computational tools.

1.2. Microgravity testing platforms

Microgravity can be simulated in a number of platforms. An above ground *drop tower* or below ground *drop shaft* consist of a long, vertical conduit within which an experiment package is dropped to achieve microgravity during free fall. They provide very high quality residual gravity ($<1 \times 10^{-4}\, g_e$) for relatively short durations between 2.2 and 10 s (2.2 s for NASA Glenn Research Center's 24-m drop tower, 5.2 s for NASA Glenn Research Center's 132-m drop shaft, 4.6 s for NASA Marshall Space Flight Center's 105 m drop tower, 4.72 s for Germany Drop Tower Bremen's (ZARM's) 110-m drop tower, and 10 s for Japan Microgravity Center's (JAMIC's) 700-m drop shaft) [21]. Because of their relatively short microgravity duration, drop towers and drop shafts are typically used for initial validation of experiments before more comprehensive experiments are carried out in long-duration microgravity onboard the International Space Station (ISS). Key drawbacks of drop towers and drop shafts are (i) limited time available to achieve steady two-phase flow or to collect sufficient data for statistical analysis without a significant number of repetitive drops (since only one set of operating conditions can tested in a single drop), and (ii) inability of experimenter to manually interact with the experimental package.

Sounding rockets are another option for microgravity tests. They are sub-orbital carriers (they do not go into orbit around the Earth) and provide 3 to 13 min of low gravity with good residual gravity control ($<1 \times 10^{-4}\, g_e$) [21]. Like drop tower and drop shaft experiments, they preclude manual access to the experimental package and are intended for initial validation.

The ISS provides the ultimate testing environment for microgravity two-phase flow and heat transfer, providing long duration, quasi-steady environment below $1 \times 10^{-4}\, g_e$ [22], operator access to the experimental package, as well as automatic and remote control capabilities. However, ISS experiments are very expensive and require many years of development and safety certification, which causes great delays in the performance of much-needed microgravity experiments.

Parabolic flight aircraft provide a cost effective means to achieving microgravity with durations of 15–30 s. Preceded and followed by durations of high gravity, the microgravity period is achieved several tens of times as the aircraft undergoes a series of parabolic maneuvers. Despite relatively lower quality of residual gravity ($+/-0.01\, g_e$), which is influenced both by pilot skill and weather related turbulence, parabolic flight experiments offer significant