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Review

Review of flow boiling and critical heat flux in microgravity

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A B S T R A C T

Space agencies worldwide are actively exploring the implementation of two-phase thermal management systems to support astronaut life onboard future space vehicles and planetary bases. Key motivations for these efforts are to increase the efficiency of power utilization and reduce overall weight and volume. These advantages are realized by orders of magnitude enhancement in heat transfer coefficient achieved with flow boiling and condensation compared to single-phase systems. This study will review published literature concerning two-phase flow and heat transfer in reduced gravity. Discussed are the different methods and platforms dedicated to exploring the influence of reduced gravity, including ground flow boiling experiments performed at different orientations relative to Earth gravity, as well as reduced gravity adiabatic two-phase flow, pool boiling, flow boiling and CHF experiments. Despite the extensive data and flow visualization results available in the literature, it is shown that there is a severe shortage of useful correlations, mechanistic models and computational models, which compromises readiness to adopt flow boiling in future space systems. Key recommendations are provided concerning platform, heater design, and operating conditions for future studies to expedite the deployment of two-phase thermal management in future space missions.

Contents

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Nomenclature

A	cross-sectional area of flow channel
b	ratio of wetting front length to wavelength
Bo	Bond number
$C_{f,i}$	interfacial friction coefficient
C_o	distribution parameter in Drift Flux model
c_p	specific heat at constant pressure
D	diameter
D_h	hydraulic diameter, $4A/P$
f	friction factor
Fr	Froude number
G	mass velocity
g	gravity
g_e	Earth gravity
g_n	component of gravity normal to heated wall
$g_{//}$	component of gravity opposite to direction of fluid flow
H	height of channel's cross-section
h	heat transfer coefficient
H_f	mean thickness of liquid layer
h_{fg}	latent heat of vaporization
H_g	mean thickness of vapor layer
j	superficial velocity
k	thermal conductivity; wave number $(2\pi/\lambda)$
L	heated length
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	perimeter
p	pressure
Pr	Prandtl number
Q	volumetric flow rate
q''	wall heat flux
q''_m	critical heat flux (CHF)
q''_w	wetting front lift-off heat flux
Re	Reynolds number
T	temperature
$\Delta T_{sub,o}$	outlet subcooling, $T_{sat,o} - T_{b,o}$
U	mean liquid inlet velocity
U_f	mean velocity of liquid layer
U_g	mean velocity of vapor layer
$U_{g,n}$	mean vapor velocity in wetting front normal to heated wall
U_∞	bubble rise velocity
W	heated width of channel's cross-section
We	Weber number
x_e	thermodynamic equilibrium quality
z	stream-wise coordinate
z_o	distance from leading edge of heated wall to location where vapor velocity surpasses liquid velocity

Greek symbols

α	vapor void fraction
δ	mean thickness of vapor layer
δ_h	heated wall thickness
η	interfacial perturbation
η_o	amplitude of interfacial perturbation
λ	wavelength
λ_c	critical wavelength
μ	dynamic viscosity
ν	kinematic viscosity
Π	dimensionless group
ρ	density
ρ''	modified density
σ	surface tension
τ	shear stress
θ	flow orientation angle

Subscripts

asymp	asymptotic
b	bulk liquid
f	saturated liquid
g	saturated vapor
h	heated wall
i	interface
in	inlet to heated wall
m	critical heat flux
min	minimum
max	maximum
o	outlet from heated wall
sat	saturation
sub	subcooling
w	wetting front; heated wall

1. Introduction

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

Many modern applications requiring the dissipation of large concentrated heat loads rely on two-phase thermal management systems that employ both flow boiling and condensation. Unlike single-phase systems, which rely entirely on sensible heat rise of the working fluid to remove the heat, two-phase systems capitalize upon latent heat in addition to the sensible heat, which allows them to achieve orders of magnitude enhancement in heat transfer coefficient and much lower temperatures of the heat dissipating device compared to single-phase counterparts [1]. Associated with heat-flux controlled flow boiling, critical heat flux (CHF) is arguably the most important design parameter for two-phase thermal management systems. Since exceeding this limit can lead to catastrophic failure, a key goal in designing a two-phase thermal management system is to increase CHF in order to broaden the useful nucleate boiling heat flux range. This important goal has spurred many recent research efforts to both increase and predict CHF using a variety of boiling configurations, including pool [2,3], channel flow [4,5], mini/micro-channel [6], spray [7,8], and jet [9–11], as well as hybrid cooling configurations [12,13].