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Gravity effects on subcooled flow boiling heat transfer

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Subcooled flow boiling measurements using HFE-7000 were obtained in a vertical 6 mm ID sapphire tube during upward and downward flow at various gravity levels including hypergravity and microgravity. Temperature sensitive paint (TSP) applied to the inside of the tube was used to measure time and space resolved temperature and heat transfer distributions at the wall–fluid interface, and this data along with flow visualization were used to characterize the heat transfer for different flow patterns. Time-averaged heat transfer coefficients were compared at nine gravity levels, four mass fluxes, six heat fluxes, and two subcoolings. The average heat transfer coefficient typically increased with heat flux, mass flux, and absolute gravity level. In microgravity, the lack of mixing at low heat fluxes due to the absence of natural convection and bubble slip velocity resulted in a decrease in heat transfer coefficient compared to downward and upward conditions. The heat transfer was strongly dependent on the flow regime, causing certain data points at high mass flux or low gravity to deviate from the typical trends due to deactivation of nucleation sites. The heat transfer coefficient became less dependent on gravity as the mass flux and heat flux increased. Flow regimes were very sensitive to the competition between buoyancy and inertial forces, which in turn affected the heat transfer. Mechanisms by which heat is transferred under various conditions are discussed.

1. Introduction

Two NASA workshops [1,2] and two NRC reports [3,4] highlighted thermal management (and phase change heat transfer in particular) for advanced life support and propulsion as one of the technologies critical for successful deployment of long duration missions. Most existing spacecraft thermal subsystems rely on single-phase heat transfer, but the drive towards lighter, smaller, higher power subsystems to make future missions possible will require use of two-phase thermal systems. The key challenge in developing two-phase thermal systems is the development of a heat transfer database and reliable models for flow boiling in variable gravity environments from which the performance of two-phase heat exchangers in spacecraft can be predicted confidently. The use of two-phase thermal systems on spacecraft has been greatly hampered by the inability to predict with sufficient confidence their performance at various gravity levels (Earth, Mars, and lunar gravity and low-g). The performance prediction of two-phase systems under these conditions requires a sufficient heat transfer database and reliable models, both of which are not currently available.

Past research using parabolic aircraft has resulted in better understanding of how flow boiling is altered in microgravity for a variety of test section geometries, working fluids, and flow regimes. Ohta [5] observed heat transfer deterioration in microgravity for R113 annular flow through an 8 mm ID tube using a heated thin gold film on the inner wall to obtain average temperature values. He suggested the deterioration was due to the larger thickness and lower frequency of passing liquid troughs in the thin film that were observed in microgravity. Heat transfer became gravity independent at a mass flow of 600 kg/(m^2·s). Baltis et al. [6] measured heat transfer of FC-72 along a horizontal tube using thermocouples along the outer wall of 2 mm ID, 4 mm ID, and 6 mm ID tubes. Heat transfer and bubble size became independent of gravity level above a mass flux of 425 kg/(m^2·s) for their 6 mm ID tube. For their 4 mm ID tube, a maximum difference of ±8% was observed between microgravity and terrestrial gravity heat transfer coefficients. Significant flow instabilities and thermal crises were observed for their 2 mm ID tube at low gravity, making direct comparisons for tube diameter non-trivial. They also reported heat transfer enhancement for conditions where the microgravity flow was intermittent and terrestrial flow was

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Nomenclature

Cp	specify heat capacity (J/kg·K)
D	tube diameter (m)
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2·K)
h_{lv}	latent heat (kJ/kg)
I	LED excitation intensity (bits)
k	thermal conductivity (W/m·K)
l	tube length (m)
Nu	Nusselt number (*Nu* = hD/k) (dimensionless)
Pr	Prandtl number (*Pr* = ν/α) (dimensionless)
q″	heat flux (W/m^2)
R	resistance (Ω)
Re	Reynolds number (*Re* = VD/ν) (dimensionless)
x (dimensionless)	flow quality
z (m)	distance along tube from tube inlet

Greek

ΔT	temperature difference (°C)
α	thermal diffusivity (m^2/s)
λ	wavelength (m)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

F	forced
in	inlet
l	liquid
m	mean
N	natural
sat	saturation
sub	subcooling

bubbly. Narcy et al. [7] studied microgravity flow boiling for HFE-7000 in a 6 mm ID sapphire tube heated by a transparent ITO layer on the outside. At low mass flow rate in microgravity, the bubbles sizes were larger than in 1-g upward flow and the heat transfer was lower. For mass fluxes greater than 540 kg/(m^2·s), little difference in bubble size and shape were observed. The heat transfer became independent of gravity for mass fluxes greater than 200 kg/(m^2·s). The differences in mass flux limits among the researcher can perhaps be attributed to variations in the researchers' test tube dimensions, working fluids, and heat flux ranges.

CHF in flow boiling can occur by applying a large wall heat flux to a short tube, thereby raising the wall temperature sufficiently to vaporize the near-wall liquid and "lifting off" the fluid from wall (reverse annular flow). Zhang et al. [8,9] developed a model that assumes CHF occurs when the wetting fronts of a wavy interface that periodically rewet a heated wall lift off due to vapor produced at the wall. Zhang et al. [10] used a 101.6 mm long rectangular channel with a single heated wall using FC-72 to validate their model. They performed experiments on parabolic aircraft with mass fluxes between 230 and 2500 kg/(m^2·s) and heat fluxes up to 28.4 W/cm^2. When CHF occurred in the channel, a wavy vapor layer almost fully separated the bulk liquid flow from the heated wall. The wavy vapor layer became superheated while the liquid remained subcooled at the outlet, resulting in little change in quality in the flow direction. They found the difference between CHF in microgravity and horizontal 1 g flow decreased with increasing mass flux, and the CHF performance converged at a mass flux of 2500 kg/(m^2·s).

CHF can also occur by applying a small wall heat flux along a sufficiently long channel during which various flow regimes such as bubbly, slug, slug-annular, and annular flow are often observed. CHF is thought to occur due to dryout or breakdown of the thin film in the annular region. The authors are not aware of any data regarding gravity effects on CHF during low heat flux heating. This dearth of data is likely due to the difficulty of designing a test apparatus that has sufficiently long heated length since space and/or power can be limited on microgravity platforms (drop towers, parabolic aircraft, sounding rockets, and other space-based systems).

Measurement techniques which allow the local wall heat transfer distribution to be obtained are desired so heat transfer mechanisms can be identified. IR thermometry has been used in the past [11], but there are drawbacks to this technique. The tube must be made of an IR-transparent, high thermal conductivity material such as silicon, which restricts visual access since it is opaque at visual wavelengths. The process of isolating the inner wall temperature using IR thermometry involves accounting for the effects of self-emission of the tube and reflection from the surroundings. This process can be computationally expensive depending on the tube wall construction and accurate values of the optical properties of the tube materials are needed.

There is a strong need for a low-cost, optical measurement technique by which local heat transfer coefficients can be measured. Fluorescent paints that are sensitive to oxygen concentration (pressure sensitive paints, PSP) and temperature (TSP) have been used to measure shear stress, surface pressure, and wall temperature distributions in aerodynamic applications since the 1980s [12,13]. To measure temperature alone, the sensitivity to oxygen can be eliminated by encapsulation or removal of oxygen from the system. The paints are typically excited by blue/UV light and fluoresce at a longer wavelength. As temperature increases, the intensity of the emitted light decreases and the peak in the spectrum shifts to longer wavelengths. TSP calibration can be performed in-situ which eliminates intensity variation due to concentration. Kim and Yoda [14] developed a technique to measure fluid temperature within 100 nm of a wall using evanescent waves to illuminate a fluorescing tracer within the bulk fluid in single-phase flow, but this method becomes difficult to apply to two-phase flows since the local dye concentration can fluctuate due to evaporation. Shibuya et al. [15] applied TSPs to measure time varying two-phase flow heat transfer in a microgap. Al Hashimi et al. [16] demonstrated a temperature sensitive paint (TSP) technique to measure time resolved wall temperature and heat transfer distributions during pool and flow boiling. A film of fluorescing paint was laminated directly onto a surface of interest, and they were able to document the unique wall heat transfer signatures during pool boiling, and single phase and two-phase flows in tubes.

The goal of the current research was to obtain local flow boiling data at the lower mass and heat fluxes where gravity was found by past researchers to influence the heat transfer coefficient so models to predict the influence of gravity can be developed. Flow boiling of 3M™ Novec™ 7000 ($C_4F_9OCH_3$) was studied using TSP in a 6 mm ID × 120 mm long tube during upflow, downflow, with laminar inlet flow conditions and low heating rates at various gravity levels. Data were obtained at four mass fluxes, six heat fluxes, two subcoolings, and nine gravity levels, and observed differences in wall heat transfer trends are discussed. Heat transfer