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An experimental method for controlled generation and characterization of microchannel slug flow boiling

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ABSTRACT

This study uses high-speed imaging to characterize microchannel slug flow boiling using a novel experimental test facility that generates an archetypal flow regime suitable for high-fidelity characterization of key hydrodynamic and heat transfer parameters. Vapor and liquid phases of the fluorinated dielectric fluid HFE-7100 are independently injected into a T-junction to create a saturated two-phase slug flow, thereby eliminating the flow instabilities and flow-regime transitions that would otherwise result from stochastic generation of vapor bubbles by nucleation from a superheated channel wall. Slug flow boiling is characterized in a heated, 500 μm-diameter borosilicate glass microchannel. A thin layer of optically transparent and electrically conductive indium tin oxide coated on the outside surface of the microchannel provides a uniform heat flux via Joule heating. High-speed flow visualization images are analyzed to quantify the uniformity of the vapor bubbles and liquid slugs generated, as well as the growth of vapor bubbles under heat fluxes ranging from 30 W/m^2 to 5160 W/m^2. A method is demonstrated for measuring liquid film thickness from the visualizations using a ray-tracing procedure to correct for optical distortions. Characterization of the slug flow boiling regime that is generated demonstrates the unique ability of the facility to precisely control and quantify hydrodynamic and heat transfer characteristics. The experimental approach demonstrated in this study provides a unique platform for the investigation of microchannel slug flow boiling transport under controlled, stable conditions suitable for model validation.

1. Introduction

Two-phase flows are commonly encountered in nuclear, power generation, petroleum, and other industries. In general, two-phase flows can be classified according to whether phase change is occurring, which leads to strong differences in the underlying physics. Flows not undergoing phase change involve two different immiscible chemical components, and are sometimes referred to as two-component, two-phase flows (*e.g.*, nitrogen-water flow) [1]. Phase-change flows contain a single component but comprise two different phases separated by an interface; steam-water flow is an example of a single-component, two-phase flow. Phase-change flows can be either condensing (flow condensation) or evaporating (flow boiling).

Slug flow is one of the most common two-phase flow regimes in applications at the microscale [2–5], ranging from lab-on-a-chip devices in medical and pharmaceutical industries [2] to microchannel flow boiling heat sinks for electronics cooling [6,7]. The slug flow boiling regime, schematically illustrated in Fig. 1, is characterized by elongated vapor bubbles that are circumferentially confined and partitioned in the streamwise direction by liquid slugs. A thin liquid film separates the vapor bubbles from the channel wall; evaporation in this thin liquid film has been shown to be the dominant heat transfer mechanism in slug flow boiling [8]. During flow boiling in microchannels, nucleation and departure of vapor bubbles from the channel wall almost immediately leads to a slug flow regime for channel sizes below a critical value, due to the influence of surface tension and vapor confinement [9]. As a result, the slug flow regime is observed across a wide range of operating conditions and is of significant interest.

The design and optimization of two-phase microchannel cooling systems will likely be accomplished using a combination of reduced-order mechanistic models and direct numerical simulation of flow boiling. Several mechanistic slug flow boiling models of increasing complexity have been proposed. Peles et al. [10] developed a one-dimensional model featuring distinct liquid and vapor regions partitioned by an evaporating interface. Jacobi and Thome [11] proposed a ‘two-zone’ model consisting of an evaporating vapor bubble region surrounded circumferentially by a thin

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Nomenclature

A_s	inside surface area of the microchannel
Bo	Bond number $[(\rho_l - \rho_v)gD^2/\sigma_l]$
D	microchannel diameter
D_b	vapor bubble diameter
g	gravitational acceleration constant
L_b	vapor bubble length
L_m	microchannel length
L_s	liquid slug length
L_0	initial vapor bubble/liquid slug length
P_{in}	input power
P_{loss}	power loss
P_{total}	total power
q''	heat flux
Re_D	Reynolds number (V_bD/ν_l)
t_w	microchannel wall thickness
V_b	vapor bubble velocity
x	transverse position relative to microchannel centerline
y	axial position relative to T-junction center
y'	axial position relative to camera field of view
z	vertical position relative to microchannel centerline

Greek letters

δ	liquid film thickness
θ	angle between normal and incident/refracted light
ν_l	liquid kinematic viscosity
ρ_l	liquid density
ρ_v	vapor density
σ_l	liquid surface tension

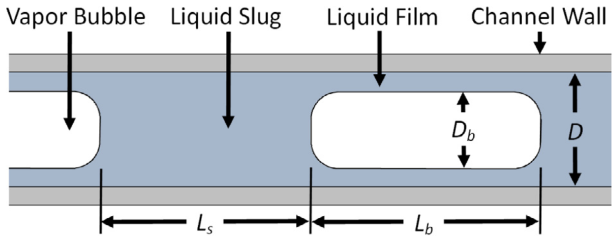

Fig. 1. Schematic diagram illustrating the slug flow boiling regime.

liquid film, with successive bubbles partitioned by a liquid slug region. A model for the conduction resistance of the thin liquid film was used to describe the effective evaporative heat transfer coefficient. A 'three-zone' model was presented by Thome et al. [8] by including an additional vapor slug region, where no liquid film exists, and a method for prediction of the liquid film thickness. This model was later adapted by Harirchian and Garimella [12] to include a correlation for the liquid film thickness specific to microchannel length scales. While the aforementioned two- and three-zone models were strictly developed for circular microchannels, a 'four-zone' model was developed by Wang et al. [13] to account for a partial dryout region resulting from corner effects in microchannels of rectangular cross-section. These modeling efforts have significantly advanced the understanding of the underlying flow boiling physics, such as the realization that thin-film evaporation governs microchannel flow boiling performance (rather than nucleate boiling) and that cyclic variations in the heat transfer coefficient result from the passage of different fluid zones.

Several recent studies have developed multiphase numerical models for flow boiling that account for complex vapor–liquid interfacial transport phenomena [14–18]. For example, Pan et al. [17] demonstrated a cost-effective approach for modeling microchannel flow boiling using a volume-of-fluid (VOF) approach coupled with a saturated-interface-volume phase change model and a moving-reference-frame method that suppresses spurious currents [19]. The growth of single, evaporating vapor bubbles flowing in heated microchannels was simulated. While this was an important step toward the ultimate goal of a comprehensive numerical simulation of the complete flow boiling problem, a continuous stream of vapor bubbles is more representative of two-phase flows and poses additional challenges for modeling due to the hydrodynamic and thermal interaction between successive vapor bubbles [20]. Magnini and Thome [3] computationally investigated the hydrodynamics and heat transfer characteristics of microchannel slug flow under saturated flow boiling conditions using a continuous stream of artificially generated vapor bubbles. The first vapor bubble entering a fully developed liquid-phase flow and temperature profile had a significantly higher evaporation rate relative to successive vapor bubbles due to the large amount of sensible heat available in the superheated liquid regions; time-periodic behavior was observed after approximately five vapor bubbles.

Despite the recent significant advances in modeling, these state-of-the-art techniques are still validated using test problems for which simplistic analytical solutions are available [15,17,18,21,22], comparison to temporally and spatially averaged transport quantities that can be easily measured experimentally [16], or cross-comparison between the different numerical modeling approaches [17]. There is a clear need for high-fidelity benchmark experimental data that can be used as a common basis for validation of sophisticated flow boiling models.

Two-phase flows are traditionally generated in flow boiling experiments by vapor bubble nucleation from a heated surface. This incipience-based approach gives rise to a streamwise progression of flow regimes, typically transitioning from bubbly to slug to annular flow. Large stochastic hydrodynamic variations, flow instabilities, and the close proximity of successive vapor bubbles that arise from the nucleation process confound the development of a comprehensive database of well-conditioned experimental results that is amenable for use in the validation of flow boiling models.

Recent experimental efforts have explored innovative techniques that control vapor bubble generation by avoiding a reliance on spontaneous nucleation. Bigham and Moghaddam [23] demonstrated active nucleation control from a 300 nm-diameter heated cavity. By varying the amplitude and period of a pulsed square wave, different time-periodic flow regimes ranging from bubbly to slug to annular were realized in a 120 μm-hydraulic diameter microchannel at very low Reynolds numbers. A method for producing the desired two-phase flow characteristics while completely avoiding nucleation has also been proposed. Scammell and Kim [24] fabricated a test facility capable of producing a single vapor bubble of a desired length which was then injected into a liquid vertical upflow in an optically opaque, heated 6 mm macrochannel. There is a need for experimental approaches capable of producing a continuous stream of vapor bubbles that appropriately emulates the physical behavior of slug flow boiling, with successive vapor bubbles separated by liquid slugs. Such an approach would enable characterization of key hydrodynamic and heat transfer parameters under well-defined boundary and flow conditions that are commonly encountered in microchannel heat sinks.