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Heat transfer and flow characteristics of rising Taylor bubbles

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ABSTRACT

The heat transfer enhancement due to slug flow has been widely studied both experimentally and numerically, yet identification of the main heat transfer mechanisms has been debated and little experimental evidence is available. In this work, an infrared thermography technique, high-speed visualization, and a film thickness sensor were used to characterize vapor Taylor bubbles rising in a vertical, co-current, liquid flow. Measurements of the local heat transfer around each bubble indicated that the largest enhancement resulted from turbulent mixing in the bubble wake due to vortex shedding at the tail. The effect of the vortices on heat transfer was found to decline with increasing liquid velocity as a result of shortened residence time of the bubbles over a particular tube location. Liquid film thickness measurements showed excellent agreement with correlations when the film was fully developed. Bubble velocities and vortex shedding frequencies were experimentally determined for several liquid velocities.

1. Introduction

Slug flow, characterized by elongated bubbles separated by liquid slugs, is frequently seen in pulsating heat pipes, microchannels, and in macro-scale channels at low vapor qualities. Vapor/gas slugs rising in a vertical column are called Taylor bubbles, and have been widely studied-a review of the literature prior to 1992 is given in Fabre and Line [1]. A review of some of the more recent work follows. Polonsky et al. [2] analyzed high speed video of rising Taylor bubbles in air–water vertical flow to characterize the bubble velocity and shape. Oscillations in the bubble tail were found to be of higher frequency and amplitude for longer bubbles. Nogueira et al. [3] used non-intrusive particle image velocimetry (PIV) to track the flow field around rising bubbles within stagnant and flowing fluids of varying viscosities in a 32 mm inner diameter (ID) tube. Comparison of the experimental data to theoretical correlations found that both film velocity and thickness were under-predicted for film Reynolds numbers greater than 80. In a similar study, Nogueira et al. [4] observed the velocity patterns in the wake behind rising bubbles and related the wake flow pattern to the dimensionless parameter N_f for stagnant liquid conditions, and a modified Reynolds number for co-current flow. Shemer et al. [5] used PIV to study the velocity profiles in the wake of single bubbles rising in both laminar and turbulent background flows. They found the wake flow field could be effectively turbulent even when the base flow was laminar. Turbulent velocity quantities calculated from the data showed that the initial mixing process occurred in the near wake region and persisted a few diameters downstream of the bubble tail.

Thickness measurements of the liquid film surrounding bubbles in 0.3, 0.5, 0.7, 1, and 1.3 mm ID tubes were carried out by Han and Shikazono [6] using a laser focus displacement meter. They proposed correlations to predict the initial bubble film thickness using the collected experimental data. They later expanded their study to include the effect of evaporation and developed relations for calculation of the film thickness [7]. Llewellin et al. [8] calculated the film thickness based on the observed bubble length for experiments conducted with liquids of varying viscosities and tube IDs of 10, 20, and 40 mm. Two correlations were proposed (one theoretical and one empirical) for the fully-developed film thickness of Taylor bubbles rising in stagnant liquid.

Accurate prediction of liquid film thickness and other bubble characteristics are crucial in the development of physics-based models for determining the heat transfer in slug flows. One such model by Jacobi and Thome [9] featured a two-zone representation of evaporation for elongated bubble flows where the regime was divided into a liquid slug region and a thin film region. It was suggested that the main mechanism of heat transfer was evaporation of the thin film trapped between the bubble and heated channel wall. This model was modified by Thome et al. [10] to include three zones: a liquid slug, an evaporating elongated bubble, and a vapor slug. As with the two-zone model, evaporation in the thin liquid film provided heat transfer several orders of magnitude higher than the single phase heat transfer due to the liquid slug.

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Nomenclature

General

C	velocity drift constant
D	tube diameter
g	gravitational acceleration
G	liquid mass flux
h	heat transfer coefficient
h_{lv}	latent heat
k	thermal conductivity
L	length
P	pressure
q''	heat flux
r	radial position
R	tube radius
Re	Reynolds number
T	temperature
U	velocity
x	vapor quality
z	axial distance

Greek

α	absorptivity
δ	film thickness
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

abs	absolute
act	actual
B	bubble
cam	IR camera
f	film
L	liquid
meas	measured
p	polyimide
sat	saturation
Si	silicon
SP	single phase
v	vortex
0	stagnant conditions

Magnini et al. [11] numerically obtained the shape, length, and local heat transfer of Taylor bubbles during boiling of several fluids in a 0.5 mm circular channel. They found that as the bubble entered a heated channel containing a developing thermal boundary layer, evaporation of the liquid film removed heat from the fluid and caused the heat transfer to become larger than for single-phase flow. The heat transfer coefficient rose monotonically from the bubble nose towards the tail, with the highest values occurring in the bubble wake region. Based on these results, they modified the three-zone model by Thome et al. [10] to include unsteady conduction through the liquid, and obtained better agreement with the simulations.

The experimental heat transfer work to date has largely focused on measuring the overall heat transfer enhancement of slug trains with respect to single phase flow, rather than on the mechanisms of heat transfer around each bubble. For example, Walsh et al. [12,13] utilized an infrared (IR) measurement technique in which the outer wall temperature of a 1.5 mm diameter stainless steel tube was measured when air–water bubble trains were present. The observed outer wall temperature was used as a boundary condition for a thermal resistance problem to obtain the time-averaged heat transfer coefficient. The maximum heat transfer enhancement over fully developed Poiseuille flow occurred at a liquid slug length to diameter ratio of unity. A correlation to predict the fully developed Nusselt number at other ratios was proposed.

Mehta and Khandekar [14] utilized a similar IR technique in bubble train experiments using deionized water and air within a 5 mm × 5 mm square mini-channel. The heat transfer coefficient along the channel length was calculated using the experimentally measured channel wall temperature contours. An enhancement in heat transfer coefficient of 1.2–2 times over thermally developing single-phase flow was observed depending on the axial location.

Hetsroni and Rozenblit [15] briefly touched upon the mechanisms of heat transfer in slug flow. A thin heated film was installed within a 74 mm ID tube and coated with black paint to allow temperature measurement using an IR camera. Wall temperature profiles were observed to be uniform for passing liquid slugs, while faint higher temperature streaks occurred on the wall when the bubbles passed. This suggests a higher heat transfer coefficient in the liquid slug than in the liquid film, but no quantitative data was presented.

The objective of the current work is to identify the contributions of various heat transfer mechanisms acting on a heated tube in the presence of a single Taylor bubble. Additionally, observations of the bubble shape and dynamics allow for predictions of the flow field which complement the heat transfer measurements. The collected data can be utilized to update current models for slug flow heat transfer or develop new models.

2. Experimental facility

To characterize the heat transfer and dynamics of rising Taylor bubbles, a flow boiling experiment was conducted in which measurements of the local wall heat transfer and film thickness along with high speed images were obtained as single bubbles of varying length rose in a vertical column containing upward flowing liquid. The study of single bubbles was chosen in lieu of bubble trains so flow conditions upstream and downstream of the bubbles could be measured, reducing the complexity in approximating the flow patterns and understanding the heat transfer profile around each bubble.

2.1. Flow loop description

A schematic of the experiment flow loop is shown in Fig. 1. The working fluid was 3M Novec HFE 7100 ($C_4F_9OCH_3$), a non-toxic, dielectric fluid with a normal boiling temperature of 57 °C. Properties at saturation conditions for 1 bar of pressure are summarized in Table 1.

HFE 7100 was pumped in a subcooled liquid state using a gear pump (Micropump L21755) as the flow rate was measured by a turbine flowmeter (Omega FLR1009). The liquid was heated to saturation at the test section inlet using a stainless steel preheater powered by a modified 1000W computer power unit (Silverstone