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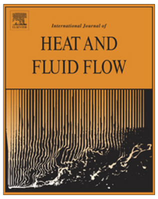

Measurement of local heat transfer coefficient during gas–liquid Taylor bubble train flow by infra-red thermography

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ABSTRACT

In mini/micro confined internal flow systems, Taylor bubble train flow takes place within specific range of respective volume flow ratios, wherein the liquid slugs get separated by elongated Taylor bubbles, resulting in an intermittent flow situation. This unique flow characteristic requires understanding of transport phenomena on global, as well as on local spatio-temporal scales. In this context, an experimental design methodology and its validation are presented in this work, with an aim of measuring the local heat transfer coefficient by employing high-resolution InfraRed Thermography. The effect of conjugate heat transfer on the true estimate of local transport coefficients, and subsequent data reduction technique, is discerned. Local heat transfer coefficient for (i) hydrodynamically fully developed and thermally developing single-phase flow in three-side heated channel and, (ii) non-boiling, air–water Taylor bubble train flow is measured and compared in a mini-channel of square cross-section (5 mm × 5 mm; $D_h = 5$ mm, $Bo \approx 3.4$) machined on a stainless steel substrate (300 mm × 25 mm × 11 mm). The design of the setup ensures near uniform heat flux condition at the solid–fluid interface; the conjugate effects arising from the axial back conduction in the substrate are thus minimized. For benchmarking, the data from single-phase flow is also compared with three-dimensional computational simulations. Depending on the employed volume flow ratio, it is concluded that enhancement of nearly 1.2–2.0 times in time-averaged local streamwise Nusselt number can be obtained by Taylor bubble train flow, as compared to fully developed single-phase flow. This enhancement is attributed to the intermittent intrusion of Taylor bubbles in the liquid flow which drastically changes the local fluid temperature profiles. It is important to maintain proper boundary conditions during the experiment while estimating local heat transfer coefficient, especially in mini-micro systems.

1. Introduction

Transport mechanisms of heat, momentum and species under two-phase flow conditions in mini/micro systems are greatly affected by local distribution of the phases or flow patterns in the channel. Taylor bubble train flow, a sub-set of slug flows occurring in mini/micro-systems, is typically characterized by a sequence of long bubbles which are trapped in between liquid slugs. Geometrical distribution of the liquid slugs and bubbles is fundamentally governed by the resultant of gravity, surface tension, inertia and viscous effects. For a given liquid–gas system, interplay between the gravity and surface tension forces mainly depends on the size of the channel, i.e. the applicable Bond number (Bo). When surface tension dominates over gravitational body force, Taylor bubbles adopt the characteristic capsular shape, with a liquid thin film separating the gas/vapor phase with the wall. In horizontal flow conditions when Bo is high enough ($Bo > Bo_{cr} \approx 1.835$ (Bretherton, 1961)), gravity force dominates over surface tension and the liquid film essentially takes the lower part of the channel cross-section, whereas in the upper part, a negligibly thin liquid film may or may not exist. The existence of liquid film on the wall depends on Ca and surface energy characteristics (hydrophobic or hydrophilic) of the channel wall (Serizawa et al., 2002; Cubaud and Ho, 2004; Ajaev and Homsy, 2006).

Taylor bubble train flow is expected to occur and, is employed in many new and upcoming systems and devices in diverse branches of engineering ranging from bio-medical, bio-chemical to thermal management of electronics, micro-two-phase heat exchangers and reactors, nuclear rod bundles, micro-fluidic devices, loop heat pipes, etc. (Triplett et al., 1999; Devesenathipathy et al., 2003; Spernjak et al., 2007; Moharana et al., 2011a). Quite frequently, due to the mini/micro fabrication techniques, such as laser machining, chemical etching, micro-milling, abrasive jet machining etc., emerging technological solutions employing internal convective flows, make use of channels of non-circular cross sections. Rectangular micro-channels are of particular interest as they are used extensively in heat sinks of microelectronic devices,

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Nomenclature

A	area of cross section (m^2)
c_p	specific heat at constant pressure (J/kg K)
D_h	hydraulic diameter (m)
Δf	number of frames
h	heat transfer coefficient (W/m^2 K)
J	phase superficial velocity (m/s)
k	thermal conductivity (W/m K)
ℓ	length specified in image (m)
L	length of the channel, characteristic length (m)
m	ratio of relative bubble velocity to bubble velocity (–)
N	number of observed bubble
n	frames per second
p	perimeter (m)
Q	volumetric flow rate (m^3/s), heat input (W)
q''	heat flux (W/m^2)
R	radius (m)
S	slip ratio (–)
T	temperature (K)
T^*	non-dimensional temperature (–)
t	time (s), thickness (m)
U	velocity (m/s)
x	gas fraction (–)
Z	distance from inlet (m)
Z^*	thermal non-dimensional distance ($=Z/Re \cdot Pr \cdot D_h$)

Greek symbols

δ	substrate thickness (m)
β	volume flow ratio (–)
ε	void fraction (–)
η	liquid film thickness (m)
ζ	frequency of bubbles (Hz)
μ	dynamic viscosity (Pa s)
ρ	mass density (kg/m^3)
φ	heat flux ratio (–)
ψ	ratio of bubble velocity to total superficial velocity (–)
σ	surface tension (N/m)

Non-dimensional numbers

Bo	Bond number $D_h \cdot \{(\rho_l - \rho_g) \cdot g/\sigma_l\}^{0.5}$
Ca	Capillary number $(\mu_l \cdot U_b/\sigma_l)$
Nu	Nusselt number $(h \cdot D_h/k_l)$
Pr	Prandtl number $(\mu_l \cdot c_p/k_l)$
Re	Reynolds number $(\rho_l \cdot J \cdot D_h/\mu_l)$

Subscripts

b	bubble, bulk, base
f	fluid
g	gas
h	hydraulic, hydrodynamic
in	input
l	liquid
s	slug
sf	solid–fluid
tot	total
TP	two-phase
uc	unit cell
w	wall

as well as for catalytic reactors for micro-fuel processors, biological sensors, lab-on-chip devices, water management of PEM fuel cells, high heat flux dissipating heat exchanger equipment etc. Mostly in these mini/micro-scale devices, heat transfer process is conjugate in nature, i.e. the diffusion in the solid wall of the channel affects the thermal boundary condition (uniform heat flux or uniform wall temperature) which the fluid experiences at the solid–fluid interface. This conjugate nature of thermal transport increases the level of complexity in the estimation of local heat transfer, demanding an effective means of accurate non-intrusive field measuring instruments as against intrusive point measurements, such as by micro thermocouples (Majumder et al., 2013). In this context InfraRed Thermography (IRT) has emerged as an effective non-intrusive field measurement technique in the recent past (Hetsroni et al., 1996, 2003) to address the local measurement of a variety of complex problems involving high spatial temperature gradients. In the present work, we have made an attempt to estimate the local heat transfer coefficient under such demanding conditions involving (i) Intermittent Taylor bubble train flow, (ii) non-circular (square) mini-channel, by employing non-intrusive field measurement by InfraRed Thermography. The paper presents an experimental design methodology so that local heat transfer can be estimated by minimizing the conjugate heat transfer effects in the system. As will be revealed in the survey of open literature, which is presented in the subsequent section, understanding of local species transport under such flow conditions is quite an involved problem.[1]

2. Literature review

In one of the seminal works on Taylor bubble flows, it was observed that a bubble does not rise spontaneously in a water filled vertically oriented circular capillary under the effect of gravity for $Bo < 1.835$ (Bretherton, 1961) and film thickness scaling was found as $(\eta/R) \sim Ca^{2/3}$, valid for $10^{-3} \leqslant Ca \leqslant 10^{-2}$. Deposition of thin liquid film due to displacement of the wetting fluid by a gas bubble inside a circular capillary wall has been studied (Fairbrother and Stubbs, 1935) and another scaling for film thickness was given as $(\eta/R) \sim Ca^{1/2}$ for $10^{-5} \leqslant Ca \leqslant 10^{-1}$. Under Taylor bubble train flow conditions, the bubble velocity will not be equal to the liquid due to the existence of liquid film that separates the bubble from the wall (Fabre and Liñe, 1992; Thulasidas et al., 1995, 1997). Presence of bubble interfaces at front and back of the liquid slugs modifies the flow field inside it. Circulation takes place inside the liquid slug due to existing wall shear stress, which in turn enhances the species transport. It has been hypothesized that for low Ca, circulation patterns in the liquid slug will be observed with paired set of vortices, which tend to disappear for higher Ca, leading to bypass flows (Taylor, 1961). More recent numerical and experimental studies (Taha and Cui, 2004, 2006; Kashid et al., 2005; He et al., 2010; Bajpai and Khandekar, 2012) have confirmed these findings. In recent years focus on Taylor bubble flows in non-circular channels has also attracted attention. Shape of the bubble cross-section in a square capillary has been experimentally determined and it is concluded that for $Ca \leqslant 0.1$, bubble cross-section is non-axisymmetric. As the total superficial velocity increases and Ca becomes greater than 0.1, the increased inertia forces tend to make the bubble cross-section axisymmetric (Kolb and Cerro, 1993; Han and Shikazono, 2009). Numerical study of the flow of long bubble in a square capillary suggested that liquid deposition on capillary wall is a function of flow Ca (Kamisli, 2003). Flow pat-

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[1] It must be noted here that the issue of accurate experimental measurement of the bulk mean-mixing temperature of the respective fluid-phases, under such intermittent flow conditions, is not trivial. The procedure adopted in this work to estimate this temperature requires further refinement (refer Section 3.3). Other major aspects towards estimating the correct local heat transport parameters have been included in the design of the experiment presented here.