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Local Nusselt number enhancement during gas–liquid Taylor bubble flow in a square mini-channel: An experimental study

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A B S T R A C T

Taylor bubble flow takes place when two immiscible fluids (liquid–liquid or gas–liquid) flow inside a tube of capillary dimensions within specific range of volume flow ratios. In the slug flows where gas and liquid are two different phases, liquid slugs are separated by elongated Taylor bubbles. This singular flow pattern is observed in many engineering mini-/micro-scale devices like pulsating heat pipes, gas–liquid–solid monolithic reactors, micro-two-phase heat exchangers, digital micro-fluidics, micro-scale mass transfer process, fuel cells, etc. The unique and complex flow characteristics require understanding on local, as well as global, spatio-temporal scales. In the present work, the axial streamwise profile of the fluid and wall temperature for air–water (i) isolated single Taylor bubble and, (ii) a train of Taylor bubbles, in a horizontal square channel of size 3.3 mm × 3.3 mm × 350 mm, heated from the bottom (heated length = 175 mm), with the other three sides kept insulated, are reported at different gas volume flow ratios. The primary aim is to study the enhancement of heat transfer due to the Taylor bubble train flow, in comparison with thermally developing single-phase flows. Intrusion of a bubble in the liquid flow drastically changes the local temperature profiles. The axial distribution of time-averaged local Nusselt number ($\overline{Nu}_z$) shows that Taylor bubble train regime increases the transport of heat up to 1.2–1.6 times more as compared with laminar single-phase liquid flow. In addition, for a given liquid flow Reynolds number, the heat transfer enhancement is a function of the geometrical parameters of the unit cell, i.e., the length of adjacent gas bubble and water plug.

1. Introduction

Transport mechanisms of heat, momentum and mass under two-phase flow conditions in mini-/micro systems are greatly affected by the local distribution of phases, or flow patterns in the channel. The two-phases may be composed of gas–liquid two-component system or a vapor–liquid single-component system (in the context of the present study, we restrict the discussion to gas–liquid two-component systems; however, it is noted that non-miscible liquid–liquid two-component systems can also give rise to unique transport mechanisms). Slug flow is one of the important multiphase flow patterns, which belongs to a class of intermittent flows. Taylor bubble train flow, a sub-set of slug flows, is typically characterized by a sequence of long bubbles which are trapped in between liquid slugs. Typically, in mini-/micro-scale systems, 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. Such Taylor bubble train flows in confined mini-/micro-scale geometries have singular distinctive local thermo-hydrodynamic transport features. This is due to their intermittent nature, dominance of surface tension, interfacial dynamics, geometrically confined bubbles, effect of local wettability resulting in enhanced heat/mass transport [1].

Under laminar flow conditions, viscous forces interact with surface tension, giving rise to Capillary number scaling ($\mu U/\sigma$). The existence of a thin film surrounding the Taylor bubbles gives rise to bubble slip motion i.e., a higher bubble velocity than the total superficial velocity of the flow defined by $U_b = \psi \cdot J_{tot}$. Film thickness depends on the Capillary number, channel geometry and local wettability between fluids and tube/channel wall (hydrophobic or hydrophilic) [2,3]. For very thin films (sub-microns) around Taylor bubbles, which may form at very low Ca and/or flows in super-hydrophobic ducts, interaction of additional disjoining pressure with the flow field has also been argued [1].

Understanding of the species transport under such a flow configuration is quite a challenging problem. In recent years, research on Taylor bubble train flow has increased due to development of mini-/micro-scale systems in diverse branches wherein such flows are encountered such as, ranging from bio-medical, bio-chemical to

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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	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 velocity to bubble velocity (−)
N	number of bubble observation (−)
n	frames per second (s^{-1})
Q	volumetric flow rate (m^3/s)
R	radius (m)
q''	heat flux (W/m^2)
t	time (s)
T	temperature (K)
T^*	non-dimensional temperature $(= T - T_{fi}/(q''\cdot D_h)/k_l)$
U	velocity (m/s)
Z	distance from inlet (m)
Z^*	thermal non-dimensional distance $(=Z/Re\cdot Pr\cdot D_h)$

Greek symbols

α	thermal diffusivity (m^2/s)
δ	liquid film thickness (m)
ξ	volume flow ratio (−)
ε	void fraction (−)
ϑ	frequency of bubbles (Hz)
μ	dynamic viscosity (Pa s)
ρ	mass density (kg/m^3)
ψ	ratio of bubble velocity to total superficial velocity (−)
σ	surface tension (N/m)

Non-dimensional numbers

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 $(\rho_l\cdot J_l\cdot D_h/\mu_l)$
We	Weber number $(\rho_l\cdot U_b^2\cdot D_h/\sigma_l)$

Subscripts

b	bubble, bulk
l	fluid
fi	fluid inlet
g	gas
h	hydraulic, hydrodynamic
l	liquid
s	slug
tot	total
uc	unit cell
w	wall

thermal management of electronics, water management of fuel cells, micro-two-phase heat/mass exchangers and reactors, nuclear rod bundles, DNA separation and analysis, lab-on-chips, micro-fluidic devices, loop heat pipes, etc. In all the above emerging technologies, Taylor bubble train flow is one of the dominant flow patterns [4–9]. Presence of quasi-periodic slipping bubble interfaces, in front and back of the liquid slugs, modifies the flow field inside the liquid slugs compared with conventional fully developed parabolic profiles as in single-phase flows. Interaction of the ensuing wall shear gradients and free-slip boundary condition at the bubble–liquid interface gives rise to strong circulation inside the liquid slugs [10–12]. These recirculation patterns within the liquid slugs enhance heat and mass transfer from liquid to wall and interfacial mass transfer between gas/vapor and liquid [13–17]. Thus, bulk transport mechanisms are influenced by the dynamics of the local isolated 'unit cell', consisting of a Taylor bubble and adjoining liquid slug. Understanding transport mechanism necessitates localized experimental observations of Taylor bubble train systems, with synchronized measurements of the resulting fluctuations in local conditions such as temperature, pressure and wall heat flux [18]. Mass transfer characteristics are also affected by the local hydrodynamics of the flow (bubble velocity, slip velocity, length of the liquid slug, shape of the bubble–liquid interface) [19]. Knowledge of local thermo-hydrodynamic characteristics of the unit cell during Taylor bubble train flow is vital for complete understanding of the behavior and improving the performance of micro-thermo-fluidic and micro-chemical systems that operate in this regime.

Many mini-/micro fabrication techniques, such as laser machining, chemical etching, micro-milling, abrasive jet machining etc., lead to channels of non-circular cross-section. Rectangular microchannels are of particular interest as they are used extensively in heat sinks of microelectronic devices, 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, micro-fluidic devices, etc. While most of the classical works on Taylor bubbles are confined to circular channels and ducts with primarily upward flow configuration. Local transport measurements in rectangular channels are needed to design many upcoming mini-/micro-scale systems. Amongst rectangular channels, a square channel provides the least wetted perimeter, for a given cross-sectional area, and therefore, is preferable from an overall pressure drop point of view. Any other rectangular variant, having the same cross-sectional area as of the square channel, leads to higher wetting perimeter; this decreases the hydraulic diameter, thereby increasing the pressure drop per unit length in the streamwise direction.

In this work, we undertake local heat transfer measurements of air–water Taylor bubble train flow in a square channel of cross-section 3.3 mm × 3.3 mm (aspect ratio ≈ 1). Gas volume flow ratio is the variable parameter. Constant heat flux boundary condition is provided at the channel bottom wall, while the other three sides are kept insulated. To estimate the local and average Nusselt number for a given heat flux condition, local temperature measurement of fluid at the center of the channel cross-section and the wall temperature at corresponding axial location along the streamwise direction, has been done for air–water (a) isolated Taylor bubble and (b) Taylor bubble train flows. Before commencing the two-phase experiments, benchmarking of the setup is done against single-phase data. Additionally, single-phase data has also been compared with trends obtained from three-dimensional numerical simulation of the experiment (hydrodynamically fully developed but thermally developing single-phase flow in one-side heated square channel, under H2 boundary condition, i.e., applied heat flux is constant axially as well as in the transverse direction) on a commercial platform (Ansys-Fluent®V6.3.26).[1] The simulation has also addressed the issue of discrepancy between the bulk-mean

[1] For brevity, details of the CFD simulations are not included here but it can be obtained from Ref. [20].