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AN EXPERIMENTAL STUDY OF LOCAL NUSSELT NUMBER FOR GAS-LIQUID TAYLOR BUBBLE FLOW IN A MINI-CHANNEL

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ABSTRACT

Taylor bubble flow or capillary slug flow takes place when a low density fluid flows through another relatively high density fluid in a tube of capillary dimensions. This kind of flow pattern is observed in many engineering devices like pulsating heat pipes, gas-liquid-solid monolithic reactors, micro-two-phase heat exchangers, digital micro-fluidics, micro-scale mass transfer process etc. The flow pattern in such device is very complex and is subjected to several unresolved issues. Hence, the understanding of the local and global behavior of such flow is important. In the present work, the temperature profile of gas-liquid (a) isolated Taylor bubbles and (b) Taylor bubble train flows has been studied on the basis of varying gas and liquid Reynolds numbers and input heat flux to understand the local and global heat transfer phenomena under specified boundary condition in a horizontal square channel. The experimental setup consists of square channel of cross section 3.3 x 3.3 mm and 350 mm in length with one side heating at constant heat flux and other boundaries are kept insulated. The heater length is 175 mm. The variation of local wall and fluid temperature are recorded to evaluate the local and average Nusselt number.

KEY WORDS*:* Taylor bubble flow, Mini-channels, Local Nusselt number, Heat Transfer enhancement

1. INTRODUCTION

Capillary slug flow or Taylor bubble flow is one of the sub-classes of conventional slug flow; this special pattern appears when surface tension dominates over gravitational body force, typically in mini-/micro-scale systems. In such geometries, the flow is essentially laminar and predominantly viscous [Bretherton 1961; Taylor, 1961; Cox, 1964]. The understanding of species transport under such a flow configuration is a challenging problem. In recent years, research on Taylor bubbles has increased due to the development of mini/micro scale systems in diverse branches of engineering wherein Taylor bubble flow is the dominant flow pattern. [e.g., refer Triplett *et al.*, 1999; Ghiaasiaan and Abdel-Khalik, 2001; Taha and Cui, 2006; Angeli and Gavriilidis, 2008; Wörner, 2010]. Pulsating heat pipes represent an important filed of application, utilizing self-sustained thermally driven passively oscillating Taylor bubble flows for enhanced heat transfer [Khandekar et al., 2010].

Taylor slug flow conditions are typically characterized by a sequence of long bubbles which are trapped in between liquid plugs; such flows therefore have strong geometric constraints. A thin liquid film, thickness of which depends on flow parameters and thermophysical properties of the fluids involved, usually always separates the bubbles from the channel wall. The presence of the film that separates the bubble from the wall means that the bubble velocity is not equal to the liquid one [Fabre and Lińe, 1992]. The presence of bubbles in front and at the back of the slugs, modifies the flow field in the liquid slug compared with single-phase flow and toroidal vortices extending the length of the slug can form [Thulasidas *et al.*, 1995, 1997]. The recirculation patterns within the liquid slugs enhances heat and mass transfer from liquid to wall and interfacial mass transfer from gas/vapor to liquid. The transport mechanisms are thus influenced by the dynamics of isolated ‘unit-cell’, consisting of a Taylor bubble and the adjoining liquid plug. Understanding transport mechanism necessitates localized experimental observations of slug-bubble systems, with synchronized measurements of the resulting fluctuations in local conditions such as temperature, pressure and wall heat flux [King *et al.*, 2007]. Such information is vital for designing micro-thermofluidic and micro-chemical reactor systems that operate in this regime.

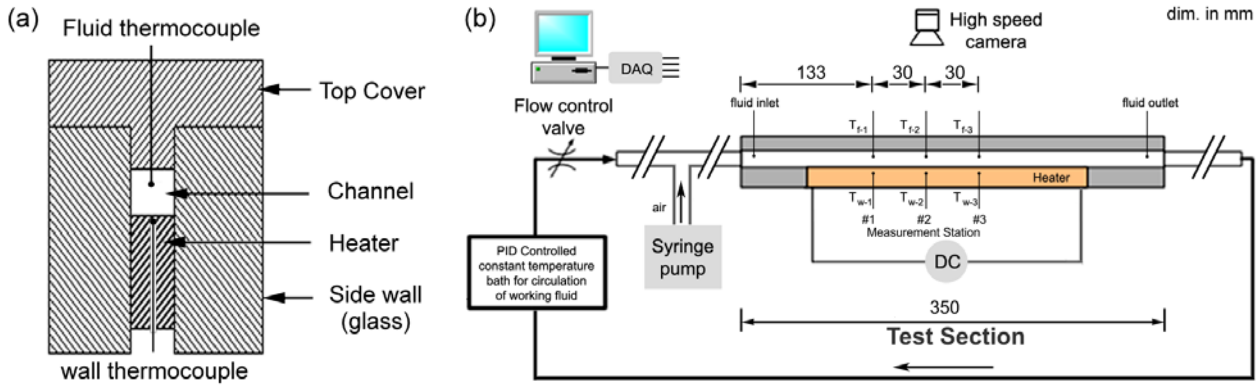

Figure 1: (a) Details of the test section and (b) Schematic details of the experimental test rig.

Bao et al. [2000] experimentally investigated non phase-change air-water flow in a circular channel of diameter 1.95 mm under constant heat flux boundary condition and observed enhancement in heat transfer coefficient due to the presence of gas. Narayanan and Lakehal [2008] conducted numerical simulation of sensible heat transfer during gas-liquid flow in small-diameter pipes and found that overall heat removal is significantly increased due to the presence of circulation as compared to the corresponding single-phase flow. Walsh et al. [2010] experimentally investigated the heat transfer rate in non-boiling two phase flow problem in a circular channel of 1.5mm of internal diameter under constant heat flux boundary conditions. They used infra red thermography to record the change in substrate temperature, to calculate the Nu. They showed that such flow pattern can be very useful for augmentation of Nu in fully developed flows, whereas, in contrast the performance degrades in case of entrance region flow. However, these observations were made without measurement of the local fluid temperature; the fluid temperature was extrapolated. In this work, we undertake local heat transfer measurements of isolated air-water Taylor bubble/ Taylor bubble-train flow, in a square channel (aspect ratio ≈1). A square channel is chosen as it provides the least wetted perimeter, for a given cross sectional area and therefore is preferable from an overall pressure drop point of view. Flow Reynolds number and the volumetric flow rate of air are the variable parameters. Benchmarking of the setup is first done against single phase data before performing the actual tests.

2. EXPERIMENTAL DETAILS

The schematic of the setup is shown in Figure 1. The channel dimensions were 3.3 mm X 3.3 mm. A constant heat flux boundary condition was applied at the bottom channel wall (DC-strip heater), while the other three channel sides were kept insulated. Heat loss to the surroundings was ~ 10%-17 % of the input heat. The side walls were made of glass for visualization of Taylor bubbles (Photron-Fastcam®-SA3 camera). The temperature profile of gas-liquid (a) isolated Taylor bubble flows and, (b) Taylor bubble train flows, was studied by varying gas and liquid Reynolds numbers and input heat flux. A precisely controlled single syringe pump (Cole-parmer-WW-74900) was used to inject air at the T-junction, as shown. The junction was located sufficiently upstream of the heated test section for achieving flow stability. Micro-Thermocouples (0.13 mm bead diameter; Type-K-Omega®) were used to measure the local wall/ fluid temperature at the three measurement stations, as shown. Thermocouples measuring the fluid temperatures were inserted from the top of the channel and were centrally located in its cross-section. Interfacial distortion of Taylor bubbles was not observed due to these thermocouples; however, they did disturb the liquid flow, as discussed later. A 24 bit DAQ (NI®-9213) was used at a sampling frequency of 20 Hz. Constant inlet temperature of distilled, degassed and deionized water was maintained within ±0.01°C by a circulator (Julabo® ME-26). The liquid flow Reynolds number was kept such that the flow was hydrodynamically fully developed but thermally developing inside the channel. The experiment was conducted in two steps. At first, the data was recorded for single-phase (water) steady-state flow at a defined flow rate. Keeping the liquid flow rate same, in the next step, air was injected to create either (i) a single isolated bubble flow or, (ii) alternately, a quasi-periodic Taylor bubble train flow; thermocouple data at the three measurement stations and image acquisition was simultaneously done.

3. RESULTS AND DISCUSSIONS

3.1 Single-phase experimental results

A typical non-dimensional plot of normalized wall and fluid temperatures versus non-dimensional axial streamwise coordinate, with constant heat flux applied to the heater, under single-phase laminar flow of water at three different Reynolds number viz. 120, 180 and 220, is shown in Figure 2. The results clearly show that the flow is developing in nature. For hydrodynamically fully developed but thermally developing flow, London and Shah [1978] suggest a thermal entry length of $z_{th} = 0.066\,\mathrm{Re}\,\mathrm{Pr}\,d_h$. It follows that for $\mathrm{Re} \le 40$, all the three measurement stations are in hydrodynamic as well as thermally fully developed regions, whereas for $\mathrm{Re} \ge 115$ all of them are in hydrodynamically developed but thermally developing region. As all the results presented here are for Re>115, it follows that these cases represent Graetz type flow. It is evident from Figure 2 that as the flow Re increases, thermal transport increasingly takes place in the thermally developing region. For Re = 120, the difference between the wall and fluid temperature tends to become constant towards the downstream direction suggesting the completion of the flow development phenomena. Several independent tests were conducted under these flow conditions and the quantitative variation in the data was within the experimental scatter range. Estimation of single-phase Nu, form this raw data, is discussed later.

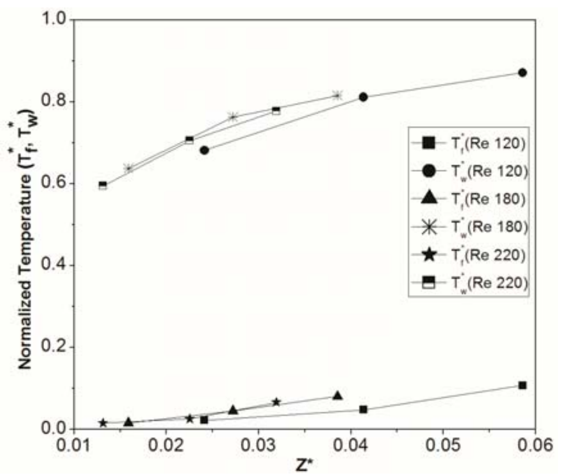

Figure 2: Streamwise variation of normalized steady state fluid and heater wall temperatures.

3.2 Single Taylor bubble flow

When steady state is reached in single-phase water flow at a given flow rate, a single isolated Taylor bubble is injected in the flow at the T-junction, which, as noted earlier, is located far upstream in the tube leading to the test section. This ensures that any flow perturbations created by sudden injection of the bubble get dissipated by the time the bubble reaches the heated test section. Typical results for the wall and fluid temperature profile respectively, at Re = 130 and heat input of 8.0 W, is shown in Figure 3(a), (b), for two bubble lengths respectively. In the present experiment, the wall temperature does not show any appreciable change as the isolated bubble passes through the three measurement stations. This is primarily because of the thermal inertia of the heater wall, its response time scale being slower than the disturbance time scale of the bubble However, once the Taylor bubble reaches the point of measurement, the bubble temperature is seen to be higher than the surrounding liquid. This is attributed to the low thermal capacity of air as compared to water. The heat flux input being constant along the streamwise direction, air temperature rises. Thus, there is a momentary apparent increase of the local heat transfer coefficient, as the difference between the wall and fluid temperature goes down. After the bubble passes, the water temperature comes back to its original level.

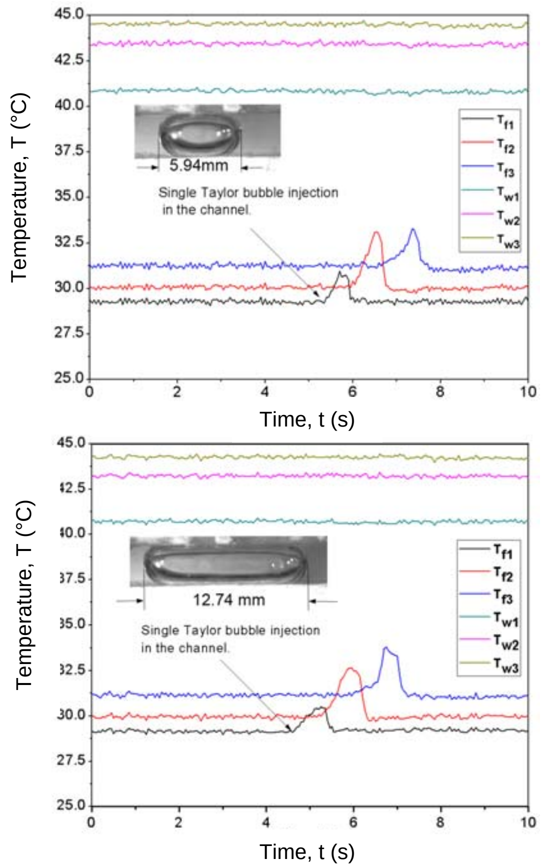

Figure 3: Temporal variation of wall and fluid temperature for a single Taylor bubble flow (Re= 130; heat input = 8.0 W).

3.3 Slug/Taylor bubble train flow

The continuous introduction of a quasi-periodic Taylor bubble train into a Graetz type flow provides the opportunity to study its effect on the effectiveness of the heat removal capability. As noted earlier, Taylor bubble train flow is achieved by injecting air from a syringe through a regulated syringe infusion pump, supplying air to the T-junction which is located far upstream. The flow rate of the air and therefore its volumetric flow ratio (ξ = the ratio of air flow rate to the total flow rate of air and water) is controlled. Results reported here are from experiments carried out at different ξ and with two flow Re, viz. 180 and 196. The fully developed flow of the Graetz-solution suggests an asymptotic constant value of Nusselt number under the said boundary condition [Shah and London, 1978]. Hence, fully developed flows saturate the heat transfer coefficient. Thermal transport enhancement under such flow conditions can be achieved by creating local flow disturbances. In the present case, this is achieved by the injection of a quasi-periodic Taylor bubble train into the liquid flow. Figure 4 (a), (b) and (c) show the temporal variation of the fluid and wall temperature versus time at the measurement station 1, 2 and 3 for a volumetric flow rate ratio (ξ) of 0.424, 0.387 and 0.321, respectively. The thermocouple data acquisition frequency is 20 Hz. Experiments starts with (i) single-phase water flow with no air-injection, followed by (ii) the commencement of air injection from the T-junction, (iii) continuation of Taylor bubble train flow till a quasi-steady state is reached and (iv) closing of the air-injection to restore the single-phase water flow. In this experimental sequence, the evolution of Nusselt number is as shown in Figure 4 (d).

No sooner the Taylor bubble train reaches the measurement stations, it causes the wall temperature to decrease at all the measurement station 1, 2 and 3, respectively. Respective wall temperatures at the measurement stations located in the streamwise direction are progressively higher. Simultaneously, an increase of the average fluid temperature is also noted, the phenomenon being similar to the single Taylor bubble case (Section 3.2). However, in the present case, as there is a continuous train of Taylor bubbles, achievement of a quasi-steady state is possible. For this large flow time scale, the wall temperature also decreases due to enhanced localized radial mixing caused by the local circulation in the liquid plugs trapped between the Taylor bubbles [Taha and Sui, 2006]. Typically, for such flow conditions toroidal vortices are present in the flowing liquid plugs which enhance the heat transfer coefficient. Due to the intermittent nature of the flow and the difference of thermal capacities of the air and

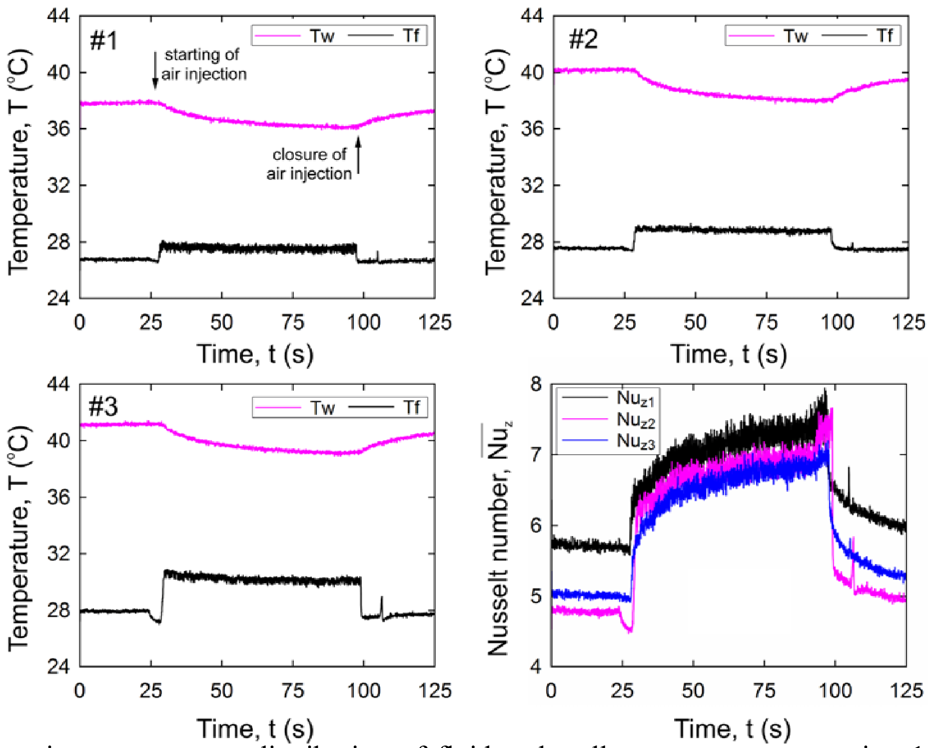

Figure 4: Transient temperature distribution of fluid and wall at measurement station 1, 2 and 3 are shown for void fraction of 0.217 in (a), (b) and (c), respectively. The liquid Reynolds number is 196. Variation of local Nu at measurement stations 1, 2 and 3 is simultaneously shown in (d).

water, the fluid temperature fluctuates quasi periodically with a dominant frequency which matches with the bubble flow time scale. The frequency spectrum analysis of the temperature data is not described here due to lack of space. The alternating pattern of liquid plug and bubble flow continually disrupts the formation of the thermal boundary layer, which gets renewed every time an air bubble passes. As can be seen in the figures, the wall and fluid temperatures come back to the original level once air injection is stopped and flow returns back to single-phase water. As can be seen from Figure 4 (d), air injection induces strong enhancement in local Nusselt number, which settles down to a new asymptotic high level once quasi-steady state is attained. Stopping the air flow brings the Nusselt number back to the level corresponding to the single-phase water flow.

For the present range of experiments, the steady-state time averaged local Nusselt number, computed at three measurement stations at various void fractions, are plotted against the non-dimensional streamwise coordinate, are shown in Figure 5. Both, results obtained from single-phase water flow experiments and Taylor bubble train flow experiments are included. Keeping the water flow rate fixed, volumetric flow ratio of air is increased by increasing flow rate of air; this results in longer lengths of Taylor bubbles. The ξ values equal to 0.451, 0.413 and 0.346 are obtained at liquid Reynolds number 180 while for Re = 196, we obtained ξ values equal to 0.424, 0.387 and 0.321, respectively. For benchmarking and comparison of the data, the average local Nusselt number for hydrodynamically fully developed but thermally developing as well as simultaneously developing flows in a square channel, under H1 boundary condition, as respectively obtained by Wibulswas [Shah and London, 1978], are also included. Results obtained from the Ansys® Fluent based CFD simulation for hydrodynamically fully developed but thermally developing flows are also shown (for brevity, details of the CFD simulations are not given here).

First, looking at the single-phase heat transfer results of the present study, it is noticed that the heat transfer coefficient is lying between simultaneously developing flow and thermally developing flow. This is predictable as, although the design of the experiment is expected to provide hydrodynamically fully developed flow, the three micro-thermocouples located in the flow path disturb the velocity boundary layer and tend to increase the local heat transfer. Overall, the single-phase results are quite satisfactory and depict the developing nature of the flow, Nusselt number gradually decreasing in the streamwise direction, as the boundary layer develops.

The results obtained for the Taylor bubble train flow clearly show that there is a significant enhancement in heat transfer when the flow is subjected to non-boiling two-phase Taylor bubble flow. It is also evident that as the void fraction decreases, $\overline{Nu_z}$ also decreases and tends to finally approach the values obtained during single-phase flow. The percentage enhancement with respect to the single-phase flow is not high in the early part of the channel. In this part of the thermal entry length, the developing nature of the single phase flow itself provide sufficiently high transport coefficient. In the latter part of the channel (Z* ~ 0.04), the advantage of Taylor bubble train flow is clearly visible. Also, it is clear that for a given flow Reynolds number, increasing volumetric flow ratio of air flow improves the Nusselt number, in the range of the present experiments.

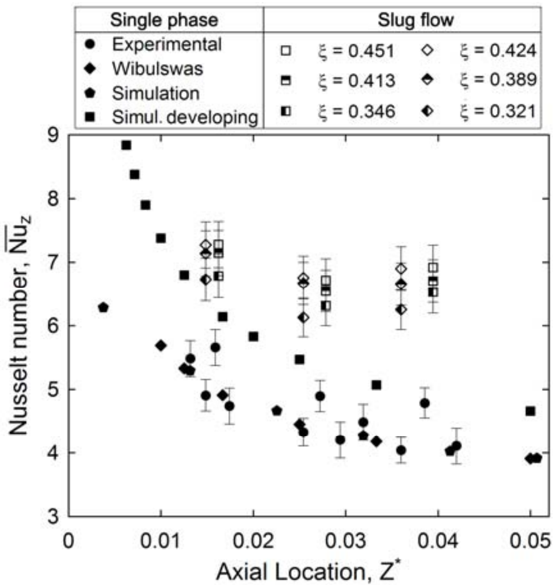

Figure 5: Variation of experimental $\overline{Nu_z}$ along the channel at various void fractions of Taylor bubble train flows, and its comparison with single-phase flow experiments, and other benchmark solutions.

Decreasing air flow rates brings the transport situation asymptotically closer to single-phase liquid flow. In contrast, as ξ increases, the liquid plug length trapped between the Taylor bubbles goes down. This increases the time scale of the recirculating toroidal vortices, improvising the Nusselt number. Logically, such an enhancement of Nusselt number with ξ will not be monotonous as after a threshold value of ξ, the flow morphology may change to churn/ annular flow.

4. SUMMARY AND CONCLUSIONS

The major conclusions of the study are as follows:

- Injection of Taylor bubbles provides an efficient means of heat transfer enhancement, up to 1.5 to 2 times, as compared to fully developed laminar single-phase. The relative enhancement may not be attractive when compared to developing single-phase flows.
- At any given location in the streamwise direction, injection of Taylor bubble train flows results in lowering of the wall temperature and increase of the average fluid temperature. Fluctuations of the wall temperature were not detectable due to the thermal inertia compared to the ensuing time scales of the transport process, when an isolated Taylor bubble is injected.
- Increasing volumetric fraction (ξ), for a fixed liquid mass flow rate, the T-junction flow mixing system resulted in longer air bubbles, i.e. smaller liquid plugs entrapped between the bubbles. This increased the time averaged local Nu, for the present range of experiments. However, such an increase may not be monotonous; this aspect needs further exploration.

NOMENCLATURE

d_h	Hydraulic diameter (m)
H1	Boundary condition refers to the constant axial and peripheral wall heat flux
Nu_z	Local Nusselt number
$\overline{Nu_z}$	Time averaged local Nusselt number
Pr	Prandtl number
Re	Reynolds number (based on liquid superficial velocity)
T_{fi}	Temperature of the fluid (ºC)
T_{wi}	Temperature of the substrate (ºC)
Z*	Thermal entry length
ξ	Volumetric flow ratio (air flow/total flow)

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