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Local instantaneous heat transfer around a rising single Taylor bubble

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ABSTRACT

Due to the complexity and intermittent nature of gas–liquid slug flow, the existing data on the local instantaneous heat transfer in this flow regime is quite limited. To gain a better understanding of the heat transfer mechanism in vertical slug flow, transient local heat transfer measurements were performed around a single rising Taylor bubble. A part of the pipe wall was replaced by a thin electrically heated metal foil. Infrared video camera was used to determine the temporal variation of the temperature field along the foil. The camera was synchronized with the passage of the Taylor bubble using an optical sensor. This arrangement made it possible to obtain ensemble-averaged data on the heat transfer augmentation as a function of the location relative to the Taylor bubble's bottom for a range of operational conditions. The effect of the local hydrodynamic parameters on the heat transfer rate is discussed.

1. Introduction

Two-phase slug flow is highly complicated and only a limited number of experimental studies on heat transfer parameters have been carried out. Vertical slug flow is characterized by a series of large axisymmetric elongated (Taylor) bubbles separated by liquid slugs. The flow field around a single Taylor bubble propagating in a vertical pipe can be subdivided into three distinct hydrodynamic regions: the gas bubble surrounded by a thin liquid film, a highly turbulent liquid wake in the vicinity of the bubble bottom, and the far wake region. Knowledge of the mean and fluctuating velocity components distribution around and behind the Taylor bubble [1] can provide a good basis for investigation of heat transfer mechanisms.

Most of the experimental studies on heat transfer in two-phase pipe flow were carried out in horizontal and slightly inclined tubes. Davis et al. [2] presented a method for predicting local Nusselt numbers for horizontal stratified gas–liquid flow under turbulent-liquid/turbulent-gas conditions. A mathematical model based on the analogy between momentum and heat transfer was developed and tested experimentally. Heat transfer parameters for continuous two-phase gas–liquid slug flow were measured by Shoham et al. [3] using an array of thermocouples. The time variations of temperature, heat transfer coefficient and heat flux were reported for different zones of slug flow. Hetsroni et al. [4,5] presented studies on heat transfer in intermittent air–water flow in horizontal and upward inclined tubes. The experimental technique was based on infrared thermography of an electrically heated wall of the tube. Measurements of the average heat transfer coefficients at various locations along the pipe were carried out by Ghajar and Tang [6] for a wide range of Reynolds numbers and different flow patterns in horizontal and slightly upward inclined pipes. The effect of Reynolds numbers and inclination on the heat transfer parameters was discussed. The mean convective heat transfer coefficient in horizontal slug flow was measured and calculated by Franca et al. [7].

Contrary to the horizontal case, only limited experiments were carried out on heat transfer in vertical slug flow. An analytical solution for the transient behavior of heat transfer in vertical upward gas–liquid slug flow was presented by Barnea and Yacoub [8]. The results allow prediction of temperature variation with time and location as well as the average heat transfer coefficients. Kim et al. [9] compared 20 correlations with previously published experimental results. No single correlation was found capable of predicting all flow conditions. Zhang et al. [10] presented an analytical model for heat transfer in gas–liquid two phase flow based on energy balance equations and analysis of the temperature differences in the liquid film, gas core and slug body. The analytical calculations were validated by experiments of Manabe [11]. Kim et al. [12] presented a correlation for the average heat transfer coefficient for turbulent vertical gas–liquid two phase flow taking into account void fraction and flow quality. The correlation was evaluated by comparing the calculated results with the experimental studies of Vijay [13], Aggour [14] and Rezkallah [15]. Heated foil infrared thermography technique was used by Hetsroni and Rozenblit [16] for the average heat transfer coefficient measurements in air–water turbulent bubbly and slug flows. Rozenblit

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et al. [17] showed experimentally that an additive of surfactant in vertical two-phase pipe flow reduces the total pressure drop and decreases heat transfer. Chang and Yang [18] examined experimentally the two-phase flow structure and heat transfer performance for air–water slug flow in a vertical pipe. Recently, some experimental [19–26] and numerical [27–30] efforts were dedicated to the determination of local heat transfer during gas–liquid elongated bubble flow in minichannels.

To improve the understanding of the transient heat transfer mechanism in slug flow, a single slug unit composed of a Taylor bubble and the liquid slug behind it was studied here. An infrared (IR) video camera, synchronized with the passage of a single Taylor bubble, was used to measure heat transfer parameters as a function of the location along the bubble and the distance from the bubble bottom, for a variety of experimental conditions.

2. Experimental facility

Experiments were carried out in a specially designed facility shown schematically in Fig. 1. It consists of an air and water supply system and a test section. The transparent vertical pipes are made of Perspex. The pipes are 6 meters long with internal diameters of 26 and 44 mm. Filtered tap water flows in a closed loop and is used as the working fluid. Water is filtered by a set of two 50 μm standard filters. Special care was taken to ensure symmetric and smooth entrance of water to the pipe. The inlet section of the pipe, shown in the inset of Fig. 1, consists of a large settling chamber, a honeycomb, a number of screens, and a converging nozzle. Water exits the pipe into a large open upper reservoir with an overflow which allows maintaining a constant water level in order to reduce pressure fluctuations. Through the overflow, water returns to the bottom reservoir to close the loop. The flow rates are regulated by taps and measured by three rotameters with maximum flow rates of 3.80 l/min, 22.9 l/min and 66 l/min. The accuracy of each rotameter is 1.6% of the full scale. The air supply system consists of an inlet air chamber and two electrically activated valves: an injection valve and a drainage valve. Air is supplied from a central compressed air line. Individual air bubbles are injected into the flowing water via a computer-controlled solenoid-activated ball valve through a pipe with an internal diameter identical to that of the test section. The air supply pipe protrudes through the honeycomb and screens. Adjustment of the inlet air pressure and the valve opening duration allows control of the length of the injected bubbles. The duration of the valve opening is controlled by software. The experimental facility was previously used for measurements of the hydrodynamic parameters in the liquid surrounding the Taylor bubble using PIV technique [1].

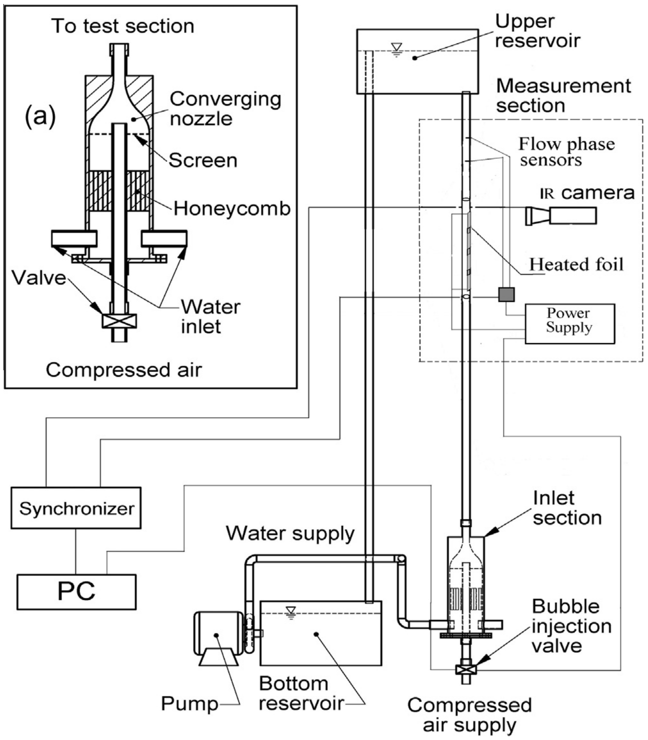

Fig. 1. Schematic of the experimental facility with heat transfer measurement unit. Details of the entrance section are given in the inset.

The heat transfer investigation is performed in the upper part of the pipes at about 5 m above the inlet, where the flow is hydrodynamically fully developed.

The measuring unit consists of T-type thermocouples, infrared (IR) camera, optical sensors and a heating unit. T-type thermocouples are installed to measure temperatures at 4 locations: in the bottom reservoir, in the upper reservoir, at the exit from the heated unit in the pipe, and outside the test section to record the environmental conditions. The temperature readings from the thermocouples are monitored and recorded by a PC. The IR camera which serves as the major measuring instrument is attached to an array of rails allowing movement in 3 dimensions. An uncooled ferroelectric sensor infrared camera with a maximum rate of 25 frames per second and a resolution of 320 × 240 pixels is used. The camera measures the radiation emitted from the sample front surface and is equipped with a lens having variable aperture and focusing control. The spatial resolution of the images is 0.175 mm/pixel. The maximum spectral response of the camera is between 2–14 μm and it has a dynamic range of 12 bits. The thermal sensitivity of the camera is 0.08 °C. The camera is connected to a PC and can be controlled by a LabView® routine.

The Taylor bubble location relative to the instantaneous imaged area has to be known to obtain ensemble-averaged quantities relative to the bubble. To this end, optical probes are used. The probes are initiated by LabView® simultaneously with the IR camera just before a Taylor bubble passage. The sample rate of the probes is 1 kHz. The optical probes can be moved easily to any location along the pipe. The distance between the probes can be adjusted to the flow conditions providing high measurements accuracy (±1%). The optical probes contain two amplified “light to voltage” sensors along the pipe. The sensors are illuminated with lasers and connected to the PC. When the bubble’s nose touches the laser beam, the beam is nudged from the sensor and the electrical circuit opens; it closes again at the instant when the laser beam enters the liquid in the bubble’s wake. Translational velocity and the length of the bubble are obtained from the synchronized data acquisition at the prescribed sampling rate.

The design of the heating unit that allows non-intrusive measurements of the local instantaneous heat transfer parameters was one of the most challenging parts of the study. An effort was made to minimize disturbance to the flow by the heating unit. In addition it was necessary to have a fast time response to temperature changes due to the passage of the Taylor bubble. Since the pipe is made of Perspex which is not infrared transparent, four successive vertical windows, $4 \times 80\ \mathrm{mm}^2$ each, were cut in the pipe wall and 12.5 μm thick stainless steel foils were used as heaters. A number of foil strips, each 18 mm wide and 400 mm long, flush with the inner wall of the pipe cover the whole inner pipe periphery including the windows. DC current heating was applied to the foils in two ways: peripheral heating – when all foils in the heating unit are operated; and a single heated foil – when only one strip is heated. Close to the top and bottom ends, each foil is covered by a thin layer of gold to facilitate electrical connections to the power