International Journal of Heat and Mass Transfer 95 (2016) 865–873

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Instantaneous heat transfer rate around consecutive Taylor bubbles

A. Fershtman, L. Shemer, D. Barnea *

School of Mechanical Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 7 December 2015
Accepted 20 December 2015
Available online 12 January 2016

Keywords:
Unsteady heat transfer
Local instantaneous heat transfer
Infrared thermography
Gas–liquid slug flow
Taylor bubble

ABSTRACT

While many studies examine the hydrodynamics of two-phase gas–liquid slug flow, the details of the heat transfer mechanism of this flow regime remain largely unknown. Analyzing the detailed hydrodynamics around a single Taylor bubble provides a basis for understanding the heat transfer mechanism. Propagation of a single Taylor bubble is approximately steady; however, in undeveloped slug flow, acceleration and coalescence of consecutive bubbles is unsteady and highly complicated. The present study is aimed to investigate the effects of developing slug flow, particularly in the region where consecutive bubbles coalesce, on the instantaneous heat transfer for different flow regimes and heating locations. To enable controlled flow conditions, experiments were carried out for two consecutive Taylor bubbles rising in a vertical pipe. Measurements of the instantaneous heat transfer coefficient as a function of the leading bubble location were carried out for different separation distances between the two consecutive bubbles. These measurements were performed for various liquid flow rates, corresponding to laminar, transitional and turbulent background flow regimes. The experiments were conducted at several locations corresponding to different heating lengths. Furthermore, a comparison between the heat transfer coefficients of a bubble that has undergone coalescence with those corresponding to a single Taylor bubble with a similar length was performed. For all conditions, it was found that the heat transfer rate is augmented in the presence of an accelerated trailing bubble. The variation of the heat transfer rates is discussed with relation to the local flow hydrodynamics.

1. Introduction

Slug flow is a two phase flow regime which occurs over a wide range of gas–liquid flow rates and for all pipe inclinations. While slug flow is very common, its complexity makes it difficult to investigate the heat transfer parameters; therefore, only a limited amount of experimental studies have been conducted. Vertical slug flow is characterized by a series of elongated axisymmetric bullet-shaped (Taylor) bubbles that are separated by liquid aerated slugs. A hydrodynamic investigation of the flow field around a Taylor bubble (Shemer et al. [1]) can provide a basis for heat transfer mechanisms studies. Three distinct hydrodynamic regions can be specified in the flow field around a propagating Taylor bubble in a macroscale vertical pipe: the gas bubble surrounded by a thin downward accelerated liquid film, a highly turbulent liquid wake in the vicinity of the bubble bottom, and the far wake region.

The majority of two phase heat transfer studies have been conducted in horizontal and slightly inclined pipes, see, e.g. Davis et al. [2], Shoham et al. [3], Hetsroni et al. [4,5], Ghajar and Tang [6] and Franca et al. [7]. Until recently, the investigation of heat transfer in vertical two phase flow was performed using approximate analytical models. Barnea and Yacoub [8] predicted the temperature variation with time and location, as well as the average heat transfer coefficient for vertical upward slug flow. An analytical heat transfer model based on energy balance equations was presented by Zhang et al. [9]; they analyzed the temperature change in the liquid film, gas core and liquid slug. Kim et al. [10] presented a correlation based on existing experimental results for the average heat transfer coefficient for turbulent background flow, considering effects of void fraction and flow quality. Comparing a variety of available two phase flow heat transfer correlations with previously published experimental results, Kim et al. [11] concluded that no single correlation can predict all flow conditions.

Hetsroni and Rozenblit [12] used a thermography technique to measure the average heat transfer coefficient for turbulent bubbly and slug flows in a vertical pipe. In recent years, heat transfer research in two-phase is focused mainly on mini and micro channels. A review on these numerical and experimental studies was presented by Bandara et al. [13].

Only few experimental studies deal with instantaneous heat transfer data during the passage of a Taylor bubble. Scammell

---

* Corresponding author.
E-mail address: dbarnea@eng.tau.ac.il (D. Barnea).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.045
0017-9310/

et al. [14] have investigated experimentally the link between the local heat transfer behind a Taylor bubble, the vortex shedding in its tail and the tail oscillations frequency. Babin et al. [15] investigated the local instantaneous heat transfer coefficient along a single Taylor bubble propagating in a co-current flow in a vertical pipe. An assessment was made of the effect of various parameters, such as the Reynolds number of the background flow, pipe diameter, bubble length, heating length and heating geometry, on the instantaneous heat transfer coefficient.

These experimental heat transfer studies have been conducted on a single Taylor bubble. As a next step towards understanding unsteady heat transfer in continuous slug flow, it is essential to investigate the local instantaneous heat transfer in the region where two consecutive Taylor bubbles interact.

Hydrodynamics of consecutive bubbles and developing slug flow have been investigated in numerous studies. Alajem Talvy et al. [16] and van Hout et al. [17] studied the effect of the separation distance between two consecutive bubbles on the trailing bubble's shape and propagation velocity and provided corresponding correlations. Additional details on the movement of two consecutive bubbles in a vertical pipe were presented by Shemer et al. [18]. The highly irregular shape that characterizes the trailing bubble was documented in Tudose and Kawaji [19] and Talvy et al. [16]. Van Hout et al. [17] evaluated statistical parameters in continuous developing vertical slug flow. They measured the ensemble-averaged velocity of the nose and tail of Taylor bubbles as a function of the instantaneous slug length ahead of each bubble. The interaction between consecutive bubbles has been studied numerically by Araújo et al. [20,21].

The goal of the present study is to gain understanding of the transient heat transfer mechanisms in developing slug flow. To this end, two consecutive Taylor bubbles were injected into a vertical pipe and an infrared (IR) camera, synchronized with the passage of the Taylor bubbles, was used to measure heat transfer parameters as a function of the location from the leading bubble bottom, for a variety of operational conditions.

2. Experimental facility

The experimental facility consists of a 6 m long transparent Perspex pipe with an internal diameter of 44 mm. Details of the facility, including description of the water and air supply systems and the injection process of Taylor bubbles can be found in Babin et al. [15].

The objective of this research is to measure the local instantaneous convective heat transfer during the passage of two interacting Taylor bubbles. The noninvasive infrared thermography technique was chosen as the major measuring instrument. To insure that the flow is hydrodynamically fully developed, the heat transfer investigation is performed in the upper part of the pipe at about 5 m above the air and water inlet. The measuring unit consists of a heated foil, T-type thermocouples, an IR camera and optical sensors.

In order to accurately measure the local instantaneous heat transfer coefficient, the measuring unit was designed to detect fast temperature changes and to avoid introducing any disturbances to the flow field. Since the Perspex pipe is not thermally transparent, four adjacent narrow vertical windows ($4 \times 80\ \text{mm}^2$) were cut along the pipe wall and replaced by a thin 12.5 μm and 40 cm long stainless steel foil. The foil is attached to the inner wall of the pipe using a special thermal adhesive, which prevents any disturbance to IR imagery. The IR camera is placed in front of a selected window. The foil's inner side is thus open to the flow and the outer side was painted with a black mat spray to maximize the emissivity. A constant heat flux, q, is supplied to the foil by a DC current power source. The estimated maximum time response of the foil to temperature changes does not exceed 34 ms. This value corresponds to a maximum distance traveled by a Taylor bubble of approximately 0.4D, which is an order of magnitude smaller than the slug unit's characteristic length.

T-type thermocouples are installed to measure the temperature at several locations: in the upper and bottom reservoirs, at the bottom of every window along the pipe, at the exit from the heated unit in the pipe, as well as outside of the test section in order to record environmental conditions. The temperature readings were monitored and recorded by a PC through National Instruments NI cDAQ-9714.

An IR camera Optris PI-450 was used. The camera is attached to an array of rails allowing movement in 3 dimensions and has a focusing control, which allows accurate measurements at different positions along the front surface of the foil. The camera has a maximum frame rate of 80 fps, a resolution of 382 × 288 pixels, a thermal sensitivity of 0.04 °C and a spectral range between 7.5 and 13 μm. The camera is connected to a PC and controlled via LabView®.

One of the objectives of the study is to find a correlation between the local heat transfer and the corresponding characteristics of the local flow field along a slug unit. Therefore, the Taylor bubbles location relative to the instantaneous imaged area has to be known. Since the IR camera presents only the instantaneous temperature distribution over the imaged foil area, optical probes are essential in order to synchronize between the bubbles' passage and the recorded thermal images. The probes and the camera are triggered by LabView® simultaneously before the Taylor bubbles reach the investigated area. The probes can be easily moved along the test section; the distance between the two probes can be adjusted to allow accurate calculation of the Taylor bubbles translational velocity, length and instantaneous separation distance. The optical probes contain two sets of light-to-voltage sensors and lasers. The sensors are illuminated by the lasers, which cause the circuit to close. When the bubble nose interferes with the laser beam, the beam is nudged from the sensor and opens the circuit; the circuit closes again once the laser beam becomes undisturbed in the liquid wake of the bubble. In other words, the optical probes record a binary signal which registers whether the laser is in front of an air bubble or of a liquid slug. The sensors data are recorded at the sample rate of 1 kHz.

To diminish environmental effects, the test section is surrounded by black PVC walls that reduce airflow over the heated surface and insure that the IR camera is not affected by ambient radiation.

Babin [22] validated the experimental procedure adopted here for hydrodynamically developed and thermally developing single phase flow. The results were shown to be in agreement with the available literature correlations.

3. Experimental procedure and data processing

Prior to studying the effect of two consecutive Taylor bubbles on the heat transfer coefficient, it is instructive to record for reference purposes the heat transfer characteristics in single phase flow, as well as during the passage of a single Taylor bubble. The experimental procedure thus consists of the following stages: calibration in a single-phase flow, measurements during a single Taylor bubble passage and finally during the passage of two consecutive Taylor bubbles.

For each measuring location along the heated foil, the local emissivity of the painted foil must be known. Each location (window) where the temperature is measured by the IR camera has a T-type thermocouple attached to foil in order to measure