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Experimental study and modeling of disturbance wave height of vertical annular flow

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ABSTRACT

Disturbance waves play an important role in interfacial transfer of mass, momentum, energy and modeling of liquid film behavior in annular two-phase flow. In view of this, air–water annular flow visualization experiments have been conducted at different gas and liquid velocity in a tubular test section having an inside diameter of 2.54 cm, and high-speed videos of vertical upflow have been analyzed to extract the liquid film and disturbance waves data by the Matlab code. The average thickness of thin liquid film has been studied as functions of both gas and liquid phase velocities, i.e. the thickness of thin liquid film increases with increasing liquid velocity and decreases with increasing gas flow, which is in the form of $\frac{\delta}{D} = 2.03\mathrm{Re}_{lf}^{0.15}\mathrm{Re}_{g}^{-0.6}$ according to the current experimental data fitting. On the basis of the thin liquid film thickness and taking the Kelvin–Helmholtz instability into account, i.e. from the perspective of the physical mechanism of disturbance wave formed, a semi-empirical model, i.e. $\frac{\Delta\delta}{D} = 1400\left(\frac{u''_g}{u_f}\right)^{-1/3}\left(\frac{(\rho_f-\rho''_g)g\delta^2}{\sigma}\right)^{5/8}$, of disturbance wave height has been proposed. Comparing the results of this model with the existing correlations available in the prediction of disturbance wave height, the model can satisfactorily predict the experimental data available in literature.

1. Introduction

Two phase gas–liquid flows are widely encountered in many different industrial applications, i.e. petroleum, chemical, civil and nuclear industries, and particularly in boiling and condensing heat transfer equipment. Annular flow is an important flow regime of two phase flow. It occurs at gas or vapor mass fraction above a few percent for pressures far from the critical in a wide range of applications such as in pressurized water reactors of nuclear power plants during a LOCA (loss of coolant accident) and in boiling water reactors during normal operation. Annular flow is normally characterized by a gas core flowing through the center of the tube; a part of the liquid, as a thin liquid film, flowing on the tube wall. The thin liquid film is composed of both thick, fast-moving disturbance wave and thin, slow-moving base film [1,2], and the thin liquid film may also contain entrained gas bubbles. While the other part of liquid as entrained liquid droplets in the gas core. As a crucial parameter, the thin liquid film thickness of annular flow has been the subject of extensive studies in the past. Kosky and Staub [3] and Okawa et al. [4] developed a model to obtain the thin liquid film thickness for vertical upward flow based upon the forces balance of the liquid film. Asali et al. [5] proposed a modification of the Kosky's correlation according to their experimental data for low liquid Reynold number. Several years later, Ambrosini et al. [6] re-correlated the Kosky's expression and Asali's correlation with a wide range of experimental data. Henstock and Hanratty [7], Tatterson et al. [8] and Fukano and Furukawa [9] investigated the thin liquid film thickness by experiments for vertical upward flow, and they also achieved the expression of the thin liquid film thickness from their experimental data. More recently, Berna et al. [10] reviewed most of the recent literature on this subject, and proposed an empirical correlation of thin liquid film thickness based on some of the open published experimental data.

Being treated as a component of the thin liquid film, disturbance wave is the most dramatic phenomena in the two phase gas–liquid annular flow. Achieving a fundamental understanding of the disturbance wave is important for a number of reasons. For example, it seems likely that disturbance wave is a necessary condition for the entrainment of droplets from wavy interfaces [1,11,12], and disturbance wave also has a dominant role in the shear stress at the interface in annular flow and measurements of wall shear stress underneath such disturbance wave reported by Martin [13] who made simultaneous measurements at the same

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Nomenclature

D	tube diameter, m
E	equilibrium entrainment fraction
f_{fi}	interfacial shear factor
g	gravitational acceleration, m/s^2
j	superficial velocity, m/s
L	axial distance from the inlet, m
Re	Reynolds number
u''_g	average velocity of the gas core, m/s
u_f	liquid phase velocity, m/s
w	mass flow rate, kg/s
We	Weber number

Greek symbols

a_e	volume fraction occupied by entrained liquid droplets
a_g	void fraction
δ	average liquid film thickness, m
$\Delta\delta$	disturbance wave height, m
λc	one dimensional Kelvin–Helmholtz critical wavelength, m
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m
τ_i	interfacial shear stress, Pa

Subscripts

f	liquid phase
g	gas phase
i	interfacial
lf	liquid film

locality of shear stress and the thin liquid film thickness. The large liquid film thickness associated with the disturbance wave corresponds to a large wall shear stress. What is more, disturbance wave also acts as a roughness to the central gas phase flow and contributes to the frictional pressure drop in annular flow. It has been also found that the motion of disturbance wave has a profound influence on the interfacial momentum transfer [14].

When a gas phase flows over a thin liquid film, several different flow regimes are possible depending on the magnitude of the gas phase velocity. For a relative small gas velocity, the interface is relatively stable; however, as the gas phase velocity increases, the disturbance wave will appear. Azzopardi [1] studied the disturbance wave in annular flow in some detail, including a review article on wave statistics in 1986 and an update to this work as part of a larger review of droplet behavior in 1997 [15]. Wave velocities and frequencies in vertical upflow increased with increasing gas and liquid flow rates, according to Hall Taylor et al. [16]. Martin [13] studied diameter effects that observed an inverse relationship between diameter and wave frequency and no strong relationship between wave velocity and diameter. Mori et al. [17] described an inverse relationship between liquid kinematic viscosity and wave frequency in vertical flow. Recently, Sawant et al. [2] investigated disturbance wave at vertical air–water flow by means of using two conductance probe traces and non-dimensional correlations for wave frequency and velocity were developed based upon their experimental data, including flow conditions at elevated pressures (1.2, 4.0, and 5.8 bar). Unfortunately, few of them devoted the researches on the disturbance wave height.

A few researchers [2,14,18–21] performed experimental work in a vertical pipe, and their experimental data confirmed that the wave height decreased when the gas mass flux increased. However, there were limited data available in the open literature and many results were provided only in the form of graphs. Only Holowach et al. [22] and Han et al. [19] obtained the expression for the disturbance wave height. Holowach et al. [22] proposed an expression for the wave height that was dependent on fluid properties and interfacial shear. This methodology came from Ishii and Grolmes [23], which assumed that the motion of the wave crest with respect to the liquid film can be expressed by a shear flow model. The height of the disturbance wave depended on the velocity difference between the two phases according to the Holowach's expression. However, for the flows of interest in the co-current upward annular flow, the gas phase velocities were much larger than the liquid phase velocities which resulted in the velocity difference between the two phases almost equaling to gas phase velocities. Thereby, the liquid phase velocity almost had no effect on the disturbance wave height according to the model. Han's expression was obtained by his experimental data fitting and found that the liquid flow rate had no influence on the wave height in the data range of their study. However, the experimental data of researchers [2,14,18,20,21] revealed that the liquid phase velocity indeed influenced the disturbance wave height. In this regard, the Holowach's model and the Han's expression diverge from reality to some extent. Hence, it is necessary to propose a new model concerning the disturbance wave height, which is the principal objective of this paper.

In view of this, in current study, air–water annular flow experiments have been performed at different gas and liquid velocity conditions in a tubular test section having an inside diameter 2.54 cm. The thin liquid film thickness and disturbance wave height are measured using the Matlab code to extract from the high-speed videos from a special designed structured channel to avoid image distortion. A semi-empirical model of disturbance wave height is proposed based on the current experimental data and the physical mechanism of disturbance waves formed.

2. Experimental apparatus

2.1. Experimental details

The flow visualization experiments have been performed on an air–water test facility available in TRSL (Thermal-hydraulics and Reactor Safety Laboratory) of Purdue University. Fig. 1 is the schematic of test facility [24].

The liquid flowing from the accumulator passes through a ball valve and a liquid magnetic flowmeter delivering to the buffer channel to distribute water to test section uniformly through three directions which have 120° angles to each other. Compressed air from gas storage tank passes through a ball valve, a filter and an air rotameter, then mixes with liquid in the two phase mixture injection system. The water flow rate is measured by magnetic flowmeter with an accuracy of ±1%, and the air flow rate is set and measured by a rotameter with an accuracy of ±4% of full scale. The mixer consists of a central porous tube having 10 μm porosity and an inside diameter similar to the test section inside diameter. Water is injected into the test section through the wall of this porous tube while air is injected from the bottom of the mixer unit directly into the test section. This method of injection is helpful