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Instability of thick liquid film under strong gas shear

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Abstract

In annular gas-liquid flow, liquid film surface is dominated by large-scale disturbance waves, which are the main source of entrainment of liquid into the gas core. These waves strongly affect pressure drop and heat transfer in annular flow, and ability to predict presence and properties of these structures is of primary importance for physical modeling of the flow. At present, neither straightforward stability analysis nor pure numerical models are capable of reproducing the experimental data. In this paper, study of wave structure is performed starting from the very inlet. After the liquid leaves the slot distributor and enters into contact with strong gas shear, an area of thick initial film exists. On its surface high-frequency waves of surprisingly strong regularity appear and develop to finally form the disturbance waves. The focus of the present paper is on measuring the properties of these initial waves to provide material for comparison to stability theories, which would make a first step towards further modeling of disturbance waves formation. The waves are studied experimentally using two independent optical techniques, both enabling spatiotemporal measurements of film thickness with high spatial and temporal resolution. Passing frequency and increments of spatial growth of the initial waves were measured by the two methods, being in reasonable agreement to each other.

1Introduction

Annular flow is a flow regime of a gas-liquid mixture in a duct which occurs at high gas velocities. In such a case the gas phase forms a continues high-speed stream in the duct core whilst the liquid phase travels as a film along the duct walls. At large gas and liquid flow rates entrainment of liquid droplets into the gas core takes place. The droplets are torn from large lumps of liquid travelling along the film surface. These lumps are referred to as disturbance waves. Stability analysis of unperturbed film in such conditions (Hewitt & Hall Taylor 1970) yields wavelength (see, e.g., Liu & Bai 2017) several order of magnitude shorter than typical distance between the disturbance waves measured experimentally (see, e.g., Dasgupta et al. 2017) Recent experimental studies show that the disturbance waves are formed very close to the flow inlet and undergo complex downstream evolution. Immediately after the inlet, short high-frequency initial waves appear, presumably to Kelvin-Helmholtz instability. Further downstream these waves undergo multiple coalescence, which leads to eventual formation of the large-scale disturbance waves [1]. Thus, modeling of disturbance waves has to start from the initial waves, observed in the vicinity of the inlet. In the present work, we focus on the experimental study of the very initial stage of waves development. Measuring the properties of these waves may provide a first step of comparison to theories to test the applicability of widely used theoretical approaches to large Reynolds numbers in both liquid and gas phases and to construct a basis for modeling the later stages of waves development.

2 Experiments

In the present work downward air-water adiabatic annular flow is studied in a 11.7 mm inner diameter vertical pipe. The inlet is organized as a tangential slot of 0.5 mm thickness (see Fig. 1). The measurements are conducted at the distances 0-40 mm beyond the slot outlet. Liquid Reynolds numbers based on the film thickness are varied in the range between 140 and 300; the range of superficial gas velocities is 15-57 m/s. Two independent optical methods of film thickness measurements are employed, namely, LIF and shadow techniques. Both techniques allowed us to perform spatiotemporally resolved measurements with high temporal (10 kHz) and spatial (40 µm/pixel) resolution. LIF technique is based on an integral form of the Lambert-Beer law, relating the brightness emitted by fluorescent dye dissolved in a layer of liquid to the thickness of that layer (see Alekseenko et al. 2015 for details). In the present study it is modified to take into account the effect of film stabilization within the proximity of the inlet, using the shadow profile of thin free falling film as a reference value. The shadow method is based on the dimensions of the backlit image of the liquid film. It was found this method can be used not only to support LIF technique, but also as a self-standing measurement technique. Despite this method is limited by two-dimensional measurements and may be vulnerable to three-dimensionality of the waves, it is applicable to study the initial waves, which were found to be two-dimensional to a large extent (see Isaenkov et al. 2017). Instantaneous film thickness profiles can be obtained with this method by application of edge detection approaches (see Fig. 2).

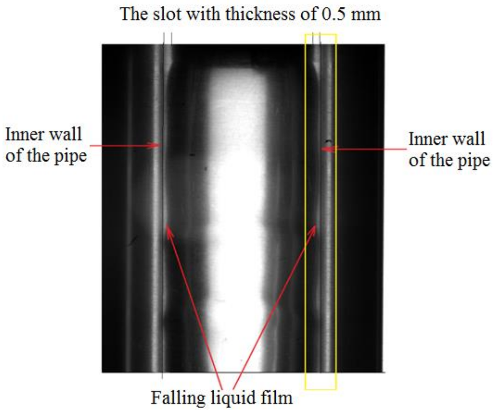

Fig. 1. Backlit image of the inlet proximity during test experiments. Flow of thin (Re_L=30) falling film (V_G=0) is shown.

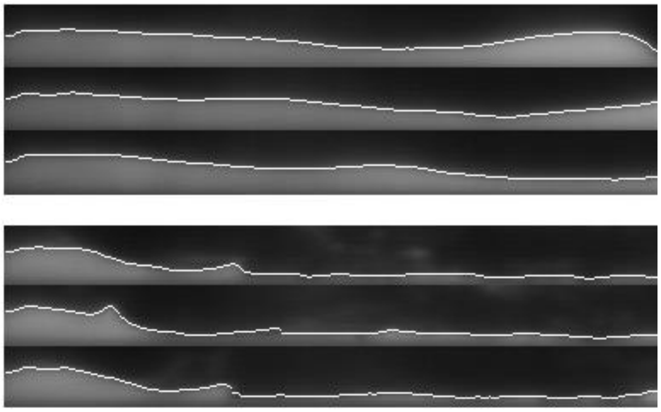

Fig. 2. Interface detection in the shadow images. Top image: Re_L=140, V_G=15 m/s; Bottom image: Re_L=300, V_G=36 m/s. Time step is 5 ms.

3 Results

Both techniques were found to be in reasonable agreement to each other in terms of film thickness measurements. At the slot outlet thickness of the liquid film is larger than that observed far downstream and even larger than the slot thickness (Fig. 2). Length of this initial thick layer increases with liquid flow rate and decreases with gas velocity. The initial waves are formed on the surface of the thick initial layer and are of two-dimensional shape (Isaenkov et al. 2017). These waves are surprisingly regular in terms of passing frequency despite the absence of any regular external perturbations. Downstream evolution of spectra of temporal records of film thickness shows existence of a prominent peak at certain frequency. This frequency remains nearly constant during the first few centimeters below the inlet within the same flow conditions. The frequencies of the initial waves grow rapidly with gas velocity and, in a weaker manner, with liquid flow rate (Fig. 3). They reach high values which are still an order of magnitude smaller than the prediction by simplified inviscid analysis by Hewitt & Hall Taylor (1970). It can be expected that modern stability theories based on Orr-Sommerfeld equations, proper evaluation of variation of shear and normal stresses along a wave's profile and thorough analysis of the dispersion relationships would yield better agreement to the data, especially if the non-equilibrium film thickness at the initial stage is taken into account.

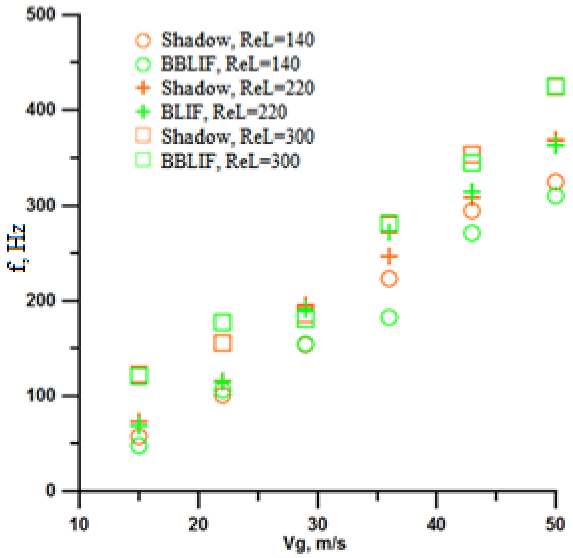

Fig. 3. Passing frequency of the initial waves.

Analysis of amplitude and phase of the main frequency shows that both amplitudes and velocities of the initial waves grow rapidly downstream. The downstream evolution of spectral amplitude of the waves shows a very short (a few millimeters) stage of linear growth, ending by saturation of the growth and, further downstream, by energy transfer to different (lower) frequencies due to coalescence of the initial waves. Within this range of distance it was possible to make a rough estimation of the increment of magnitude growth (see Fig. 4). Despite the large scatter of the data, it can be concluded that the increment grows linearly with gas velocity and rather decreases with liquid flow rate.

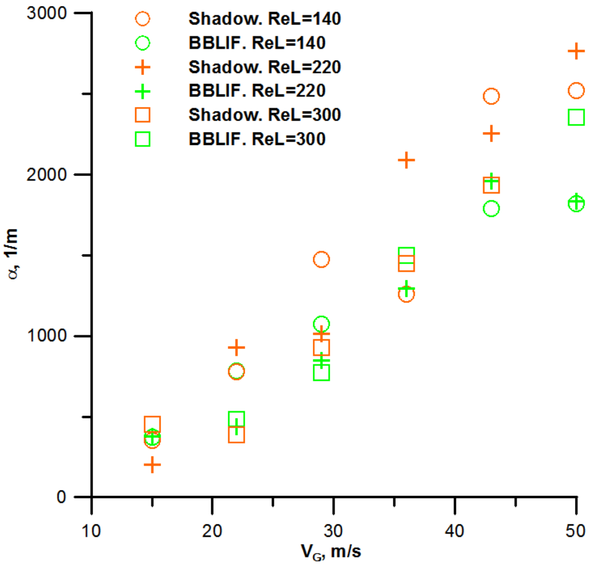

Fig. 4. Increment of spatial growth of amplitude of the initial waves.

4 Conclusions

The initial waves appearing under strong gas shear on thick liquid layer leaving a slot distributor were studied experimentally using two optical approaches. Frequency and spatial increments of magnitude growth were measured within a wide range of gas and liquid flow rates. These data are expected to be useful for validation of the stability models in the ranges of large gas and liquid flow rates which have not previously received much attention. The next logical step is to compare the obtained quantities to the properties of the waves of maximum growth in Kelvin-Helmholtz instability model. After that, modeling of nonlinear evolution of the initial waves and their coalescence into disturbance waves and further disturbance waves modeling may be possible.

Acknowledgements

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