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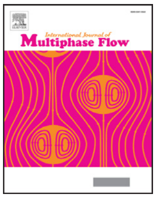

Study of formation and development of disturbance waves in annular gas–liquid flow

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ABSTRACT

Wavy structure of downward annular gas–liquid flow with liquid entrainment in 15 mm pipe was studied using high-speed laser-induced fluorescence technique. Measurements were performed near the inlet, which was organized as a tangential slot. Spatiotemporal records of film thickness were obtained over the first 100 mm of the pipe length in order to investigate formation and initial stages of development of the disturbance waves. It was shown that for high enough gas and liquid flow rates disturbance waves appear and start to dominate in the wavy structure of liquid film within the area of interrogation. Disturbance waves were found to be formed due to coalescence of small high-frequency waves appearing at the inlet. Similar mechanisms of formation of large waves with fast ripples on them were observed far downstream for waves near transition to entrainment and for ephemeral waves in flow regimes with entrainment. Significant individual acceleration of disturbance waves at the initial stage of their development was observed. Spectral analysis has shown strong energy transfer from high to low frequencies, which is in agreement to the proposed mechanism of waves formation.

Introduction

In annular gas–liquid flow liquid flows as a film along the pipe wall in presence of high-velocity gas stream in the pipe core. This flow regime exists in a wide range of industrial equipment. Integral properties of the flow (such as pressure drop and heat transfer) are substantially different from those in single-phase flows and are difficult to predict because of complex interaction between the phases. The complexity increases at large enough gas and liquid flow rates when liquid droplets are torn from film surface and entrained into the gas core. Transition to entrainment drastically increases pressure drop and heat transfer. Complexity of the film flow increases due to appearance of multi-scale surface waves, deposition of droplets from the gas core and entrapment of gas bubbles into the film. The flow properties depend on flow rates and physical properties of gas and liquid, size, shape and orientation of the duct, configuration of the inlet and distance below the inlet.

The wavy structure of film surface in presence of liquid entrainment is dominated by so-called disturbance waves. These structures represent large lumps of liquid travelling with large speed and carrying major fraction of liquid. Their height is several times larger than the thickness of base film layer between them. Surface of both disturbance waves and base film is covered with small-scale ripple waves. Presence of the disturbance waves is necessary for entrainment, since the droplets are torn from the tops of the disturbance waves. Modelling of annular flow requires understanding of structure of the disturbance waves and processes of their formation, evolution and interaction. The disturbance waves were intensively studied for over fifty years, but, due to numerous methodological difficulties, understanding of their nature is still far from perfect.

Two different interpretations of the disturbance waves are available in literature. According to the first interpretation, the disturbance waves are considered to be high-amplitude nonlinear waves with steep front, shallow rear slope and well-pronounced crest. This shape resembles the shape of solitary waves observable on thin falling films. The disturbance waves indeed have such appearance in the temporal records of film thickness obtained with pointwise low-resolution measurement techniques such as conductance probes (Chu and Dukler, 1974; Han et al., 2006; Al-Sarkhi et al., 2012; Zhao et al., 2013).

Application of spatially resolved methods results in different appearance and, hence, different interpretation of the disturbance waves. As it was first reported by Hewitt et al. (1990), the

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disturbance waves resemble relatively shallow plateaus covered by high-frequency large-amplitude ripple waves. By now this interpretation is supported by numerous observations using planar laser-induced fluorescence approach (Schubring et al., 2010; Farias et al., 2012; Zadrazil et al., 2014) and backlit side-view visualization (Pham et al., 2014; Setyawan et al., 2014; Pan et al., 2015). Alekseenko et al. (2008) studied both spatially and temporally resolved film thickness data and observed that the ripples are generated at the rear slopes of the disturbance waves, and may either accelerate and travel over the disturbance waves or decelerate and slide back to the base film. The scenario of evolution of a particular ripple was shown to be defined by the relative coordinate of the point of its inception. Such spatiotemporal behaviour could be explained by existence of eddy motion under the humps of the disturbance waves (Alekseenko et al., 2009). Recently, Hall Taylor et al. (2014) proposed a model for the disturbance waves in which eddy motion plays the central role. Zadrazil and Markides (2014) observed numerous eddies inside the large waves on thick falling films.

Choosing one of the two interpretations of the disturbance waves exerts important influence on the further line of thought. For example, different hypotheses about the mechanism of liquid entrainment correspond to different interpretations of the disturbance waves. Another – more relevant to the goal of the present paper – consequence is selection of a criterion of identification of the disturbance waves. This implies in the development of a suitable method to distinguish the disturbance waves among the waves on film surface and to understand whether the disturbance waves are present or not in particular flow conditions. The first interpretation implies that the differences between the disturbance waves and any other waves are mainly quantitative. This usually leads to development of semi-empirical amplitude-based criteria. E.g., a wave could be counted as a disturbance wave if its profile crosses the level of mean film thickness twice (Chu and Dukler, 1974) or if its height overcomes the mean film thickness more than 1.6 times (Zhao et al., 2013). Usage of the second interpretation leads to criteria related to presence of ripples on top of the disturbance waves. Based on the aforementioned observations of Alekseenko et al. (2008) it can be proposed to define disturbance wave as a wave generating ripples faster than the wave itself. This criterion will be used in further analysis throughout the paper.

Border of the area of existence of disturbance waves in flow maps is of hyperbola-like shape (Woodmansee and Hanratty, 1969; Andreussi et al., 1985). Area of existence of the disturbance waves encompasses the area of presence of entrainment; the former is only slightly larger than the latter. Exact position of the border depends on numerous factors. Flow orientation stronger affects the region of low gas and large liquid flow rates. The border is shifted depending on whether gravity exerts stabilizing or destabilizing influence on the waves. Thus, in vertical flow transition to the regimes with the disturbance waves occurs at lower gas velocities than in horizontal flows. In downward flow the disturbance waves are considered to appear even at zero gas velocities at large liquid flow rates (Webb and Hewitt 1975). In particular, Zadrazil and Markides (2014) reported existence of fast ripples on top of large waves at thick falling films. At moderate liquid flow rates and low gas velocities the disturbance waves coexist with waves typical to falling film regimes (Webb and Hewitt, 1975). Despite various quantitative differences, disturbance waves in flows of different orientation most likely belong to the same type of waves, since the processes of generation of fast and slow ripples are qualitatively the same in different conditions (Cherdantsev et al., 2014).

Liquid viscosity is more important in the region of low liquid and high gas flow rates; its increase shifts this part of the border towards even lower liquid flow rates. In this region, transition line is so steep that the idea of critical liquid Reynolds number Re_{Lcr} is often used for practical purposes (Ishii and Grolmes, 1975). Below Re_{Lcr} the film is covered by waves of two types, termed as “primary” and “secondary” waves (Alekseenko et al., 2009). Faster primary waves generate slower secondary waves on their back slopes exactly as the disturbance waves generate the slow ripples. Nonetheless, the primary waves cannot be counted as the disturbance waves, since the secondary waves normally do not travel faster than the primary waves and, hence, do not climb over them.

In the disturbance waves region, two other types of waves – except disturbance waves and ripples – are sometimes specified (Sekoguchi and Takeishi, 1989; Sekoguchi and Mori, 1997). The huge waves are distinguished from the disturbance waves by even larger amplitude, size and velocity. They are mostly observed at low gas and large liquid flow rates and are supposedly related to transition from slug/churn to annular flow. The ephemeral waves appear at the rear slopes of the disturbance waves and lag behind them, moving over the base film. This behaviour is similar to that of slow ripples, but the ephemeral waves are much larger in amplitude than the slow ripples and are much rarer. Wolf et al. (1996) supposed that appearance of the ephemeral waves is related to excess film flow rate, which is gathered due to deposition of droplets from the gas core.

The flow is considered to be stabilized at the distances of several meters below the inlet (100–150 pipe diameters, according to Wolf et al., 2001). Between the inlet and the stabilization region local properties of the flow (including film properties) undergo essential changes. In particular, velocity of the disturbance waves grows with downstream distance (Azzopardi, 1997; Wolf et al., 2001), whereas the passing frequency essentially decreases (Hall Taylor and Nedderman, 1968; Zhao et al., 2013). The latter occurs due to coalescence of the disturbance waves, when a faster wave overtakes a slower one and a new wave is formed. As it was observed by Hall Taylor et al. (1963) and recently confirmed by Alekseenko et al. (2014), at large enough distances below the inlet the waves appearing due to coalescence most likely travel with the velocity of the faster coalescing wave. Without coalescence a disturbance wave may travel over large distances with constant velocity (Hall Taylor et al., 1963).

Formation of the disturbance waves occurs not far from the inlet (Hanratty and Engen, 1957; Hall Taylor et al., 1963; Zhao et al., 2013). Upstream the point where the disturbance waves are first observed, the film is covered by wavelets of high frequency and small amplitude (Zhao et al., 2013). It is still unclear if there exists any kind of interrelation between the initial waves and the disturbance waves appearing downstream. Hanratty and Hershman (1961) and Andreussi et al. (1985) developed a model in which formation of the disturbance waves occurs due to instability of gas-sheared films to long-wave perturbations. The calculated neutral stability conditions showed good agreement to the regime maps of existence of the disturbance waves in horizontal flow.

By present time, no direct experimental studies of process of formation of the disturbance waves were made. The goal of the present paper is to study the formation and the initial stages of development of the disturbance waves. For this, spatiotemporal measurements of film thickness were performed in the vicinity of the inlet.

Experimental setup and measurements technique

In the present work, downward adiabatic air–water flow is studied. The full scheme of the flow loop is described, e.g., in Alekseenko et al. (2012). Test section is a vertical cylindrical acrylic resin pipe with length of 1 m and inner diameter $d = 15$ mm (Fig. 1). Gas enters the working section trough coaxial metallic tube with inner diameter of 13.4 mm and wall thickness 0.3 mm. Liquid enters through a ring-shaped tangential slot between the inner surface of the main pipe and the outer surface of the gas-feeding tube. Under such configuration of the inlet, liquid is introduced as a film, and annular flow regime takes place from the very beginning.

Superficial gas velocity, V_g, and liquid Reynolds number, Re_L, were chosen as quantities characterizing the flow rates of the phases.