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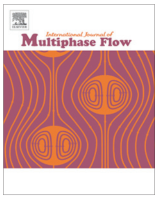

Analysis of spatial and temporal evolution of disturbance waves and ripples in annular gas–liquid flow

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ABSTRACT

Wavy structure of liquid film in downward annular gas–liquid flow is studied with high-speed laser-induced fluorescence technique. Film thickness measurements are resolved in both longitudinal distance and time with high spatial and temporal resolution. A method is developed to identify the characteristic lines of individual disturbance waves. Change of frequency of disturbance waves with downstream distance is modelled based on the obtained distributions of the disturbance waves by velocity and separation time. Using obtained characteristic lines further investigation of ripples' properties is performed in reference system moving with the disturbance wave. As a result, velocities, amplitudes and frequencies of ripples are measured with relation to the distance from disturbance waves. Fast ripples travelling over crests of disturbance waves and slow ripples travelling over back slopes of disturbance waves and over the base film are studied separately. Besides, the average length of crest and back slope of disturbance waves were measured.

Introduction

In annular flow liquid film is flowing along pipe walls, sheared by high-velocity gas stream. At high enough gas and liquid flow rates liquid droplets are entrained from film surface into the core of gas stream. This flow pattern occurs in a wide range of industrial equipment, and prediction of its integral characteristics (in particular, entrainment rate and pressure drop) is of high practical importance. Appearance, evolution and interaction of waves on the film surface are the key processes, defining the mentioned characteristics. Any physical models of the flow should be based on the waves' dynamics and their interaction to the gas shear. To create such models, experimental information on the wavy structure of liquid film is necessary.

Wavy structure of liquid film in annular flow with liquid entrainment is represented by large-scale disturbance waves and small-scale ripple waves. Disturbance waves are separated by thin base film layer; ripples are travelling either over the base film surface or over the disturbance waves. Presence of disturbance waves is considered to be the necessary condition for the inception of entrainment (Azzopardi, 1997). They are distinguished from the ripples by large values of amplitude, velocity, longitudinal size and lifetime.

In the last fifty years large number of experimental works was devoted to studying the properties of disturbance waves. Disturbance waves are created not far from the liquid inlet. Supposedly, they are formed from the high-frequency small-amplitude initial disturbances (e.g., Zhao et al., 2013). Properties of individual disturbance waves vary in a wide range of values. In particular, their velocity obeys normal distribution; its standard deviation is nearly constant at different gas velocities (Hall Taylor and Nedderman, 1968). Due to variation in velocity, multiple events of coalescence of individual disturbance waves occur. Because of coalescence, frequency of disturbance waves gradually decreases downstream. In most cases, when a faster wave overtakes a slower one, the resulting wave moves with the velocity of the faster wave (Hall Taylor et al., 1963). Under this scenario of coalescence, the average velocity of disturbance waves is expected to increase downstream (Azzopardi, 1997). Average amplitude of disturbance waves is also expected to increase downstream, since the velocity of individual disturbance waves is proportional to the waves' amplitudes. Without coalescence, disturbance waves pass large downstream distances with nearly constant velocity.

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Properties of disturbance waves are affected by flow parameters as well. Passing frequency and velocity of disturbance waves grow linearly with superficial gas velocity, whereas the amplitudes of disturbance waves decrease with gas velocity. Increase of liquid flow rate leads to increase in all these properties (e.g., Chu and Dukler, 1975; Azzopardi, 1986; Han et al., 2006; Sawant et al., 2008). Longitudinal size of disturbance waves does not change much with gas velocity (Han et al., 2006). Frequency of disturbance waves is larger in small diameter pipes (Alamu and Azzopardi, 2011).

Transverse size of disturbance waves is larger than their longitudinal size. The disturbance waves form full rings around the pipe circumference in small diameter pipes. In larger pipes circumferentially localized disturbance waves appear and the fraction of localized disturbance waves increases with pipe diameter (Azzopardi, 1997). Amplitudes of disturbance waves are not uniform along the circumferential coordinate (Belt et al., 2010; Alekseenko et al., 2012).

Ripples are less studied; they were mostly studied independently of disturbance waves. Chu and Dukler (1974) measured amplitude, velocity and longitudinal size of ripples on the base film. They found that ripples have very short lifetime in comparison to that of the disturbance waves.

The majority of mentioned works used either high-speed imaging visualization or conductance technique to study the disturbance waves. The former does not give any quantitative information on local film thickness; the latter has low spatial resolution and is unable to provide information on the properties of ripples and on structure of disturbance waves. In temporal records of film thickness obtained with conductance probes disturbance waves normally look like smooth high-amplitude waves with steep fronts, shallow rear slopes and pronounced crests. The shape is quite different when studied with high-resolution techniques such as planar laser-induced fluorescence (PLIF). In PLIF data, disturbance waves look like relatively flat ‘plateaus’ of higher thickness, covered with high-amplitude ripples (Hewitt et al., 1990; Schubring et al., 2010a; Farias et al., 2012; Zadrazil et al., 2014). Schubring et al. (2010a) performed separate study of film thickness behaviour in the base film zone and in the disturbance waves’ zone. They have shown that the average thickness in the waves’ zone is approximately twice larger than that of the base film. Standard deviation of film thickness (related to the amplitude of ripples) is 0.3 of the average film thickness in the base film region and 0.2 in the waves region. All the mentioned ratios were shown to be the same for a wide range of gas and liquid flow rates. Pham et al. (2014) performed visualization of gas-sheared liquid film at the outer surface of a cylinder (part of a rod bundle). The film surface profile was obtained with high-speed video. In these data the fast ripples on disturbance waves can also be observed. They appear in the rear part of the disturbance wave and move toward its front. It was found that the fast ripples can be disrupted to droplets by the gas shear near the front of a disturbance wave.

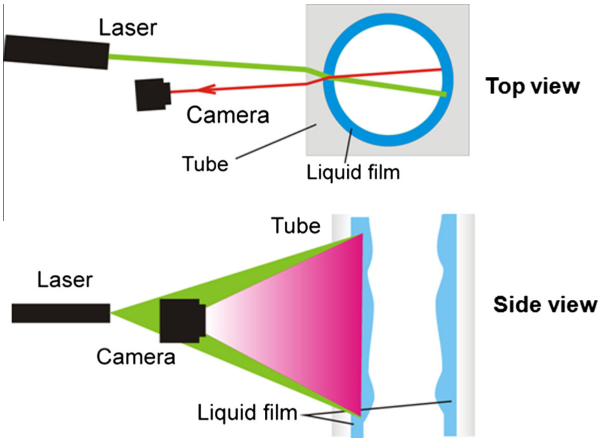

Fig. 2. Layout of camera and laser.

Alekseenko et al. (2008, 2009) used LIF technique in rather different approach, which could be called ‘brightness-based LIF’. They studied the spatio-temporal evolution of the film surface with good spatial and temporal resolution in one longitudinal section of the pipe with length 10 cm and duration of 2 s. In particular, it was found that all the ripples are generated at the rear slopes of the disturbance waves. Depending on the relative position of the point of origin, the ‘newborn’ ripples might travel either faster or slower than ‘parent’ disturbance waves. The slow ripples slide back to the base film behind the parent disturbance waves and travel over the base film with nearly constant velocity until the following disturbance wave absorbs them. The fast ripples travel over the parent disturbance wave toward its front and disappear there. This disappearance is supposed to occur due to disruption of the fast ripple by the gas shear into droplets, as it is was first observed by Woodmansee and Hanratty (1969).

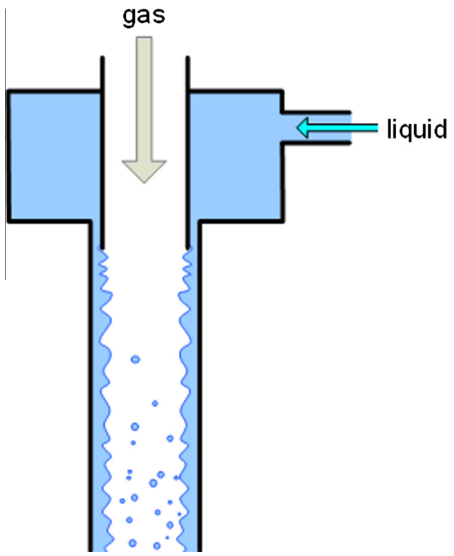

Fig. 1. Scheme of the inlet section.

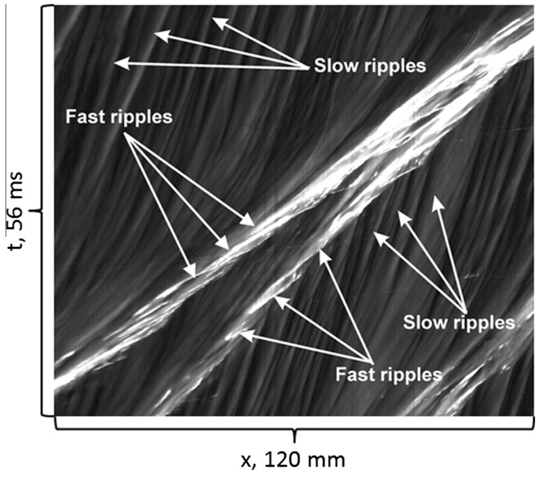

Fig. 3. Example of spatial and temporal fragment of film surface.

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