Spectral analysis of wavy structure of thin liquid films under strong gas shear

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Summary Wavy structure of thin liquid film, sheared by high-velocity gas stream, was investigated using laser-induced fluorescence technique. Spectral analysis was performed in both spatial and temporal domains. Influence of flow parameters on spectral structure of film thickness records was investigated. Self-similarity of power spectra at essentially different velocities of gas stream was observed in the region where gas shear is much higher than gravity.

Annular flow represents flow of liquid film along the walls of a duct in presence of high-velocity gas stream. When the gas shear dominates over gravitational force, the wavy pattern and characteristic scales of liquid film flow become essentially different. Film is accelerated several times by the gas shear and its thickness decreases proportionally. Recent studies using laser-induced fluorescence (LIF) technique [1] showed that at low liquid flow rates two-wave structure appears at the film surface, with fast long-living primary waves generating slow short-living secondary waves on their back slopes. This structure is similar to that of the annular flow with thicker films, characterized by appearance of high-scale disturbance waves and entrainment of liquid from the film surface into the gas core [2]. While the wavy structure in regimes with entrainment was studied for long time, flow regimes without liquid entrainment require the systematic investigation.

LIF method provides the possibility to obtain film thickness data, resolved in both space and time. Spatial and temporal resolution (0.2 mm and 0.2 ms, respectively) of this method are sufficient to get all the necessary information about waves of different scales. Obtained data can be presented in form of x-t-surfaces of film thickness. Figure 1 shows two examples of such surface for no-entrainment regime. Horizontal axis corresponds to longitudinal coordinate (total length is 100 mm), vertical axis corresponds to time (total length 100 ms). Brightness is directly proportional to local film thickness. Brighter bands with large slopes to the vertical axis (i.e., higher velocity) represent primary waves (flow direction is from left to right); darker bands with lower velocity, beginning at the rear side of primary waves, represent secondary waves.

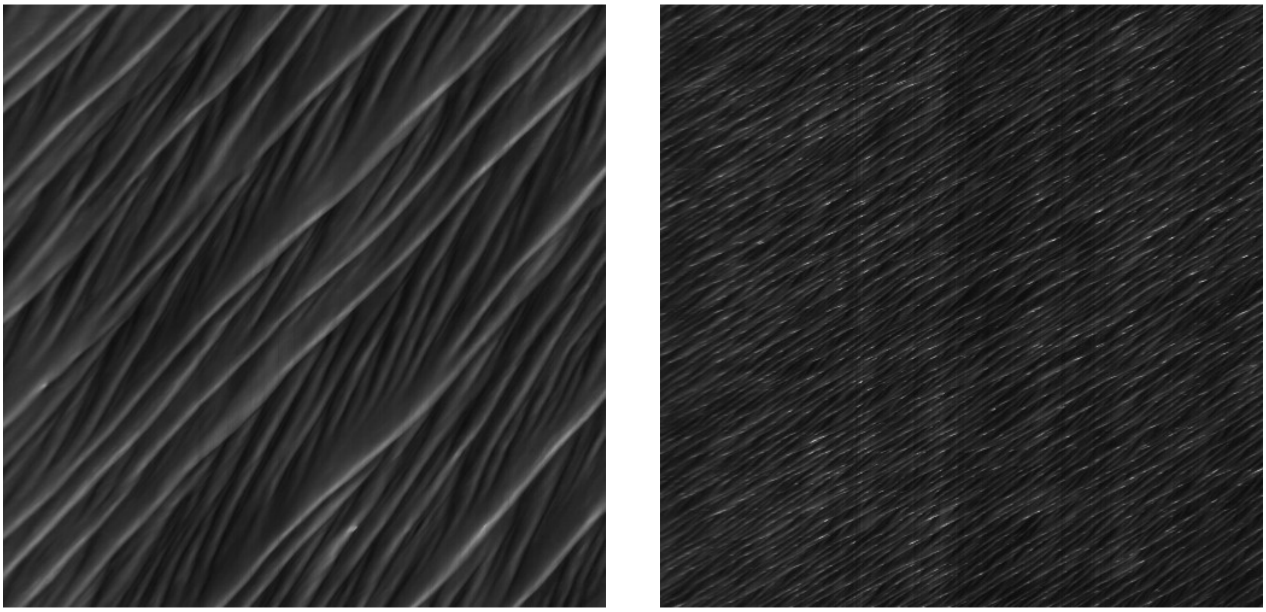

Figure 1. Spatial and temporal evolution of waves on liquid film surface. Downward annular flow in 15mm i.d. pipe, liquid Reynolds number 40, liquid viscosity $2*10^{-6}$ m^2/s. On the left: gas velocity Vg=27 m/s; on the right: Vg=58 m/s.

It can be seen that the increase in gas velocity leads to the increase of velocity and both temporal and spatial frequencies of waves, simultaneously decreasing amplitude of waves. To study the effect of gas flow on the wavy structure of liquid film, spectral analysis was applied. Since the data are resolved in space and time, such analysis can be performed in both spatial and temporal domains. Spatial and temporal sizes of the area of averaging the signal are much less than spatial and temporal size of waves. At the same time, total sizes of spatial and temporal area of measurements (12 cm and 2 seconds, respectively) are much larger than spatial and temporal periods of the signal. For each realization temporal spectrum of the signal represents the average of 600 temporal spectra, obtained in 600

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different coordinates, and spatial spectrum is, respectively, the result of averaging of 10000 spatial spectra, obtained in different moments of time.

Power spectra in both domains are characterized by one-humped shape with long exponential tail. Increase in the gas velocity leads to the increase in frequency of maximum power, and to decrease in total power of the spectrum (see left-hand part of Figure 2). Comparison to the results of application of developed by our group algorithm of data processing [3] shows that frequency of maximum power corresponds to the frequency of primary waves. Temporal frequency shows parabolic dependence on Vg, spatial frequency shows linear dependence on Vg. Influence of liquid viscosity, liquid Reynolds number and pipe diameter on the main properties of primary waves was also investigated.

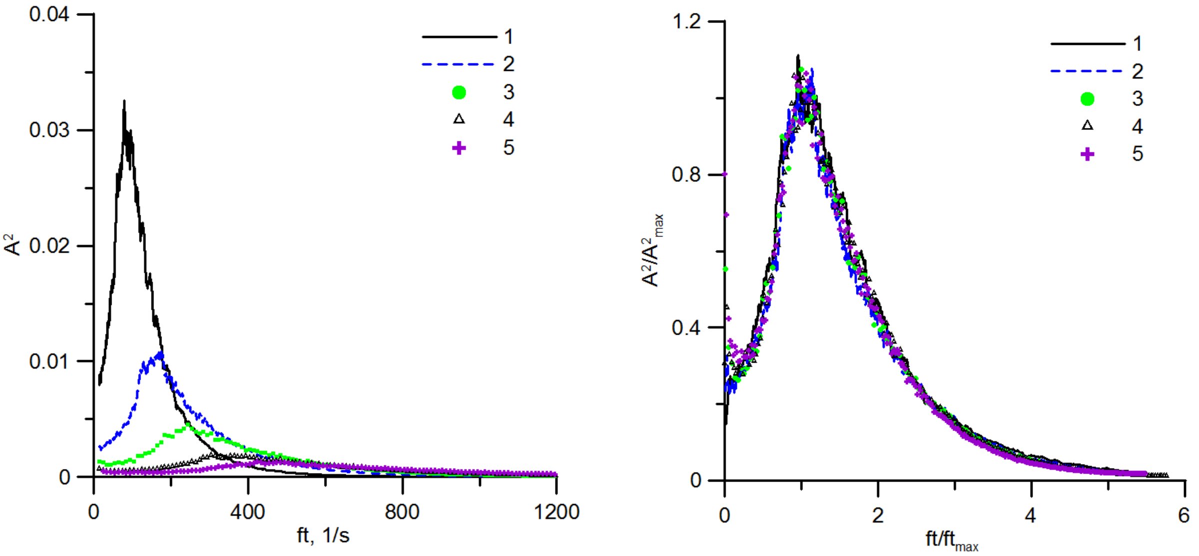

Figure 2. Example of power spectra of film thickness records in temporal domain. Re=20, working liquid – water. Vg=27 m/s (1), 36 m/s (2), 44 m/s (3), 52 m/s (4), 58 m/s (5).

The similarity of power spectra at different gas velocities was observed. Power spectra, linearly normalized along vertical axis by total power, and linearly normalized along horizontal axis by frequency of maximum power, show identical shape independently on Vg (right-hand part of Figure 2). Deviations from this universal shape become essential at low gas velocities, where gravity effect is not negligible in comparison to the shear stress. Thus, wavy structure of liquid film in annular flow at high gas velocities is characterized by the universal spectrum. Influence of gas velocity can be described by linear change of scale.

Additional investigation was performed to obtain the frequency of generation of the secondary waves by the primary waves. Combination of spectral analysis and mentioned above automatic algorithm allowed to measure the generation frequency in the reference system, moving with the primary wave. It was shown that the generation frequency shows very similar dependence on flow parameters, as the frequency of the primary waves does.

Acknowledgements

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