Application of high-speed LASER-induced fluorescence technique for studying annular gas-liquid flows

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Wavy structure of liquid film in annular gas-liquid flow was studied using high-speed modification of LIF technique. At high enough gas and liquid flow rates entrainment of liquid from film surface into the core of gas stream occurs.

Experiments were performed in downward annular flow, organized inside vertical cylindrical tube with inner diameter 15 mm. Measurements were performed at the distances 5-20 cm and 55-70 cm below the inlet. Superficial gas velocity varied in the range of 14-58 m/s. Two working liquids were used during experiments: distilled water and water-glycerol solution with kinematic viscosity of 3 cSt. Liquid Reynolds numbers Re varied from 18 to 350. Re was defined as \( \frac{q}{\pi d v} \), where \( q \) is volumetric liquid flow rate, \( d \) – tube inner diameter and \( v \) – kinematic viscosity of liquid. Low Re (less than 70 for water and less than 40 for water-glycerol solution) corresponded to flow regimes without entrainment, and high Re – to the regimes with entrainment. Rhodamin-6G in low (30 mg/l) concentration was used as fluorescent matter.

Experiments were performed in 2D and 3D approaches. The former provided measurements with high temporal resolution along one longitudinal section of the channel, and the latter gave possibility to study three-dimensional structure of liquid film.

Analysis of spatial and temporal evolution of local film thickness in regimes with entrainment in 2D-approach has shown that ripple waves do not appear randomly. All the ripple waves represent the result of secondary instability of film surface on the back slopes of disturbance waves. Areas of inception of ripple waves are limited by back slopes of disturbance waves and divided into two adjoining parts.

Ripples, generated in the part closer to disturbance wave’s crest, go faster than parent disturbance wave, and are disrupted by the gas shear, contributing to entrainment. Ripples, generated in the other part, move slower than parent disturbance wave, and at the end they are being absorbed by the following disturbance wave. In flow regimes without entrainment we observed two types of waves, in contrast to the generally accepted picture.

The two types differ significantly in lifetime and velocity, and, moreover, faster long-living waves generate slower short-living waves on the back slopes. Behavior of these two types of waves (that we named primary and secondary waves, respectively) is rather similar to the behavior of disturbance waves and ripples, observed in entrainment regimes. The main difference between regimes with and without entrainment consists in the absence of fast secondary waves in regimes without entrainment. This is possibly related to low amplitude of primary waves in regimes without entrainment, in comparison to the amplitude of disturbance waves. Thus, transition to entrainment with liquid flow rate increasing, supposedly happens due to sharp growth in amplitude of primary waves, not due to appearance of new disturbance waves, as it was supposed earlier.

Three-dimensional structure of waves was also investigated. Transverse size of primary waves is always larger than that of working area (12 mm). Primary waves are localized by transverse coordinate, and do not form full rings around the circumference of the tube. Generation of secondary waves takes place at the edges of primary waves as well as at the central parts of primary waves. Secondary waves of ‘flat’ shape and ‘horseshoe’ shape were observed in present experiments. Both waves belong to the same type, and the only difference between them is caused by peculiarities of generation process.

Existance of transverse instability of primary waves at high liquid Reynolds numbers was shown. In regimes with high Re height of crests of primary waves changes essentially in transverse direction (see Figure).

Regions, where crest is higher, generate secondary waves more frequently. In regimes with entrainment areas of higher crests do also generate fast secondary waves more often. Characteristic transverse size of secondary waves in case of high Re is limited by ‘wavelength’ of transverse instability.