Change in wave characteristics during the transition from gravitational to shear flow of gas-sheared liquid films

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Abstract. The evolution of thin liquid films sheared by a co-current gas flow in a vertical cylindrical channel with an internal diameter of 11.7 mm was studied using a high-speed implementation of the laser-induced fluorescence method. The main purpose of the work was to study the characteristics of the waves during the transition from the gravitational to the shear flow regime. The effect of gas velocity, liquid Reynolds number, and liquid viscosity on wave characteristics has been studied.

Introduction
With the flow of gas-sheared liquid films, flow regimes with dominance of gravity ("gravitational" mode) and with dominance of friction from the gas side ("shear" mode) can be distinguished. In the gravitational mode, the film surface is covered with solitary nonlinear waves with a pronounced capillary precursor. The characteristics of such waves were measured in a large number of works [1-3]; also, theoretical models [1, 4] that provide satisfactory agreement with experiment are well developed for this region. When the film is sheared by high-speed gas flow, the capillary precursor is suppressed, but slower secondary waves are generated on the rear slopes of the waves [5]. Much less attention has been paid to measuring the wave characteristics in the shear mode [6–7]; isolated studies [8–9] are devoted to theoretical modelling of waves in this mode. To facilitate the modelling of the shear mode, it seems reasonable to experimentally study changes in the wave pattern during the transition from the gravitational mode to the shear mode. At a qualitative level, such a study was carried out in a recent paper [10]; in this work, the regime borders for the existence of secondary waves and capillary precursor were determined. It was found that the transition occurs in the range of average flow rates of gas from 8 to 16 m/s. This behaviour is observed for the whole investigated range of liquid Reynolds numbers from 10 to 60. It was also hypothesized that the suppression of the capillary precursor occurs due to its interaction with secondary waves. This work is a continuation of work [10] and is devoted to a quantitative study of changes in the characteristics of primary waves in the transition region, which was previously not given due attention.

Experimental setup and measurement technique
The studies were carried out in the downwards adiabatic flow of gas-sheared liquid films in a vertical cylindrical channel with an inner diameter of 11.7 mm. The liquid was supplied to the walls of the channel through a slot distributor 0.5 mm wide (see Fig. 1) and wetted the entire inner surface of the pipe. The measurement area is one longitudinal section of the channel (two-dimensional approach) at a distance of 20-30 cm from the inlet. In regimes without liquid entrainment, flow is fully developed at small distances below the inlet [11]. Superficial gas velocity \( V_g \) varied in the range from 0 to 24 m/s,
and the Reynolds number of the liquid, $Re$, from 10 to 60 (in increments of 10). Distilled water with kinematic viscosity $\nu = 1.15 \times 10^{-6} \text{ m}^2/\text{s}$ (at a working temperature of 16 °C) and water glycerin solutions WGS1 ($\nu = 2 \times 10^{-6} \text{ m}^2/\text{s}$) and WGS2 ($\nu = 3.5 \times 10^{-6} \text{ m}^2/\text{s}$) were used as working liquids.

![Figure 1. Scheme of the inlet and two-dimensional LIF method.](image)

The method of laser-induced fluorescence (LIF) was used to measure the local thickness of the liquid film. Fluorescent dye (Rhodamine-6G) at a concentration of 10 mg/l was dissolved in the working fluid. A continuous laser with a power of 2 W and a wavelength of 532 nm was used as the light source. A detailed description of the LIF method can be found in [11]. In these experiments, the sampling frequency is 5 kHz; spatial resolution - 0.1 mm/pixel.

**Data processing**

In this paper, an algorithm was used to automatically search for the characteristic lines of the primary waves. The algorithm is based on the search for local maxima of the film thickness in each longitudinal section, the values of which are greater than the specified threshold value $h_T$. The value of $h_T$ was chosen so that it exceeded the average amplitude of the secondary waves and is equal to $1.1 \times h_m$, where $h_m$ is the average thickness of the liquid film. To increase the efficiency of the search for the characteristic lines of the primary waves, a procedure was carried out to smooth the spatial records of the film thickness, which prevented the identification of random noise on the film surface. The size of the smoothing window was less than the characteristic wavelength for a given regime point. The local maxima found at different times are combined into characteristic lines. An example of the spatial-temporal evolution of the liquid film thickness profile with marked characteristic lines of the primary waves is presented in Fig. 2. The characteristic lines can be used to measure the amplitude of the primary waves. At relatively low gas velocities, this technique almost does not miss the primary waves, so it can also be used to measure their frequency.
Results and discussion

The average velocity of the primary waves was measured using a cross-correlation analysis of temporal records of film thickness obtained at a given distance from each other. The velocity of the primary waves increases with increasing gas velocity and viscosity of the working fluid (Fig. 3). It can also be seen that in the "shear" mode the growth rate is higher than in the "gravitational" mode.

Using the algorithm to automatically search for the characteristic lines of the primary waves, the average amplitude of the waves was measured. From Fig. 4 it can be seen that the viscosity of the working fluid significantly affects the amplitude of the primary waves. For low gas velocities, up to 10 m/s, the effect of gas velocity is weak and roughly constant; after the transition to the "shear" mode, it shows rather strong decrease.
Figure 4. Mean film thickness and amplitude of primary waves.

Figure 5. Frequency of primary waves.

The frequency of the primary waves is weakly dependent on the gas flow rate in the "gravitational" mode and increases after the transition to the "shear" mode (Fig. 5).

Conclusions
The effect of increasing gas shear on wave flow of thin liquid films is investigated. In addition to qualitative changes shown previously ([10]), namely, suppression of the capillary precursor of primary waves and appearance of secondary waves, the transition is accompanied by change in behavior of the main characteristics of primary waves on gas velocity. In contrast to what could be expected, the waves properties are nearly insensitive to the gas flow until its superficial velocity reaches some critical value. The critical value depends on both liquid Reynolds number and liquid viscosity, but it lies within the same range where qualitative changes occur.

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