

# The effect of increasing gas shear on wave structure of thin liquid films

*Sergey Isaenkov*<sup>1</sup>, *Ivan Vozhakov*<sup>1,2</sup>, *Mikhail Cherdantsev*<sup>1</sup>, and *Andrey Cherdantsev*<sup>1,2</sup>

<sup>1</sup>Kutateladze Institute of Thermophysics, 1 Lavrentiev ave., Novosibirsk 630090, Russia

<sup>2</sup>Novosibirsk State University, 2 Pirogov str., Novosibirsk 630090, Russia

**Abstract.** Evolution of thin liquid films sheared by co-current gas stream in a vertical 11.7 mm pipe is studied experimentally using BBLIF technique. The main goal is to investigate the transition of wave patterns due to increase in the gas stream velocity,  $V_G$ , from 0 to 24 m/s. Apart from relatively weak quantitative changes in the characteristics of the primary waves, replacement of capillary precursor by slow secondary waves is found. The transition is identified in the range of  $V_G = 8 - 16$  m/s for all liquid flow rates. It is observed that the appearing secondary waves may be the main reason of the decay of the capillary precursor. The experimental results are compared to prediction of evolutionary theoretical model, showing qualitative agreement on secondary waves generation, but with no agreement on precursor's disappearance. Introducing artificial perturbations mimicking the action of turbulent pulsations in the gas phase is recommended to improve the model.

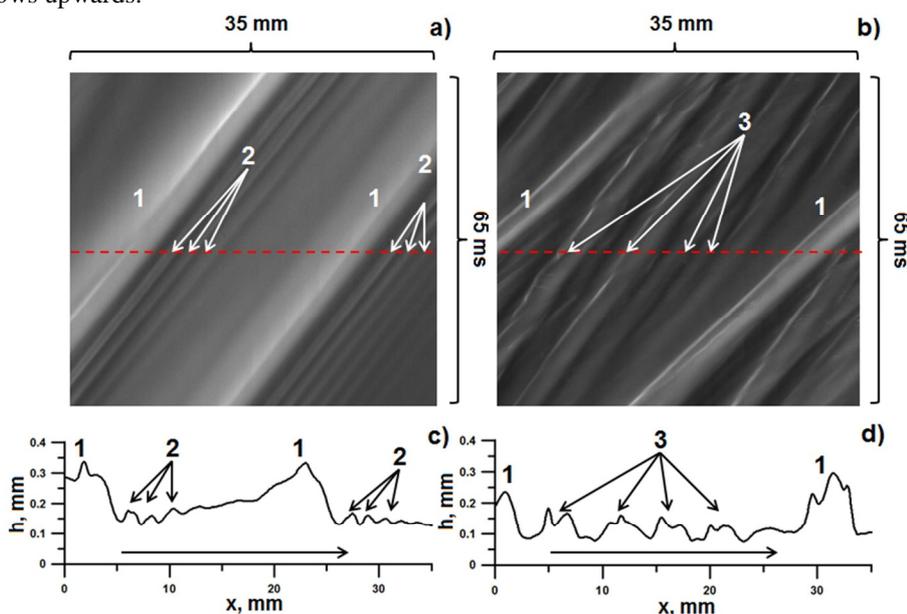
## 1 Introduction

Joint flow of liquid film along pipe walls and high-speed gas stream is referred to as annular flow. At large liquid flow rates this flow is strongly complicated by formation of large-scale disturbance waves and entrainment of liquid droplets from the film surface. Even at low liquid flow rates, in absence of entrainment, two kinds of waves appear on film surface: fast long-living primary waves with unstable rear slopes generating slow short-living secondary waves [1]. This picture is different to the case of liquid films flowing under action of gravity in absence of gas stream: in this latter case short-length capillary precursors exist in front of the nonlinear waves, whilst no secondary waves are observed.

At present, modeling of gas-sheared liquid films is mostly conducted in frames of linear stability analysis in the range of low gas and liquid flow rates [2]. Further stages of downstream development of non-linear waves are usually modeled in frames of pseudo-stationary approach in the reference system of a moving nonlinear wave, which prevents generation of smaller wavelets with different propagation speed. This issue can be solved by application of evolutionary approach, such as in a recent paper [3], which showed that secondary waves may appear in the modeled film thickness traces. The present paper is a continuation of this work, aimed at systematic study of the wave pattern transition with gradual increase in the gas velocity.

## 2 Experimental part

The experiments were conducted in downward vertical co-current annular flow in a 11.7 mm pipe. The liquid was fed onto the pipe inner walls through a ring-shaped slot with thickness 0.5 mm. Superficial gas velocity,  $V_G$ , varied in the range of 0 - 24 m/s; liquid Reynolds number varied from 10 to 60 and was defined as  $Re_L = Q(\pi d \nu)^{-1}$ , here  $Q$  is volumetric liquid flow rate,  $\nu$  - kinematic viscosity of liquid (water at working temperature 16°C has viscosity of  $1.15 \cdot 10^{-6} \text{ m}^2/\text{s}$ ),  $d$  - inner pipe diameter. Distilled water with small addition of Rhodamine 6G (at a small concentration of 10 mg/l the dye does not affect the physical properties of the liquid) was used as working liquid. To measure local thickness of liquid film, brightness-based laser-induced fluorescence technique was employed. For excitation of fluorescence continuous 2W 532 nm laser was used. The laser sheet illuminated a longitudinal section of the pipe. The region of measurements was 100 mm long and was located at the distance of 200 mm below the inlet. The fluorescence intensity was measured with high-speed camera equipped with an orange optical filter. Camera spatial resolution was 0.1 mm/pixel and sampling frequency was 5 kHz. The scheme of experimental setup, detailed description of BBLIF technique and recalculation of brightness into film thickness are given in [4]. BBLIF technique obtains instantaneous profiles of film thickness along the investigated section of the pipe with high sampling frequencies. The results can be analyzed in form of spatiotemporal matrices of film thickness,  $h(x,t)$ . Example fragments of such matrices are shown in Fig. 1(a) and (b), respectively, in a graphical form (local brightness of such images is directly proportional to local film thickness, white corresponds to  $h = 0.5 \text{ mm}$ ). Flow direction is from left to right; time grows upwards.

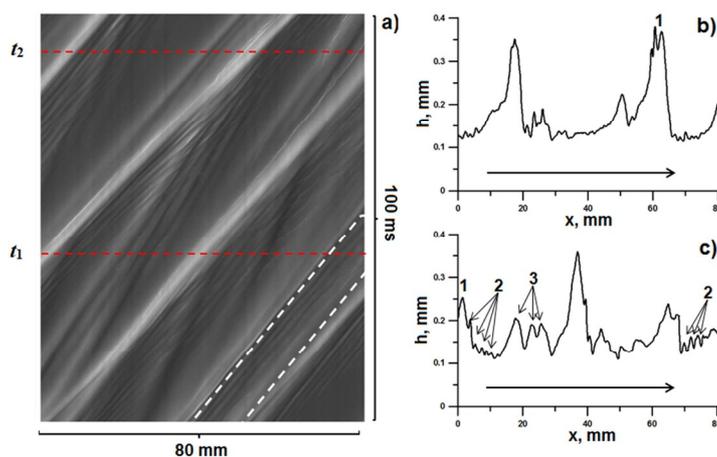


**Fig. 1.** Example fragments of experimental spatiotemporal matrices of film thickness (a, b) and instantaneous profiles of film thickness (c, d).  $Re_L = 30$ . a,c)  $V_G = 6 \text{ m/s}$ ; b,d)  $V_G = 18 \text{ m/s}$ . 1- primary waves, 2- capillary precursor, 3 - secondary waves.

At low  $V_G$  (Fig. 1a) the primary waves (1) generate capillary precursor (2) in front of them, moving with the same speed as the primary waves. At high  $V_G$  (Fig. 1b) there is no capillary precursor; instead, secondary waves (3) are generated at the rear slopes of the

primary waves and travel with low speed over thin base film layer in between the primary waves until the following primary wave absorbs them. Figures 1(c) and 1(d) show instantaneous profiles of film thickness at the moments marked by the dashed red lines.

The first events of generation of secondary waves were detected at  $V_G = 8$  m/s. The transition occurs gradually in the range of  $V_G$  from 8 to 16 m/s. During the increase in  $V_G$  within this range, fraction of primary waves generating secondary waves grows, whilst the fraction of primary waves with capillary precursor decreases. This process also evolves with time within the same flow: an example shown in Fig. 2 for  $V_G = 10$  m/s demonstrates the primary wave (1) with the precursor (2) in front of it at time instant  $t_1$  (Fig. 2c), which does not exist anymore at time instant  $t_2$  (Fig. 2b). It is possible that the precursor is disrupted due to interaction with secondary waves (3). This hypothesis is supported by the observation that in absence of absorption of secondary waves the precursor is conserved (see the region within the dashed parallelogram in Fig. 2a). The observed regularities are common for the whole studied range of film Reynolds numbers, from 10 to 60.

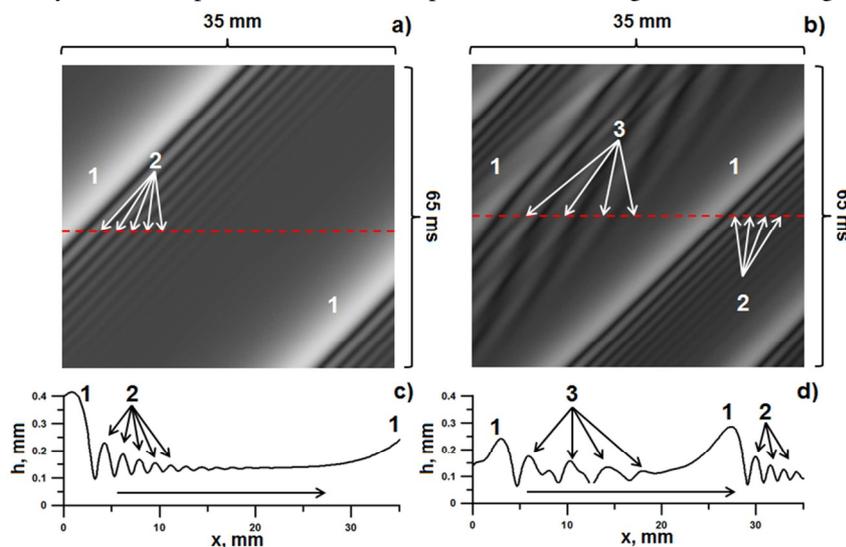


**Fig. 2.** (a) Example fragments of spatiotemporal matrices of film thickness. (b, c) Instantaneous profiles of film thickness at time instants  $t_2$  (c) and  $t_1$  (b).  $Re_L = 30$ ,  $V_G = 10$  m/s

### 3 Modeling

The modeling is conducted within the frames of long-wave integral model [5] taking into account viscosity effects up to second order [6, 7], as shown in [3]. To identify the response of tangential,  $\tau(k)$ , and normal,  $p(k)$ , stresses on a perturbation of the interface, a linear model of turbulent flow over the wavy wall [8] was used, based on transfer of the boundary conditions to the unperturbed level, leading to Orr-Sommerfeld equation. The average velocity profile in the gas phase was taken from [9]. The solution was represented in form of spatial Fourier series, to obtain an infinite system of equations for Fourier-harmonics,  $h_n(t)$  and  $q_n(t)$ . The system was limited to large but finite number of harmonics and solved by the 4th order Runge-Kutta method. The modeling results are presented in Fig. 3 in the same form as that used for the experimental data. For low  $V_G$  (Fig. 3a, c) the experimental and theoretical results are in good agreement on both qualitative and quantitative levels (compare to Fig. 1a, c). In both cases solitary nonlinear waves with well-pronounced capillary precursor are observed. The main difference is manifested in higher amplitude and larger number of distinguishable periods of the precursor in the theoretical results. For large  $V_G$  (Fig. 3 b, d), the differences are more significant. The model reproduces the phenomenon of generation of secondary waves (3), which interact with the precursor,

making it less regular. On the other hand, for the primary waves which do not absorb the secondary waves, the precursor is still well-pronounced and regular, unlike in Fig. 1 (b, d).



**Fig. 3.** Example fragments of modeled spatiotemporal matrices of film thickness (a, b) and instantaneous profiles of film thickness (c, d).  $Re_L = 30$ . a, c)  $V_G = 6$  m/s; b, d)  $V_G = 18$  m/s. 1- primary waves, 2- capillary precursor, 3 - secondary waves.

The picture modeled for  $V_G = 18$  m/s rather reminds the transitional regime (see Fig. 2). The possible reason of the discrepancy is related to absence of strong perturbations in the modeled signal, apart from those of pure numerical nature. To overcome the discrepancy, the model should be modified by artificially introducing the external perturbations mimicking the action of vortices in the turbulent gas stream onto the film surface.

The work was supported by Russian Foundation for Basic Research (project №18-31-00269).

## References

1. Alekseenko, S.V., Antipin, V.A., Cherdantsev, A.V., Kharlamov, S.M., Markovich, D.M., *Phys. Fluids*, **21** (2009)
2. Alekseenko, S.V., Aktershev, S.P., Cherdantsev, A.V., Kharlamov, S.M., Markovich, D.M., *Int. J. Multiphase Flow*, **35** (2009)
3. Vozhakov, I. S., Cherdantsev, A. V., & Arkhipov, D. G. *Fluid Dynamics Research*, **48**(6) (2016)
4. Alekseenko, S.V., Cherdantsev, A.V., Cherdantsev, M.V., Isaenkov, S.V., Kharlamov, S.M., Markovich, D.M., *Exp. Fluids*, **53**(1) (2012)
5. Shkadov V. Y., *Fluid Dynamics*, **2**(1) (1967)
6. Shkadov V. Y., *News of Moscow University. 1: Mathematics and Mechanics*, **(4)** (2013) (in Russian)
7. Ruyer-Quil C., Manneville P., *The European Physical Journal B-Condensed Matter and Complex Systems* **15**(2) (2000)
8. Demekhin E. A., *Fluid Dynamics* **16**(2) (1981)
9. Geshev, P.I., 1981. *Institute Thermophysics, SB AS USSR*, 73: 81 (in Russian).