Application of the PTV with the use of a light-field camera to study three-dimensional wave regimes of liquid film flow

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Abstract. We present the results of studying the influence of surfactants on three-dimensional waves, in particular, on the flow structures in the wave. Volumetric fluid velocity measurements in waves, as well as the determination of their shape, were carried out using a light field camera. An aqueous solution of the nonionic surfactant Triton-X was used as a working fluid. The presence of surfactant leads to a significant change in the structure of the transverse flow regions under the main hump of the wave. Besides, capillary precursor and backflow in it are suppressed.

1. Introduction

Falling liquid films are extensively used in numerous technical applications. In some cases, surfactants are used as part of technological processes, or the presence of the surfactants in the working fluid may result from the contamination. The effect of the surfactants on the rheology and surface morphology of the falling liquid films is actively studied. However, the influence of surfactants on the wave hydrodynamics of falling liquid films is underinvestigated. Currently, there are few works dedicated to the study of three-dimensional (3D) waves formed during the film flow of a liquid in the presence of a surfactant. For example, soluble surfactant Triton-X was used in experimental work [1]. Damping of the waves was observed at low and moderate surfactant concentrations. At large surfactant concentrations, the 3D waves start to grow again, but the initial stage of two-dimensional (2D) waves evolution, typical for pure liquids flow was not observed. Numerical simulation of the liquid film flow in the presence of an insoluble surfactant was performed in [2]. In this case, the influence of the Marangoni stresses appeared due to gradients of the interfacial surfactant concentration. Suppression of the humps of the traveling waves and capillary precursors were found. However, a more detailed study of the wave characteristics in the presence of a surfactant is required.

In this work, we present the results of studying the influence of surfactants on characteristics of 3D waves, in particular, on the flow structure in a wave. For this purpose, light-field particle tracking velocimetry (LF-PTV) was used. This method allows obtaining velocity fields in liquid film simultaneously with data about film thickness. Besides, our goal was to demonstrate the applicability of this method for studying the film flow of fluids with different physical properties.
2. Experimental Method

Experimental setup and methods are described in detail in [3]. Liquid film flow was formed by a slot distributor on a vertical glass plate 16×25 cm in size. The schematic view of the LF-PTV and LIF measurement system is shown in figure 1. Volumetric velocity measurements were carried out using Raytrix R11m light-field camera and principles of the particle tracking velocimetry. Light-field camera (otherwise called plenoptic camera) allows determining the position of the tracer particles (tracers) in volume. Images obtained were used also to reconstruct the local film thickness using laser-induced fluorescence (LIF) method. For these purposes, fluorescent dye Rhodamine 6G and fluorescent tracers were added to the working fluid. The working area was illuminated by a pulsed laser with a wavelength of 532 nm. Illumination and recording were performed from the dry side of the glass plate. The brightness of the fluorescing liquid and tracers was recorded by the camera. The fluorescence brightness is proportional to the local thickness of the liquid film. This thickness was restored according to the algorithm described in [4]. Achieved spatial resolution in the X–Z plane was 6.7 µm/pix. The position of the tracers in Z direction was determined with an accuracy of ± 25 µm. The flow rate was modulated with frequency F to generate regular waves. Distilled water with density $\rho = 998$ kg/m$^3$, kinematic

![Diagram of experimental setup](image)

**Figure 1.** Light–field PTV and LIF measurement system.

![Reconstructed surface and velocity field](image)

**Figure 2.** Reconstructed (a) surface of the 3D wave and (b) phase averaged velocity field at the distance of 150 - 200 µm from the wall. Distilled water with surfactant (2000 mg/l). Re = 40; F = 14 Hz.
viscosity $\nu = 0.994 \times 10^{-6}$ m$^2$/s, and surface tension $\sigma = 0.073$ kg/s$^2$, and water solution of nonionic soluble surfactant Triton X-100 with the concentration $C = 2000$ mg/l, $\rho = 998$ kg/m$^3$, $\nu = 0.997 \times 10^{-6}$ m$^2$/s, $\sigma = 0.03$ kg/s$^2$ were used as a working fluids. All experiments were performed at a working fluid temperature of 24°C. The choice of the surfactant concentration was due to the fact that at lower concentrations, the decay of three-dimensional motion is observed, while at $C = 2000$ mg/l, three-dimensional waves begin to grow again [1]. A liquid film was formed at the Reynolds number $Re = 40$. Here $Re = q/\nu$, $q$ is the specific flow rate of the liquid. The frequency of the flow rate modulation for distilled water was $F = 19$ Hz, and for surfactant solution $F = 14$ Hz. Formed 3D waves were recorded in a certain position. After that, obtained instantaneous velocity fields were phase averaged and interpolated into a regular grid.

3. Results

![Figure 3](image-url)

**Figure 3.** Spanwise velocity $V_z$ in the different parts of the wave. Areas marked in black outline correspond to the regions of the liquid outflow from the wave. Areas marked in white outline are regions of the liquid inflow to the wave; black arrows mean velocity components $V_z$, white arrows – general direction of the transverse flow. (a), (b) - distilled water, $Re=40$, $F=19$ Hz; (c), (d) distilled water with surfactant, $Re = 40$, $F = 14$ Hz.
The reconstructed shape of the 3D wave for the case of surfactant solution flow is presented in figure 2(a). The characteristic phase averaged velocity field in 3D wave for the case of the surfactant solution film is shown in figure 2(b). This velocity field refers to a layer with a thickness of 50 μm centered at a distance of 150 μm from the wall. As can be seen, liquid flow in 3D wave has a complicated structure with spanwise flows being identified. Characteristics of the 3D wave on flowing water film with surfactant differ from those for the case of distilled water flow. The 3D waves have a different shape (Figure 3), and LIF data analysis shows that the maximum height H of the 3D wave was 420 μm and phase velocity V = 0.42 m/s for distilled water, while for water with surfactant H = 550 μm and V = 0.46 m/s. The brightness of the background in figure 3 corresponds to the film thickness. Phase-averaged velocity fields at different distances from the wall and images of the waves are shown in figure 3 for both distilled water (figure 3(a,b)) and water with surfactant (figure 3(c,d)). It can be seen, that flows within the film have a different structure. It may be related to the differences in waveform between the pure water flow and surfactant solution flow, in particular with the weakly expressed capillary ripple on the free surface in the case of the surfactant solution. Backflows are not observed and flows along the capillary precursor minimum and maximum are weaker compared to the case of distilled water flow.

Analysis of the transverse velocity component fields presented in figure 3 shows that for both cases the flow in the region under the trailing edge of the wave is directed towards its central part and regions of the liquid outflow decreasing with growth in distance y from the wall. It can be seen also that size of the liquid outflow area (the layer at Y = 150 μm) in the case of the water flow with surfactant is larger than the size of a similar area in the case of pure water flow. Besides, one can observe a difference in the shape of the regions, and that in the case of water flow with the surfactant, there are no zones under the wave without transverse flows.

In conclusion, we note that the presented results demonstrate that the method of volumetric velocity measurements based on algorithms of PTV using a light field camera is applicable to the study of the film flow of liquids with different physical properties, and makes it possible to reveal differences in the flow structures in three-dimensional waves.

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