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Application of a light-field camera for simultaneous volumetric velocity and film thickness measurements in falling films

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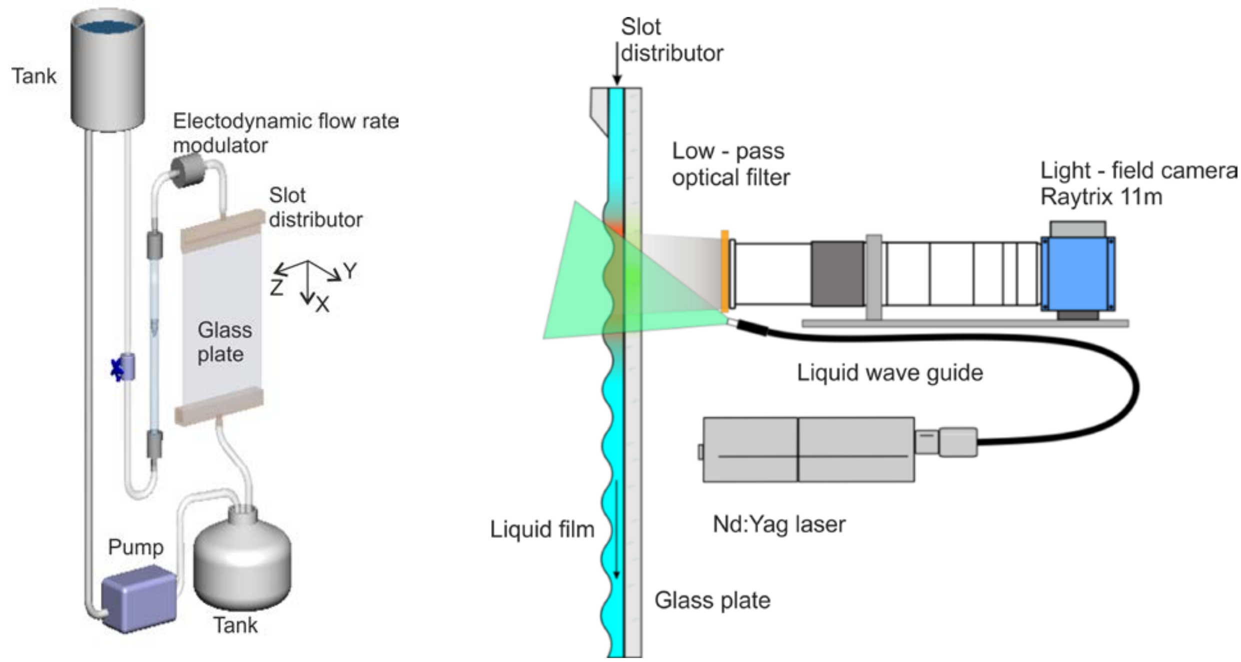
Abstract

This paper presents the results obtained with new experimental technique designed for simultaneous volumetric velocity and film thickness measurements in gravity driven liquid films. Particle tracking velocimetry is combined with laser induced fluorescence film thickness measurements by means of single light–field camera. The camera specifications allow us to reconstruct three-dimensional two-components velocity fields simultaneously with film thickness distribution. The measurements were made as for a flat film as well as for two-dimensional and three-dimensional waves. Vector fields for liquids with different physical properties as well as with addition of surfactant were obtained. The experimental results demonstrate that liquid flow in three-dimensional waves has complex structure. The areas of spanwise and backflows have been identified within three-dimensional waves. Data analysis showed that the main areas of spanwise flows are lying under the main hump of three-dimensional wave rather than in capillary precursor for the all studied cases. Flow structure differences in 3D waves in case of film flow of the liquids with different physical properties have been shown.

1 Introduction

Recently, there has been significant progress in the study of gravity-driven liquid films. Characteristics of the liquid films are well described theoretically Ruyer-Quil et al. (2000) and experimentally Guzanov et al. (2018). Nevertheless there are some discrepancies between theory and experiment, especially for the case of fully developed three-dimensional (3D) wave regime. It was found that transition from two-dimensional (2D) to 3D wave regime is accompanied by rivulets formation Kharlamov et al. (2015), not predicted by theory. Film thickness measurements are not able to provide data about flows in liquid films, especially about spanwise flows which can arise in the process of formation of 3D waves. Even though information about the film surface structure is obtained with high spatial and temporal resolution by means of laser induced fluorescent (LIF) technique Kharlamov et al. (2015), data on the velocity distribution in the waves is critical for understanding of the processes of mass transfer. While velocity measurements in 2D waves are presented in numerous works (e.g. Alekseenko et al. (1985), Markides et al. (2015) among others) there are lack of experimental results presented for 3D waves. This fact can be explained by difficulty of such measurements. The difficulties are caused by small thickness of liquid films (in the order of the hundreds of microns), relatively small size of the studied waves and presence of the free surface. Restricted measurement area limits application of the bulky systems such as stereo or tomo–PIV, when good optical access is required. Our goal was to create a measuring system adapted for the study of a wide class of phenomena in film flows, in which 2D and 3D wave structures are formed. In this paper we present the result of application of a new measuring system capable to provide volumetric particle tracking velocimetry (PTV) combined with LIF film thickness measurements to gravity driven wavy liquid film using single light-field (LF) camera. This camera allows to measure positions of the tracers in volume Canedese et al. (2012), which make it possible to reconstruct three-dimensional two-components (3D-2C) velocity fields.



(a) Hydrodynamic flow loop (b) Light –field field PTV and LIF measurement system.

Figure 1: Experimental setup.

2 Experimental setup

Sketch of the experimental setup is shown in Fig. 1. The liquid film flow was formed by a slot distributor on a vertical glass plate (Fig. 1 (a)). Polyamide fluorescent particles (with average diameter d = 5 μm and density ρ = 1.05 g/cm^3) were used as tracers for PTV, and fluorescent dye Rhodamine 6G was dissolved in the working liquid for LIF measurements in concentration of about 1 mg/l. The main idea of the LIF technique is that local film thickness is reconstructed in accordance with local light intensity emitted by a small amount of fluorescent dye dissolved in working liquid. The measurement system is shown on Fig. 1(b). It consists of light field camera Raytrix R11m with mounted through macro rings 105 mm SIGMA macro lens. Spatial resolution achieved by the optical system was 6.7 – 6.9 μm/pix. Laser light from ND:YAG pulse laser (532 nm) is directed by an optical waveguide to the region of interest. Orange filter mounted in front of the camera transmits only fluorescent light from particles and solution. Illumination and recording are carried out from the dry side of the glass plate. The velocity vectors and film thickness are reconstructed from the same images recorded with the light–field camera operated in dual frame mode. The time delay between two successive images is ranged from 200 to 250 µs. Recording sequence for each experimental run consists of about 100 to 200 image pairs. Virtual depth calibration of the light field camera is performed prior the experiments. Glass calibration target with line grid is placed in the measurement area and recorded at a variety of depths with gap between the target and the plate filled with working liquid. Finally, calibration curve was built based on the virtual depth map (Fig. 2). Measurements were first made in a flat film and in 2D waves at the upper part of the flow for testing the method. Water-glycerol solution (WGS) with $\rho = 1047$ kg/m^3, $\nu = 1.52\times10^{-6}$ m^2/s, $\sigma = 0.073$ kg/s^2 was used as working liquid. Studied flow regimes is characterized with Reynolds number Re = 40. We defined Re as q/ν, where q is specific volumetric flow rate and ν – the kinematic viscosity. 2D waves were generated by the flow rate modulation (F = 16 Hz). The next step after verification of the method was to study how flow structure in 3D waves varies depending on physical properties of liquids and presence of surfactant.

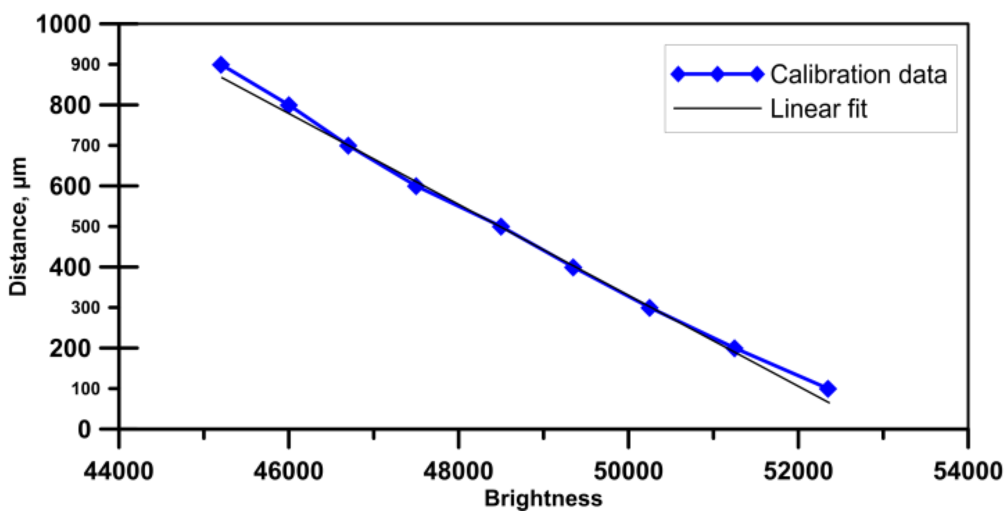


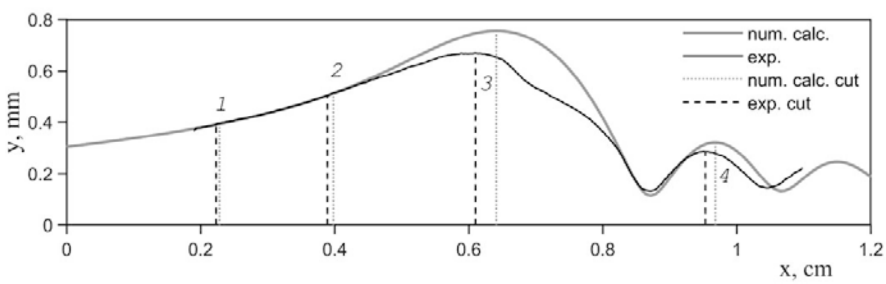
Figure 2: Depth map calibration. Nine target distances were used for calibration.

Distilled water with $\rho = 998$ kg/m^3, $\nu = 0.994\times10^{-6}$ m^2/s, $\sigma = 0.073$ kg/s^2, and water solution of non – ionic surfactant Triton X-100 with concentration of 2000 mg/l (about 14 time more than critical micelle concentration) with $\rho = 998$ kg/m^3, $\nu = 0.994\times10^{-6}$ m^2/s, $\sigma = 0.03$ kg/s^{2}were used as working liquids. The choice of surfactant concentration was made for the following reason: At low and moderate surfactant concentrations damping of waves is observed, which coincides with the results of other authors. At surfactant concentration of 2000 mg/l the waves start to grow again, but without initial stage of 2D waves development typical for the pure liquids. The absence of this initial stage is due to the formation of rivulets in the inlet of the film in the presence of the surfactant. Experiments on distilled water were carried out at Re = 40 and with flow rate modulation frequency F = 19Hz. In case of addition of surfactant studied flow regime was characterized with Re = 40 and F

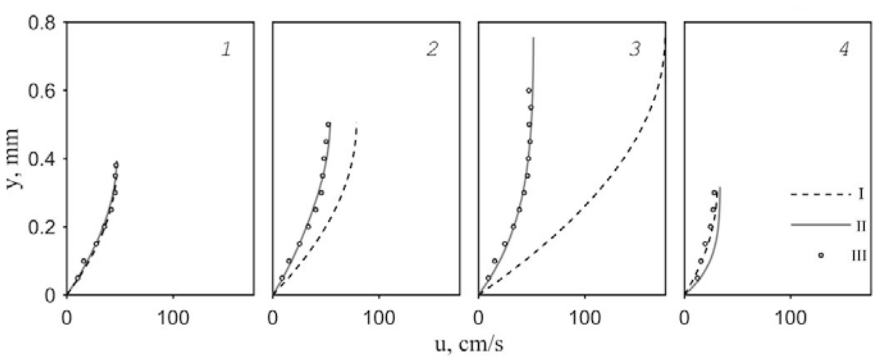
= 14Hz. The selected frequencies depend on working liquid and correspond to those at which the regular 3D waves are formed.

3 Data processing

Reconstruction of the film thickness and velocity distribution was carried out independently. Virtual depth map of the tracers and ordinary image of fluorescence brightness distribution were extracted from the RAW image using camera software. Film thickness was reconstructed using in-house developed code from the obtained image of the glowing liquid film with dissolved fluorescent dye. For the velocity measurements the consecutive image pairs were firstly pre-processed. This stage included the localization of the polyamide tracers at X-Z plane parallel to the glass plate using ActualFlow software. Next step was to determine depth (Y) of the previously localized tracers from the depth map. Depth resolution that can be achieved by the Raytrix 11m camera is up to 1/40 of the total depth of field (DoF) Seredkin and Tokarev (2016). The optical system used in our experiments had DoF = 2 mm in working liquid.



(a) Experimental and theoretical 2D wave profiles



(b) Streamwise velocity profiles built for cross sections shown in Fig. 3(a): I – parabolic velocity profile calculated using the Nusselt formula and based on maximum depth value taken from theoretical 2D profile; II – streamwise velocity profile calculated with WaveMaker; III – experimental velocity profile.

Figure 3: Experimental and theoretical velocity profiles in 2D wave. Water-glycerol solution, Re = 40, F = 16 Hz.

Thus, position of the 5 μm polyamide particles with which the flow was seeded was determined with accuracy ± 25 μm. Once all three coordinates were determined velocity vector fields were reconstructed using standard PTV processing algorithms of the ActualFlow software. Vector fields were reconstructed for layers (50 or 70 μm thick), parallel to the glass plate and at different distances with a step equal to half width of the layer. Instantaneous velocity fields were then phase averaged in accordance with wave shapes obtained by LIF method. Error in velocity measurements is related with particle position detection accuracy of 1 pixel. Additional error can arise from the procedure of averaging of velocity inside the layer. Total error does not exceed 0.03 m/s.

4 Results and discussion

As was mentioned above, the measurements were first made in a flat film and in 2D waves for testing the method. Velocity profiles in a flat film obtained experimentally coincided well with theoretical Nusselt profile. Obtained results on velocity profiles and film thickness for 2D waves are presented in Fig. 3 in comparison with simulation data for the same flow parameters calculated with WaveMaker MATLAB-based software Rohlfs et al. (2018). In calculations we used full second-order WRIBL model developed by Ruyer-Quil et al. (2000). As can be seen, the experimental and the simulation data are in good agreement for both velocity and film thickness that indicates the applicability of the designed measurement system to the diagnostics of liquid film flows.

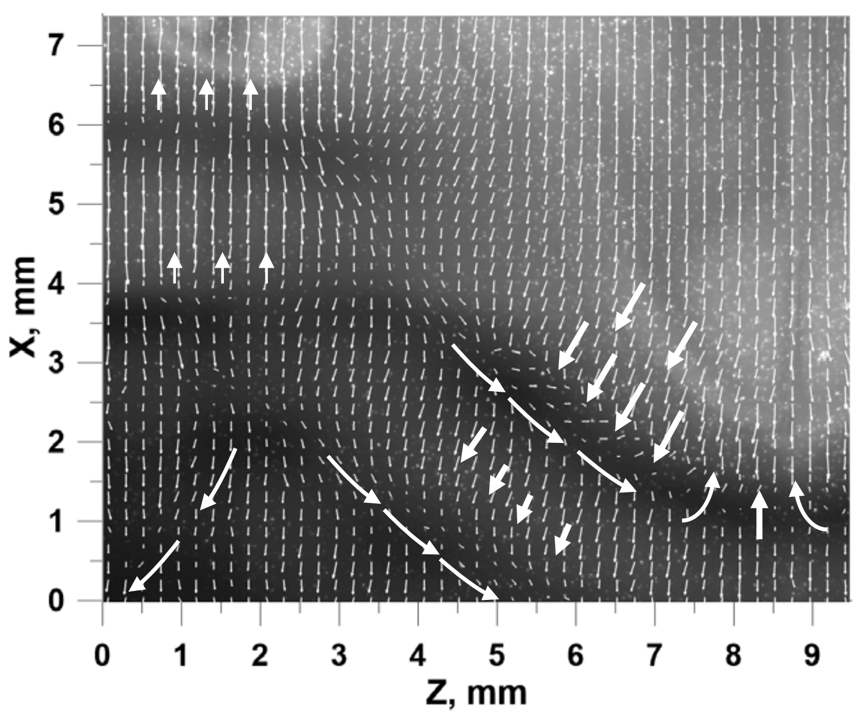
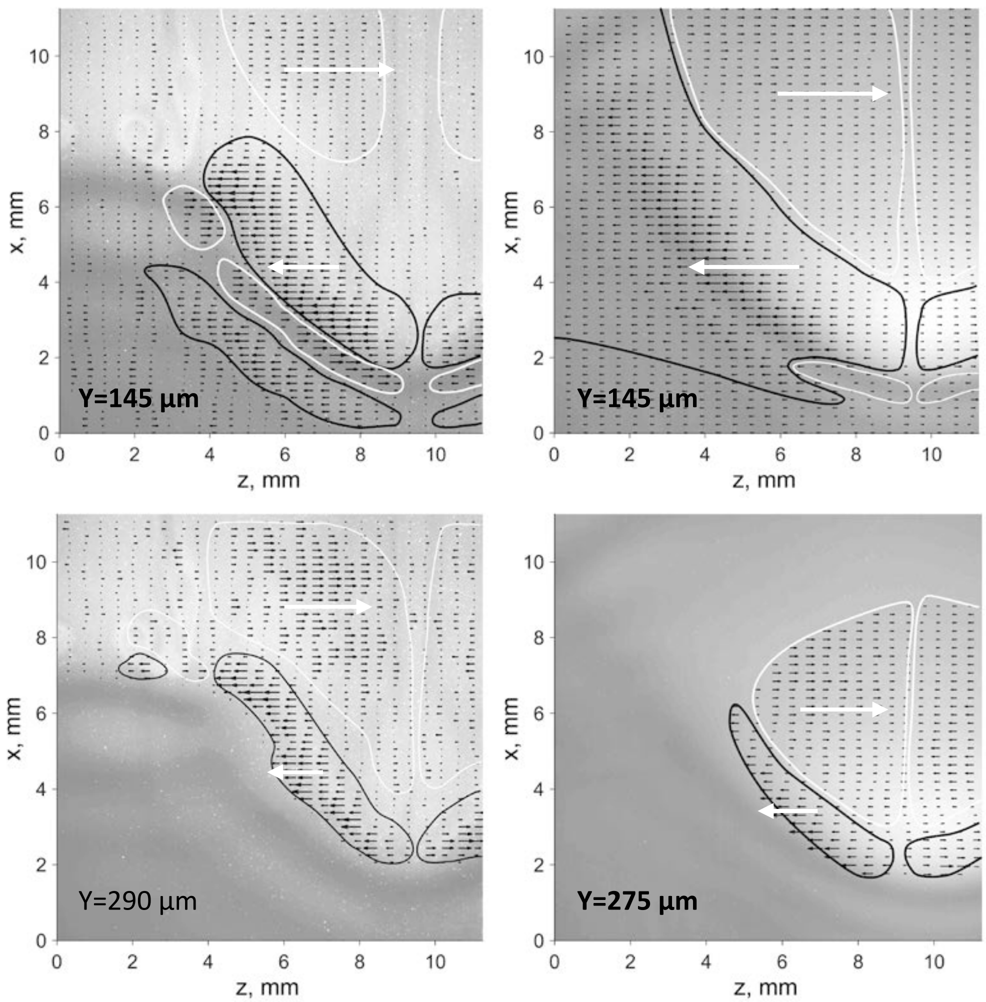


Figure 4: Phase – averaged velocity field in the layer centered at the distance y = 145 μm from the plate. Velocity field is interpolated to regular grid 32 x 32 pix. White thick arrows – general directions of the local flows. Intensity of the background corresponds to the film thickness. Water Re = 40, F =19 Hz

The next step was to study how 3D evolution scenarios and flow structure in 3D wave vary depending on physical properties of liquids. Characteristic phase averaged velocity field in 3D wave for the case of the water film is shown in figure 4. This velocity field refers to a layer with thickness of 70 μm centered at the distance of 145 μm from the wall. As can be seen, liquid flow in 3D wave has complicated structure with backflow and spanwise flows being identified. Used LF – PTV method allowed for the first time to visualize complex and delicate structure of flows in capillary ripples preceding the main hump of 3D wave.



(a) Distilled water. Re=40, F= 19Hz
Re=40, F= 19Hz

(b) Distilled water with surfactant.
Re = 40, F = 16Hz.

Figure 5: Spanwise velocity Vz in the different parts of the wave. Areas marked in black outline - regions of the liquid outflow from the wave, Areas marked in white outline – regions of the liquid inflow to the wave; black arrows –velocity components Vz, white arrows - general direction of the transverse flow

There is liquid inflow directed to the central part of the wave in the area of the capillary precursor along its minimum as well as liquid outflow in the opposite direction in the regions along the capillary precursor maximum. Presence of the negative velocities (backflows) up to 0.045 m/s was found in some areas of the capillary precursor minimum (Fig. 4). Under the main hump of the 3D wave two spatially separated zones can be singled out. The flow in the region, neighboring the leading edge of the main hump is directed from its central part. In contrast, the flow in region under the trailing edge of the wave is directed towards its central part. Characteristics of the 3D wave on flowing water film with surfactant differ from that for the case of distilled water flow. 3D waves have different shape 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 and for water with surfactant H = 550 μm and V = 0.46 m/s. Phase – averaged velocity fields at different distances from the wall and images of the waves are shown in Fig. 5 for both water (Fig. 5(a)) and water with surfactant (Fig. 5(b)). It can be seen, that flows within the film have different structure, which can be connected with wave shape differences. In case of water flow with surfactant capillary ripple is less pronounced. Backflows is not observed and flows along the capillary precursor minimum and maximum are weaker compared to the case of distilled water flow. Analysis of the experimental data 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 distance y from the wall.

5 Conclusion

A novel optical flow diagnostic technique based on light – field imaging, LIF method and PTV algorithms has been applied for simultaneous film thickness and 3D - 2C velocity measurements using single light – field camera. Test experiments have been carried out for the cases of flat falling films and 2D waves. Obtained experimental results on velocity profiles and film thickness and theoretical data for the case of flat film and 2D waves are in good agreement for both velocity and film thickness that indicates the applicability of the designed measurement system to diagnostic of liquid film flows. It was shown experimentally that liquid flow in 3D wave has complicated structure with backflow and spanwise flows being identified. 3D wave shape for the case of the water flow differs from that for the case of the water flow with addition of surfactant. Moreover application of the described experimental technique allows identifying flow structure differences in 3D waves in case of film flow of the liquids with different physical properties. Velocity field analysis showed that the main spanwise flow regions are lying under the main hump of 3D waves rather than in capillary precursor area. In the case of the water flow with surfactant capillary ripple preceding 3D wave is less pronounced and backflows was not detected

Acknowledgements

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