Flow structure in the three dimensional waves on the surface of the vertically falling liquid films

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Abstract. Results of simultaneous liquid velocity and film thickness fields measurements in the three dimensional waves are presented. The three dimensional waves formed as a result of decay of the forced two dimensional waves were studied. Liquid velocity fields were reconstructed at different distance from the film surface with reference to the specific area of the wave. It was shown that flow in the three dimensional wave has complicated structure with existence of areas with backflow and transverse flows of opposite directions. Main areas of transverse flows existence are lying under main humps of three dimensional waves.

1. Introduction

Three dimensional (3D) waves on the surface of the vertically falling liquid films are formed as a result of the decay of the two dimensional (2D) waves (fig.1a) and are the last stage of the wave evolution at moderate Reynolds (Re) numbers. Transition to the 3D wave regimes is accompanied by the rivulets formation \cite{1, 2}. In this case distribution of the liquid is not uniform across the plate and results of \cite{1, 2} indicate that transverse fluid flow is directed to the central areas of the growing 3D waves. Despite the fact that characteristics of the rivulet flow were described at \cite{3} it is not clear in which areas of the 3D wave liquid inflow takes place. However this information are needed to understand the mechanisms of the 3D waves evolution and formation of the rivulets. Therefore velocity vector field measurements in the 3D wave are required. Film flows are actively studied, but at the present time results on velocity field measurements in liquid films are presented only in a few papers because of difficulty of carrying out such measurements. For example in \cite{4} authors obtained longitudinal components of velocity $V_x$ (directed along the main stream) at different distances $y$ from the inclined wall for wavy film flow using a photochromic dye activation technique. In \cite{5, 6} modern and most efficient optical method for velocity vector field measurements known as the particle image velocimetry was used. However, as in \cite{4} in these works only $V_x(y)$ was obtained. It should be mentioned that when using PIV methods the stream is pre-seeded by particles, and velocity vectors are determined from the displacement of the particle images on two consecutive frames obtained with known delay in time. Locating the tracers is usually done using special ways of illuminating, as for example in \cite{5}, where the stream was illuminated with laser sheet, directed perpendicularly to the wall of the channel along its axis. Thus, two dimensional velocity vector fields of the flow were measured in the plane, illuminated with laser sheet. In the case of the measurements in the three dimensional wave it is necessary to determine the displacement of the tracers at least in two mutually perpendicular directions parallel to the plate and in the different parts of the wave, which is more complicated...
problem. For this reason there exists lack of experimental data about flow structure in the 3D waves, in particular data about transverse and parallel to the plate components \(V_z\) of the velocity vectors, which are connected with cross flow of the liquid. In order to determine areas of the 3D wave in which transverse fluid flows takes place, particle tracking velocimetry (PTV) technique based on using light-field camera was applied. This camera allowed determining position of the tracers in space \([7]\), thus for the first time \(V_x\) and \(V_z\) components were measured in the whole explored volume of the liquid with binding to the certain areas of the 3D wave.

2. Experimental techniques and operating conditions.
Experiments were performed for the flow regimes described in detail in \([1, 2]\). Measurements were carried out in the part of the flow in which fast growth of the rivulets due to the 2D-3D wave transition have been observed. The liquid film was formed on the transparent glass plate. Methods of PTV for velocity measurements and laser induced fluorescence for film thickness measurements were applied simultaneously. Velocity vectors and film thickness field were built from the same images, recorded by the light field camera Raytrix 11m that allows recording in double frame mode. In that case two consecutive images are recorded with a preset time delay. The depth resolution that can be achieved by using this camera is 1/40 of the total depth of field \([8]\). In our case the depth of field of the optical system was 2 mm, thus the depth position of the fluorescent 5 µm polyamide particles with which the stream was seeded was determined with accuracy ± 25 µm. During the LIF measurements fluorescent dye Rhodamin 6G was dissolved with concentration 1.25 mg/L in the working fluid. Intensity of the light emitted by the working solution was proportional to the thickness of the layer and in this way instantaneous film thickness distribution was reconstructed. Recording on the camera was carried out through the glass from the dry side of the plate in the flow area shown in fig. 1a. Fluorescence of the solution and polyamide particles in the measurement area were excited with pulsed Nd:YAG laser.
with wavelength 532 nm. More detailed description of the LIF method and its error analysis are described in [2]. Error in measurements of the film thickness did not exceed ±10 µm. Spatial resolution of the recorded images was 6.7 µm/pix. Obtained results which are illustrated below related to the flow regime characterized with Reynolds Re = 40, where Re = q/ν, q – specific volumetric flow rate, ν – kinematic viscosity. The measurements were carried out for the case of the regular decay of the periodic 2D waves, generated by the flow rate modulation with frequency $F = 19$ Hz. Formations of the 3D waves under these conditions occur at the same position and with a frequency equal to the frequency of the generated 2D waves. Recording frequency was chosen so that forming 3D waves were registered at the same place. This allowed us to collect a volume of the experimental data sufficient for the velocity vector field reconstruction.

2.1. Data processing
The processing of the obtained experimental data included stage of the image filtration, after which the film thickness fields were reconstructed and the coordinates of tracers were determined. At final stage images of the particles were sorted by layers depending on the depth of their immersion. These layers were parallel to the surface of the plate and centers of the neighboring layers where located with spacing of 36 µm from the wall (along the axis $y$). Velocity vector fields were calculated for the each layer using PTV processing algorithms of the standard software ActualFlow. All tracers laying at distances ± 36 µm from the center of the layer were considered belonging to that layer. Inaccuracy of the velocity measurements at $y \geq 72$ µm was 30% due to insufficient depth positioning of the particles in the shear flow. Nevertheless obtained results allowed us to detect areas of the wave with typical liquid flow direction.

![Fig. 2. Transverse displacement of the liquid in different parts of the wave.](image)

*a) Transverse velocity $V_z$ at distance 180 µm from the plate. I – region of the liquid outflow from the wave, II – region of the liquid inflow to the wave; b) trajectories of the movement of elementary volumes of liquid along the cross sections shown in fig. 1b at the distance 108 µm from the plate.*
3. Results and discussion

As an example velocity vector field in layer with centre at \( y = 108 \) µm is shown in fig. 1b. Intensity of the background in this picture is related to the film thickness. Film thicknesses were 90 µm and 400 µm in minimum of the capillary precursor and in maximum of the main hump correspondingly. For illustrative purposes length of each velocity vector was normalized with their magnitude and shows only direction of the flow. As seen, liquid flow in the wave has complicated structure. Liquid inflow can be seen in direction to the central part of the wave in the area of the capillary precursor along its minimum. Areas of the liquid outflow in the opposite direction from the center of the wave were observed in the regions along the capillary precursor maximum. Moreover backflow against gravity was observed in some areas of the capillary precursor minimum. These results show qualitative agreement with results [9], where backflow in the area of the capillary precursor was studied experimentally and numerically and with results of the computational simulation [10], where it was shown that significant cross flows of the liquid take place along the areas of the minimum and maximum of the capillary precursor. Under the main hump of the wave two spatially separated regions with transverse liquid flows in opposite directions can be singled out, as shown in fig. 2a. The flow in the region I, neighboring the leading edge of the wave is directed from its central part. In contrast, in the region II under the trailing edge of the wave, the flow is directed towards wave’s central part. Typical velocity magnitude in the marked areas in the case shown in fig. 2a at \( y = 180 \) µm was \( V_x = 0.25 \) m/s, \( V_z = 0.06 \) m/s for the region I and \( V_x = 0.3 \) m/s, \( V_z = 0.03 \) m/s for the region II. With moving from the plate wall the increasing of the \( V_x \) up to 0.4 m/s and \( V_z \) up to 0.08 m/s in both regions are observed while the wave velocity \( V \approx 0.42 \) m/s. In the figure 2b trajectories of the elementary volumes of liquid are shown when the 3D wave passes by. Trajectories were built based on assumption that the liquid doesn’t leave the boundaries of the layer and \( V_z \) doesn’t change in \( z \) - direction within transverse displacements of elementary volume. Trajectories were built in sections marked with dashed lines in fig.1b for the layer with center lying at \( y = 108 \) µm. The beginning of the trajectories corresponds to the position of the elementary volumes in the bottom part of the fig 1.b (in area of the capillary precursor), and the end – their position in the tail of the 3D wave, after passing of the main hump. It can be seen from fig. 2b, that transverse displacements of the liquid in the area of the capillary precursor are small in comparison with transverse displacements in the regions I (0.6 mm < \( x_s < 1.2 \) mm) and II (2 mm < \( x_s < 2.6 \) mm) under the main hump of the wave. Since the region I is decreasing and the region II is increasing in size with growth distance \( y \) from the wall it can be supposed that major liquid inflow to the wave during the rivulets formation takes place in the tails part of 3D waves. Thus it was experimentally shown that the liquid flow in the 3D wave has complicated structure with existence of the backflow areas and transverse flows, and the main regions of transverse flows are lying under the main humps of 3D waves.

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5. References

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