HYDRODYNAMICS OF THE SOLITARY WAVES TRAVELLING DOWN A LIQUID FILM

Jaroslav Tihon
Institute of Chemical Process Fundamentals, AS CR, Rozvojova 135, 16502 Prague, Czech Republic

Summary The regular solitary waves on the surface of a liquid film flowing down an inclined stationary plate were excited by means of the flow rate pulsations. The results of experimental investigations (electrodiffusion flow diagnostics, film thickness measurements, near-wall flow visualization) provided the basic characteristics of surface waves and confirmed the existence of a small backflow region located just in front of the solitary waves.

INTRODUCTION

The wavy film flow down an inclined plane is a typical representative of convective instabilities. The spatio-temporal evolution of waves on the film surface is a complex process and the different kinds of waves can be observed. Small-amplitude waves appearing at the wave inception grow rapidly and develop downstream into the large nonlinear patterns of finite-amplitude, solitary or three-dimensional waves [1]. The large solitary waves are separated by wide regions of the thin liquid film and have the typical shape characterised by a steep front and a gradual tail. Small capillary waves are usually pushed in front of these solitary waves. This region is not easy accessible for the experimental investigation, because rapid flow changes observed there take place inside the thin liquid film. The recent numerical simulation of the wavy film flow [2] has suggested that there is possibly a small backflow region in front of the large solitary waves. It has been a challenge for us to confirm or reject such a surprising finding by the relevant experiments. The electrodiffusion technique [3] using probes flush mounted into a wall has been used to measure local values of the wall shear rate.

DESCRIPTION OF THE EXPERIMENTS

The experimental investigation of the wavy film flow was carried out in an experimental set-up shown in Fig.1. The liquid film was flowing down a long stationary plate (2 m in length and 0.22 m in width). The slope of this stainless steel plate could be changed from the vertical to the horizontal position. A piston mounted into the air chamber produced periodical pulsations of the flow rate with a small amplitude (up to 10% of the mean flow rate) and low frequency (from 0.5 to 2.5 Hz). These low-frequency pulsations excited the regular solitary waves on the liquid film surface. The two-strip electrodiffusion probe was mounted into the wall to detect the wall shear rate under large solitary waves. The capacitance probe, installed at the same distance from the liquid distributor as the electrodiffusion one (x=1.5m), measured simultaneously the instantaneous film thickness. With the aim to measure the wave velocity, two capacitance sensors aligned 20 mm apart in the flow direction were used. The measurements were carried out with water and aqueous solutions of glycerine and Emkarox as the model liquids.

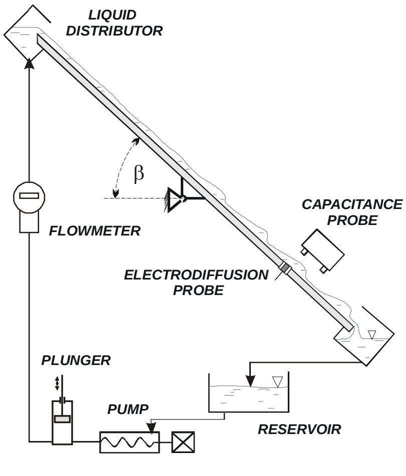

Fig.1 Experimental set-up

To perform the flow visualization the experimental set-up presented in Fig.1 was prolonged with a glass plate. The small glass spheres with a mean diameter of 20 μm were added into the liquid as tracing particles. The high speed camera Kodak Motion Corder SR provided by the telecentric measuring objective Vicotar T10/9.7L was fixed at the working distance about 0.5 m beneath the glass plate. As this microscopic objective (tenfold magnification) was focused on a sign marked on the glass plate, only the particles moving in the near-wall region were seen with sharp contours (depth of the field about 50 μm). The movement of these particles inside the field of view (180 x 190 μm) was recorded with the rate 1000 frames/s. The particle tracking technique was used to analyse changes in the near-wall velocity and to detect the flow reversal.

RESULTS AND DISCUSSION

The typical time courses of the film thickness and the wall shear rate obtained for the solitary wave regime are shown in Fig.2. This regime of regular waves was excited by low-frequency pulsations (f_p=1.8 Hz) of the entrance flow rate. The presented signals, which were simultaneously recorded by the capacitance and electrodiffusion probe, are normalised by their time-average values. The maximum film thickness observed at the wave crests is almost two times higher than the mean film thickness and the peak-to-peak distance between solitary waves is quite long (λ_s=152 mm). The short capillary waves (having λ_c~5 mm and f~53 Hz) are not so clearly seen on the film surface profile, because the signal from the capacitance probe underestimates their amplitudes. This is caused by the averaging effect of the cylindrical probe having the diameter of 3 mm. The wall shear rate profile, obtained after considering the dynamic response of the electrodiffusion probe [4], exhibits the same characteristic features as that obtained from the numerical simulation [2]. Strong fluctuations of the wall shear rate are apparent in the region of capillary waves. Then steep increasing of the wall shear rate is observed with the maximum value located just in front of the large wave crest. It is followed by a rapid decrease of the wall shear rate just under the wave crest. Finally, gradual relaxation of the wall shear rate takes place in the wave trail region. The most interesting feature is the existence of two small backflow regions characterised by negative values of the wall shear rate. The flow in front of the solitary wave is highly unsteady and that is why the observed near-wall flow reversal takes only several milliseconds.

The movement of the tracing particles in the near-wall region was recorded at the same film flow conditions. The video movie revealed strong pulsations of the near-wall flow velocity in the region of capillary waves. The time sequence of the pictures recorded just before the passage of the solitary wave front is shown in Fig.3. The time changes in particle positions clearly identify their short-time back movement.

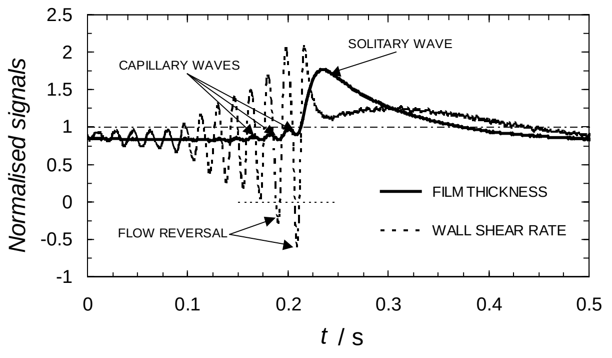

Fig.2 Film thickness and wall shear rate typical for the solitary wave regime (water data measured at f_P=1.8 Hz, Re=91, β=6.5°, x=1.5 m, h=0.63 mm, s=635 s^{-1}, c=0.28 m/s).

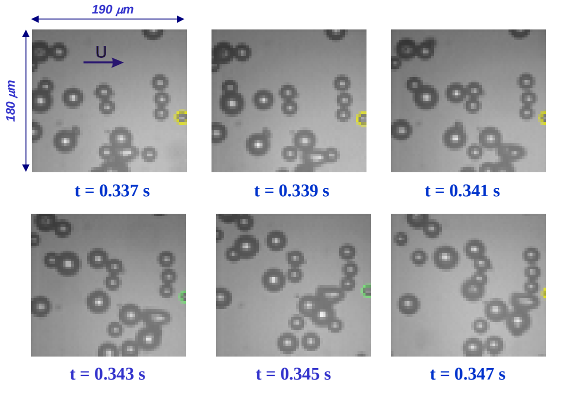

Fig.3 Visualization of the flow in the near-wall region just in front of the solitary wave.

The subsequent measurements carried out with the different model liquids covered the ranges of Re from 10 to 120 and the inclination angle β from 3° to 30°. Their results indicate that the solitary wave regime of the liquid film flow is very sensitive to the excitation conditions. It was found that:

The amplitude of solitary waves, their phase velocity and also peak-to-peak distance as well as the frequency of capillary waves is increased with the Reynolds number and decreased with the excitation frequency. The characteristics of capillary waves are especially sensitive to the operation conditions; e.g. if the excitation frequency is kept constant (f_P=1.2 Hz) and the Reynolds number is increased from 17 to 57, the frequency and wavelength of capillary waves change from 12 Hz and 14 mm to 110 Hz and 3.6 mm, respectively (data for Emkarox 5%: μ=3.9 mPa.s and the plate inclination β=5°).

The proportional relationships between the velocity and amplitude of the solitary waves, which was experimentally confirmed by Alekseenko et al. [1] for vertical films, holds also for the solitary waves appearing on the liquid film flowing down an inclined plate.

The solitary waves are travelling down a thin film substrate. Its thickness changes with the liquid viscosity and the plate inclination, but it is practically independent on the Reynolds number and the wave excitation conditions.

CONCLUSIONS

- The existence of a small backflow region located just in front of the solitary waves was detected by the electrodiffusion measurements of the wall shear rate and then confirmed by the near-wall flow visualization.
- The high-speed camera together with macroscopic objectives proved to be a good tool for near-wall flow visualization.
- The near-wall flow character in the region of capillary waves was found to be very sensitive to the wave excitation conditions, especially the excitation frequency.
- The linear dependence between the solitary wave velocity and amplitude was confirmed also for the wavy film flow along an inclined plane.

Acknowledgement
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References

[1] Alekseenko S.V., Nakoryakov V.E., and Pokusaev B.G.: Wave flow of liquid films. Begell House, New York, 1994.
[2] Malamataris N.A., Vlachogiannis M., and Bontozoglou V.: Solitary waves on inclined films: Flow structure and binary interactions. *Phys.Fluids* **14**: 1082-1094, 2002.
[3] Hanratty T.J. and Campbell J.A.: Measurement of wall shear stress, in 'Fluid mechanics measurements' (edited by J.R. Goldstein), Washington, Hemisphere, 1983.
[4] Tihon J., Tovčigrečko V., Sobolík V., and Wein O.: Electrodiffusion detection of the near-wall flow reversal in liquid films at the regime of solitary waves. J.Appl.Electrochem. **33**: 577-587, 2003.