The effects of Kapitza number and channel width on liquid film flow

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Summary

It is demonstrated experimentally that film flow in inclined channels with side-walls exhibits long-range transverse coherence that results in counter-intuitive and significant deviations from classical theory. Decreasing channel width delays the primary instability and modifies the characteristics (height, speed) of traveling waves. Deviations increase with Ka, and reach a plateau when capillary forces dominate viscous forces ($Ka > 2000$). The observed phenomena are attributed to an effective boundary condition of zero wave-height near the side-walls, which results in traveling waves with parabolically curved crestlines.

Keywords: Inclined film flow, channel width, capillary forces, transverse coherence, stationary waves, curved crestline

Film flows at inclinations θ, beyond a few tenths of a degree, are first destabilized by an interfacial mode, whose streamwise scale is significantly larger than the mean film thickness. Theoretical predictions are based on long-wave expansions using the assumption of two-dimensional flow development ($Re_c^{th} = 5/6 \cot\theta$). However, recent experimental findings [1,2] show that both the primary instability and the properties of subsequent traveling waves may be very significantly affected by channel width, even though the latter is orders of magnitude larger than the liquid film thickness. The extent of deviation from theory depends on the physical properties of the liquid, and is conveniently quantified by the Kapitza number Ka. The present study documents the combined effects of width W and Ka, and interpretes the observed phenomena in terms of the properties of traveling waves.

Experiments are performed in two facilities: one is a 3000 mm long inclined facility made in glass, with adjustable width up to 450 mm. The other is a 800 mm long by 250 mm wide channel made of Plexiglas. The width of the channels can be restricted by placing two plates of appropriate size along the sidewalls. The liquids used in the experiments are water-glycerol solutions with 0-80 wt % in glycerol (1-30 times more viscous than water). The inclination angles tested cover the range of 2-30°. With increasing inclination, the glycerol content is also increased so that the liquid film always remains thick enough to avoid rupture. At the inlet of the channel, a perturbation at desired frequency is created, in the range of 0.15-2.0 Hz and all results in disturbances are very long when compared with the liquid film thickness. Film thickness measurements are taken according to two different setups. One consists of comparing time signals of the free surface height taken by conductance probes at two locations (upstream and downstream on the centerline): the output voltage of both yields the film thickness for the two locations with a time-step of 0.01 s. The second method is based on fluorescence imaging technique: the fluid is seeded with fluorescent salt and the intensity of light is recorded by a CCD camera and converted into thickness. The 3-D structures can hence be imaged every 0.1 s.

The effect of Ka on the primary instability is shown in figure 1. Observations tend to the theoretical prediction for small Kapitza ($Ka < 100$), but deviate progressively as Ka increases and eventually reach a plateau

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in the limit of high Kapitza ($Ka > 2000$). The plateau values vary inversely with the square root of channel width. The above behavior is interpreted as a competition between streamwise viscous dissipation and transverse capillary attenuation of disturbances. The plateau is reached when capillary forces dominate over viscous forces.

It has been observed [2] that traveling waves are never two-dimensional, but attain a parabolic crestline shape, symmetric with respect to the channel centerplane (fig. 2). The height of the wave diminishes towards the side-walls and the linear phase velocity varies inversly with channel width. The apex curvature of the parabola varies inversely with channel width and Re and increases with increasing Ka. These characteristics explain the long-range transverse coherence introduced by capillary forces, which provides the additional wave attenuation mechanism. Variations in wave height and shape along the crestline set the ground for conjectures about secondary flow fields triggered by differences in capillary pressure. Such flows could involve counter-rotating eddies, transporting liquid from the center of the crestline towards the sides, and bringing it back towards the center at the wave tail. These conjectures are being investigated by appropriate PIV measurements.

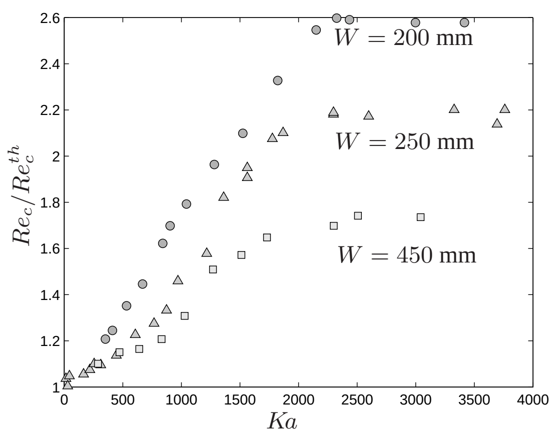

Figure 1: Experimental critical Reynolds number normalized by theoretical value Re_c/Re_c^{th} as a function of Ka.

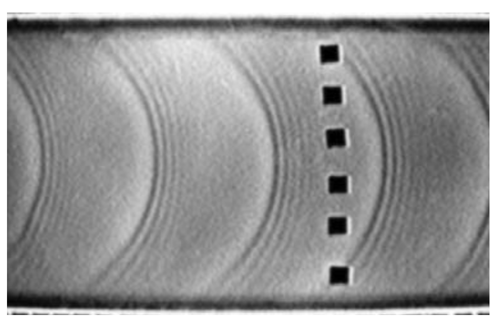

Figure 2: Parabolic waves in water, $Ka = 3300$, $W = 450$ mm, f=1 Hz, $Re = 36$, $\theta = 3°$, flowing from the left.

References

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