Experimental study of the instability of a film flowing down a vertical fiber

C. Duprat, F. Giorgiutti-Dauphiné, C. Ruyer-Quil
Laboratoire FAST (Orsay)

Fiber coating is of practical importance and occurs in many technical procedures, for example in optical fibers manufacturing process. We study the instability of a newtonian liquid film flowing down a vertical cylinder. Depending on the flow rate and the fiber radius, different regimes are observed, e.g regimes of rather symmetrical drops (Fig. 1 (a)) and solitary waves (Fig. 2 (a)). At high flow rates or fiber radii, the instability is mainly induced by inertial effects as observed on liquid films falling over planar substrates. For sufficiently small radii and flow rates the influence of a Rayleigh-Plateau instability becomes predominant.

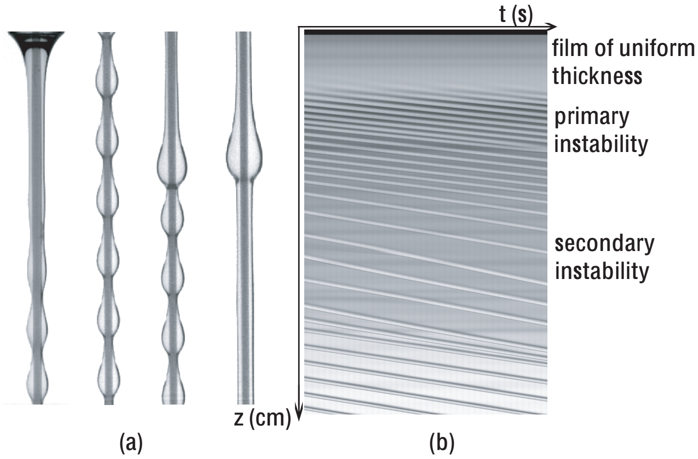

Figure 1: Results for a fiber of radius $R = 0.25\,\mathrm{mm}$: (a) Snapshots of the liquid film at different heights, with a thickness of the uniform film of $h = 0.15\,\mathrm{mm}$ (b) Spatio-temporal diagram.

In our experimental set-up, a Rhodorsil silicon oil (density $\rho = 963\,\mathrm{kg/m^3}$, kinematic viscosity $\nu = 50\,10^{-6}\,\mathrm{m^2/s}$ and surface tension $\gamma = 20.8\,10^{-3}\,\mathrm{N/m}$ at 25° C) flows on a nylon fiber maintained vertically with a weight. The inlet flow rate is controlled by varying the gap separating two cone-shaped parts of an entrance valve. This original design ensures the axisymmetry of the base flow and limits the entrance noise (film initially uniform with thickness fluctuations of 10^{-3}%). This set-up allows us to vary the fiber diameter ($0.23\,\mathrm{mm} < 2R < 3\,\mathrm{mm}$) and the flow rate ($0.01\,\mathrm{g.s^{-1}} < q < 3\,\mathrm{g.s^{-1}}$ corresponding to a range of uniform film thicknesses $0.5R < h < 3R$).We study the system response to a white noise (ambient noise) and to periodic perturbations with a wide range of forcing frequencies f.
We first consider a fiber of radius $R = 1.5\,\mathrm{mm}$ close to the capillarity length ($\kappa^{-1} = \sqrt{\gamma/\rho g}$). In this limit case, the curvature effects are dominated by the inertial effects. We can validate our experimental setup by comparing our results with the well documented case of a film flowing on a vertical plate.
The system behaves as a noise amplifier; short after the inlet, the film of uniform thickness breaks up spontaneously into a regular wavetrain with a frequency corresponding to the most spatially amplified frequency predicted by a linear stability analysis. Further downstream, a secondary instability disorganizes the flow leading to a disordered regime (see Fig. 1 (a) and (b)). We identify the cut-off frequency as the frequency for which the forcing stops affecting the dynamics of the system. For lower forcing frequencies, we obtain a periodic train of stationary saturated waves (travelling waves). The experimental data (frequency, speed, shape and thickness of the waves) compare well to the traveling wave solutions of a model consisting in two

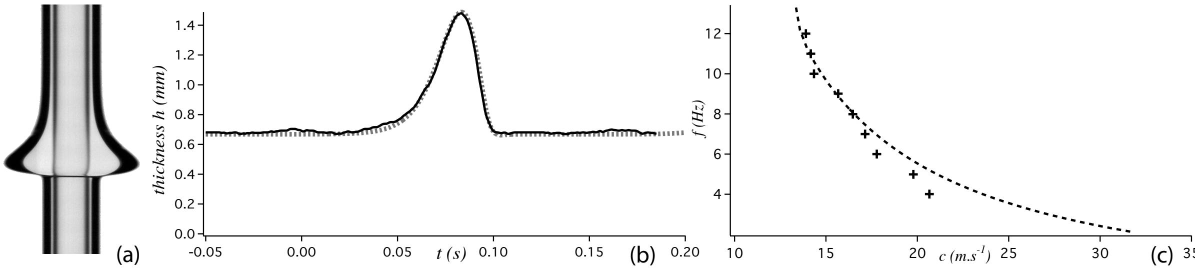

Figure 2: (a) Snapshot of a travelling wave ($R = 0.95$ mm). (b) Experimental (plain line) and simulated (dashed line) wave profile for $R = 1.5$ mm, $q = 0.66$ g.s^{-1} and $f = 6$ Hz. (c) Variation of the waves speed with the forcing frequency for $R = 1.5$ mm and $q = 0.66$ g.s^{-1} (crosses correspond to the experimental data, dashed line corresponds to the solution of the model).

evolution equations for the flow rate q and the film thickness h. Some results obtained with large fibers are summarized on Fig. 2.

We then used smaller fibers (0.23 mm $< R < 0.475$ mm) for which the Rayleigh-Plateau instability is dominant. We focus on the primary instability and observe two different regimes. At low flow rate, the system exhibits a self-sustained dynamics; the instability mechanism dominates over the advection of the waves which leads to a selection of a regular pattern with a well defined intrinsic frequency. At larger flow rates, a noise driven dynamics due to the advection of the growing waves by the flow is observed. We identify the critical flow rate at which the transition between the regular (absolute) and the noise driven (convective) instability occurs[1]. The experimental data depicted as crosses (convective regimes) and dots (absolute modes) on Fig. 3 are in good agreement with the transition obtained by resolving the Orr-Sommerfeld equation (solid line).

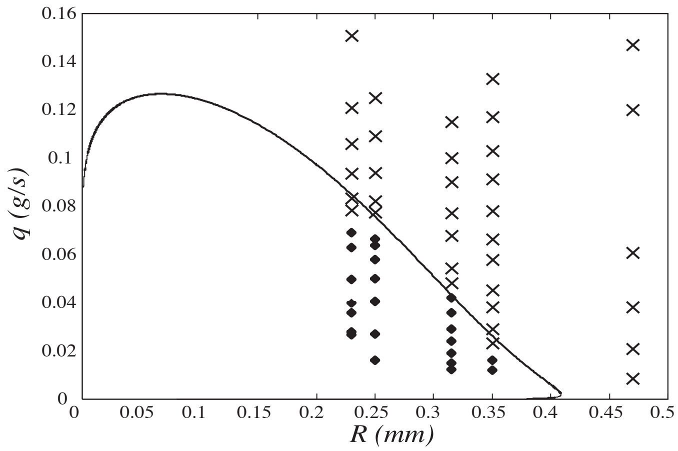

Figure 3: Critical flow rate versus fiber radius.

To conclude, the primary instability of the film has been characterised both theoretically and experimentally.

[1] C. Duprat ,C. Ruyer-Quil, S. Kalliadasis and F. Giorgiutti-Dauphiné, Absolute and convective instabilities of a film flowing down a vertical fiber, submitted to *Phys. Rev. Letter* (2007)