Chair: Physics of Fluids Department

Instability dynamics of flowing liquid films: on plates and fibers

Ever watched honey drip from a spoon or noticed how rainwater forms rivulets on a window? These everyday phenomena hide intriguing physics that governs industrial coating processes, heat exchangers, and microfluidic devices.

TL;DR

Liquid films flowing down inclined surfaces transition between distinct instability regimes as inclination angle varies. On plates, horizontal films remain stable while increasing angle triggers Kapitza waves, coupling with Rayleigh–Taylor instability beyond 90°. Fibers exhibit additional Rayleigh–Plateau instability forming beads. Using Basilisk CFD simulations, you'll map stability boundaries, characterize wave dynamics through spectral analysis, and identify instability coupling mechanisms. The project combines linear stability theory with direct numerical simulations to advance understanding of thin film flows relevant to coating processes and heat transfer applications.

Description

Liquid films flowing down inclined surfaces exhibit rich dynamics governed by competing instabilities. This project air to investigate this behavior of liquid films flowing down inclined plates (figure 1a) and fibers (figure 1b), focusing on the influence of the angle of inclination and the onset of various instabilities on the flow dynamics. While the behavior of films on vertical and horizontal surfaces are well-studied, the transition between different instability regimes as inclination angle θ varies from 0° to 180° remains open to further investigation. This project will address how Kapitza instability (wave formation), Rayleigh–Taylor instability (gravitational dripping), and Rayleigh–Plateau instability (bead formation on cylinders) interact and transition as geometry and inclination change. Using high-resolution computational fluid dynamics (CFD) simulations, you will map the stability boundaries, characterize wave dynamics, and identify the mechanisms governing instability coupling. The work will advance fundamental understanding of thin film flows while informing applications in coating technology, heat transfer enhancement, and process intensification where controlling film stability is crucial.

Deep dive

The two systems under study are a liquid film flowing down an inclined plane and a liquid film streaming down an inclined fiber. Both systems are driven by gravity and are subject to instabilities that can significantly influence their flow dynamics. However, they exhibit different behaviors and are subject to different types of instabilities due to their distinct geometries.

In the case of a liquid film flowing down an inclined plane (Craster and Matar, 2009), the stability of the film is determined by the angle of the plane. When the plane is horizontal, the film is stable. As the angle increases, Kapitza instability occurs, characterized by the formation of waves on the surface of the liquid film. As the angle increases, particularly beyond 90 degrees, Kapitza instability couples with Rayleigh-Taylor instability as the liquid drips. When the plane reaches 180 degrees, only Rayleigh-Taylor instability remains.

On the other hand, a liquid film flowing down a vertical fiber is an unstable open-flow hydrodynamic system that exhibits a variety of wave phenomena and transitions (Craster and Matar, 2006; Kalliadasis and Chang, 1994; Kliakhandler et al., 2001; Quéré, 1999). This is due to the interplay between Kapitza instability, common in films falling down vertical planes, and Rayleigh–Plateau instability, typical in a liquid layer coating a cylinder. These instabilities can lead to the formation of bead-like patterns on the fiber, which are desirable in applications where heat and mass transfer across a liquid-gas interface occurs.

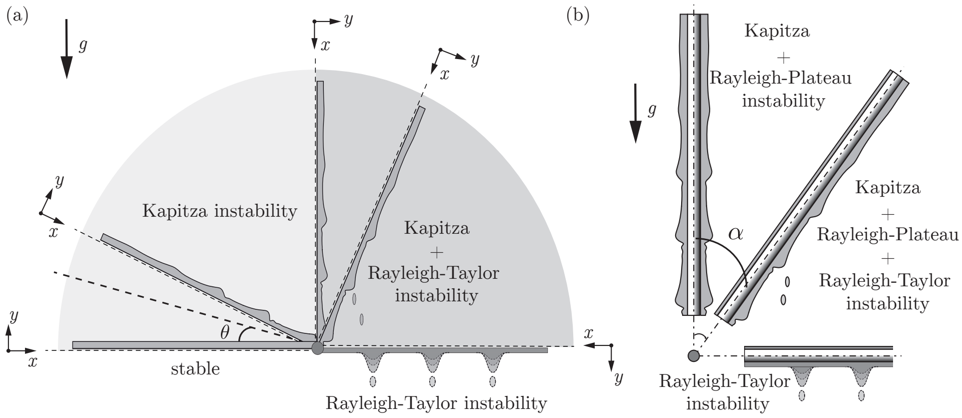

Figure 1: Schematic of the problem: (a) Liquid film flowing down an inclined plate. As the angle of inclination (θ) changes, different instabilities kick in, starting from the convective Kapitza instability, which couples with Rayleigh-Taylor instability after a critical angle of inclination is reached. (b) Liquid film flowing down a fiber. For a vertical fiber, Kapitza and Rayleigh-Plateau instability dominate. However, as a critical inclination is reached, Rayleigh-Taylor instability dominates, particularly as the inclination angle approaches π. Figure adapted from Rietz et al. (2017).

Through this research, we aim to provide a comprehensive understanding of the behavior of liquid film flows on inclined fibers (Karimi et al., 2023) and plates (Craster and Matar, 2009), contributing to the broader field of fluid dynamics.
The main objectives of this study are:

1. How does the angle of inclination influence the stability of liquid films on fibers and plates? We will systematically vary the angle of inclination and observe the resulting changes in the stability and flow dynamics of the liquid films.

2. How does the transition between different instabilities occur as the angle of inclination changes? We will conduct detailed numerical simulation to capture the transition points between different instabilities and understand the underlying mechanisms (see figure 1).

3. How do different instabilities interact and influence the flow dynamics of liquid films? We will study the interactions between Kapitza, Rayleigh-Taylor, and Rayleigh-Plateau instabilities and their collective impact on the flow dynamics.

4. What are the underlying mechanisms that govern the gravity-driven flow of liquid film down an incline or a fiber?

5. To identify and explore the different timescales relevant for this process (see the introduction of Sanjay (2022d)).

What will you do and what will you learn?

For this project, we are looking for enthusiastic students to work on this topic.

1. You will learn about fundamental fluid dynamics.
2. You will get hands-on experience with Computational Fluid Dynamics (CFD).
3. You will learn how to do basic and advanced data analysis.
4. You will learn how to document and publish read-to-use codes and share them with the community, similar to Sanjay (2022a,b,c).
5. As a part of the CoMPhy lab, you will learn and adapt open-source coding principles.

If you have any questions, fell free to contact Vatsal (details below).

Supervision	E-mail	Office
Dr. Vatsal Sanjay	vatsal.sanjay@comphy-lab.org vatsal.sanjay@durham.ac.uk	Durham University
Jnandeep Talukdar M.Sc.	jnandeep.iitp@gmail.com	Meander 246B
Prof. Dr.-Ing. Wilko Rohlfs	w.rohlfs@utwente.nl	Horst Complex, N234
Prof. Dr. Detlef Lohse F.R.S.	d.lohse@utwente.nl	Meander 261

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