

Vortical Wake Flow of Wetting Disk-Like Drops in Flat Channels

Sebastian Luckey^{1,*}, Florian Hermann¹, Sebastian Burgmann¹, Uwe Janoske¹

1: Chair of Fluid Mechanics, The University Wuppertal, Germany

* Correspondent author: luckey@uni-wuppertal.de

Keywords: wetting drop, disk-like drop, flat channel flow, Particle Image Velocimetry

ABSTRACT

The control of droplet movement, especially its initiation, plays a major role in many areas of chemical and pharmaceutical technology. In many applications, droplets wet both confining walls, resulting in the motion of a wetting liquid through a parallel-wall gap channel. Of particular interest here are the necessary conditions that lead to the onset of movement of the droplet under the influence of external forces (here flow). However, there is almost no information in the literature on the conditions for a droplet in flow, wetting on both sides, which go beyond the configuration of a Hele-Shaw cell in terms of dimensions, viscosity ratios and flow velocities, i.e. for the combination of Reynolds number Re and gap width ratio ≥ 1 .

Droplets of different sizes (10 - 50 μl) are applied to a test rig in a slit channel with a cross-section of $1 \times 20 \text{ mm}^2$, wetting both the upper and lower (glass) walls, i.e. initially forming a round liquid disk. The gas flow in the channel is successively increased and the drop deformation, the detachment of the drop and the further drop movement are analyzed using shadowgraphy. In addition, measurements are carried out using particle image velocimetry (PIV) to obtain information about the flow field of the adhering and moving droplet.

The initially round, disc-shaped droplet is deformed with increasing gas velocity in such a way that it is flattened on the upstream side. The downstream, almost semi-circular contact line does not move. If the flow velocity is increased further, the deformed droplet finally detaches, whereby it initially takes on a kidney-shaped form for larger droplets. The subsequent droplet movement downstream also occurs if the flow velocity does not increase any further. The critical gas velocity (for droplet detachment) decreases with the droplet volume, like sessile droplets in a flow channel. The almost constant drift velocity of the droplet is four orders of magnitude lower than the gas velocity. For larger droplets, a bursting of the droplet is observed during further movement.

In the droplet wake, a recirculation zone with two counter-rotating vortices develops in both the adhesion and movement phases. The length of the recirculation zone increases with increasing Reynolds number. The results also show that the vortex pair can exhibit fluctuations in the wake in such a way that one of the two vortices temporarily dominates and displaces the other, resembling a vortex oscillation pattern.

1. Introduction

Controlling the movement of drops, especially their incipient motion, plays an important role in many areas of chemical and pharmaceutical engineering as well as mechanical engineering. This is relevant not only for targeted or desired drop generation, but also for unwanted accumulation of liquids, e.g., due to oil entry, water entry from sprays, condensation, or electrochemical reactions. This is particularly problematic when this accumulation occurs in small gaps or structures of machines or machine parts. In many cases, a gas flows through this narrow geometry. If the drop only wets one wall, the configuration of an adhering drop in a shear flow is present. If the aerodynamic force is sufficiently large, the drop deforms (Barwari et al., 2019, Gupta & Basu, 2008) begins to oscillate (Burgmann et al., 2021; Costalonga & Brunet, 2020), and finally moves downstream (Barwari et al., 2019; Fan et al., 2011; Fu et al., 2014). The movement of these droplets can be influenced if, for example, additional acceleration forces such as gravity or vibration excitation are applied (Barwari et al., 2021; Rhode et al., 2022, 2024). However, previous studies in narrow geometries have been limited to adhering droplets that only came into contact with one (channel) wall.

In many applications, however, a drop wets not only one (lower) wall, but also an opposite wall, i.e., we have a wetting liquid between parallel walls. Of particular interest here are the conditions required for incipient motion of the drop under the influence of external forces, e.g., as a result of gas flow in the gap (channel) in which the drop is located.

The case of non-wetting drops between parallel walls (“pancake drops”) that are flowed around at low gas velocity is similar to the classic Hele-Shaw configuration and is well described in the literature (e.g. see (Zhu & Gallaire, 2016)). However, there are limited data in the literature for the conditions for a two-sided wetting drop affected by a gas flow that go beyond the dimensions, viscosity ratios, and flow velocities of a Hele-Shaw configuration, i.e., for the combination of Reynolds number Re and gap width ratio

$$\frac{\rho_G \cdot u_\infty \cdot h}{\mu_G} \cdot \frac{h}{l} = Re \cdot \frac{h}{l} \geq 1 \quad (1)$$

This article therefore reports on the experimental analysis of the behavior of two-sided wetting drops (static contact angle of $\theta = 38^\circ$) in a slit channel with a width-to-height ratio of 20. A Reynolds number range up to $Re_d = 3,100$ based on the diameter d of the drop, or $Re_{hydr} = 1,000$ based on the hydraulic diameter of the channel, is considered; This results in a range for Equation (1) extending up to 30. Using shadowgraphy and Particle-Image-Velocimetry (PIV) we analyze the (water) droplet behavior at rising air flow velocity and will identify critical conditions and typical phenomena.

2. Experimental setup

Figure 1 shows the test channel used. This 3D-printed channel consists of a lower housing section and cover, into which thin glass plates (standard microscope slides with English measurements) can be inserted to form the upper and lower walls of the channel. The glass plates can be quickly and easily removed and cleaned or replaced with other slides with different coatings. The gap channel measures 76 mm in length, 20 mm in width and 1 mm in height. A 3D-printed nozzle-diffuser unit with a transition piece is connected to the inlet of the channel, which connects to the hose connection of the mass flow controller.

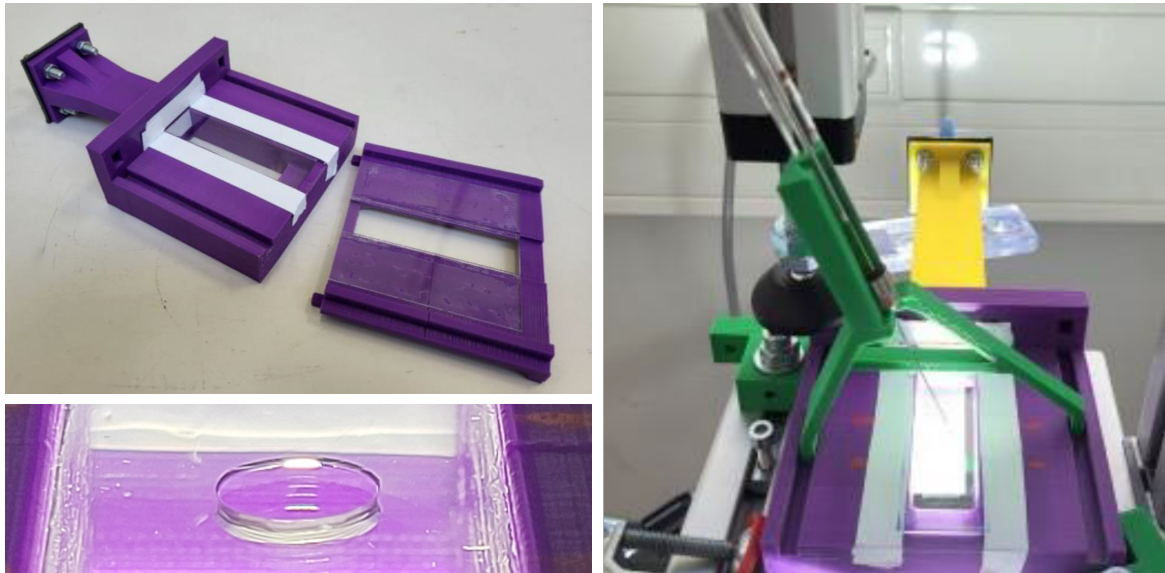


Figure. 1 3D-printed slit channel with lid removed (top left), captured, wetting drop in the slit channel (bottom left), careful drop application in the center of the the channel (right)

When open, drops between 10 and 50 μl are placed on the lower glass plate using a precision syringe, and then the channel is closed; the drop is now enclosed between the upper and lower glass plates and wets both walls (see Fig. 1). Without gas flow, the drop forms a round, disc-like shape with a concave curvature between the upper and lower wall. The static contact angle is 38° . The test channel is installed in a test rig that enables control of the mass flow controller. The gas flow in the channel is increased gradually and incrementally, with a volume flow level being maintained for 3 seconds at a time. The drop deformation, the detachment of the drop, and the further movement of the drop are analyzed using a shadow method. For this purpose, the test bench is equipped with an LED and a camera. The illumination is provided from below through the glass plate of the channel and the scene is recorded.

In addition, measurements are carried out using particle image velocimetry (PIV) to obtain information about the flow field of the adhering and moving droplets. The light section is guided horizontally from downstream into the slit channel (Fig. 2) and precisely aligned in the center of the channel using a slit aperture and leaf gauge. The light section thickness was determined to be $< 500 \mu\text{m}$. With the lens used and the magnification setting, a depth of field of $\approx 100 \mu\text{m}$ is calculated for an aperture number of $f\# = 4$. Seeding (DEHS) is generated by passing the air from the mass flow controller through an atomizer via a bypass. Fig. 2 shows a typical particle image of the drop wake for a PIV measurement performed in this way. The drop contour is clearly visible as a bright edge at the top of the image. Due to refraction and total reflection, the area directly upstream of the drop cannot be measured using PIV. The PIV measurements are performed at an effective frame rate of 10 Hz.

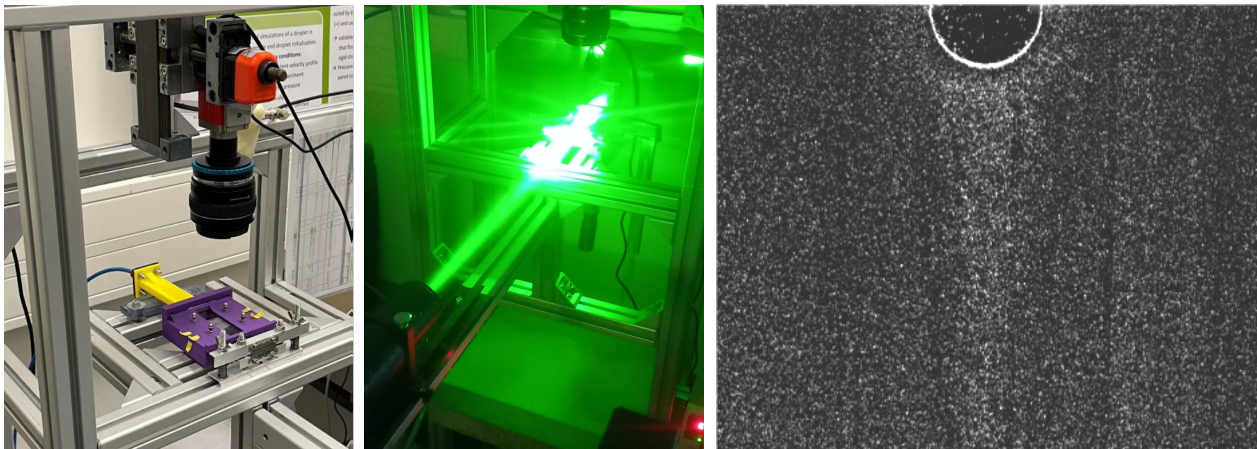


Figure. 2 Setup for a PIV measurement at the slit channel (left) with the laser light section fed in via the open side of the channel (middle) and the resulting particle image in the wake of the droplet (right)

3. Results

The following section first briefly presents the phenomenological descriptions of the drop behavior at increasing flow velocities, as determined from the recordings made using the shadow method. The initially round, disc-shaped drop is deformed as the flow velocity increases in such a way that it is flattened on the upstream side. The downstream, almost semicircular contact line does not move. Even before a major deformation occurs, an oscillation of the drop contour can be observed.

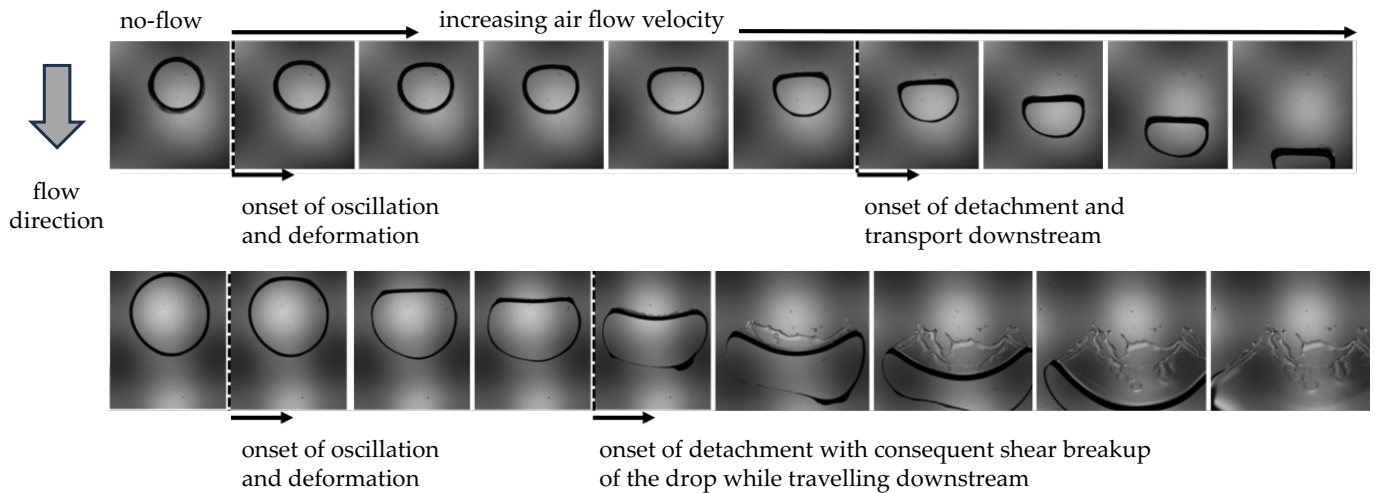


Figure. 3 Shadowgraphy of a wetting drop in a high-aspect ratio channel at increasing flow velocity. Top: 15 μl drop,
Bottom: 50 μl drop

As the flow velocity continues to increase, the deformed drop eventually detaches when a critical velocity is reached, becoming more concave on the upstream side and taking on a kidney-shaped form (see Fig. 3). After detachment, the drop continues to move downstream while retaining its deformed shape. This downstream movement of the drop also occurs when the flow velocity does not increase further.

In the case of larger drops (40-50 μl), the drop is observed to burst as it continues along its path of movement (Fig. 3). In these cases, the blockage of the channel cross-section by the undeformed drop is over 33%. As can be seen in Figure 3, the lateral expansion of the drop increases to about twice its size as it moves downstream. The extremely high shear stress on the sides of the drop is presumably the cause of the phenomenon of drop bursting. The images are analyzed using image processing and edge detection to detect the movement of the contact line. The point at which the drop detaches is defined by a significant movement of the downstream part of the drop's contact line. (Burgmann et al., 2025)

Overall, it can be seen that the critical gas velocity (for detaching the droplet) decreases with droplet volume in a similar way to sessile droplets in a flow channel, as shown in Figure 4. This figure also shows the drift velocity of the detached and deformed droplets.

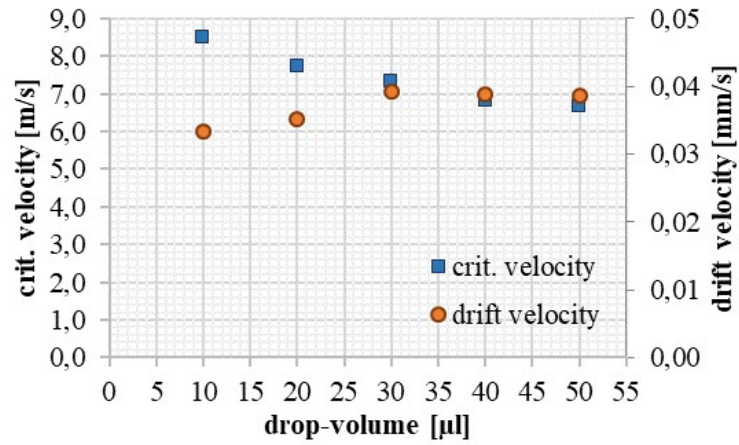


Figure. 4 Critical velocity for drop detachment and resulting drift velocity as a function of drop volume

This almost constant drift velocity of the drop is four orders of magnitude smaller than the gas velocity. It is striking that the drift velocity does not increase with increasing drop volume, although the blockage of the channel increases significantly with increasing drop volume (especially in the deformed state) (Luckey et al., 2025). It can therefore be assumed that flow structures form in the wake of the drop that impede downstream movement.

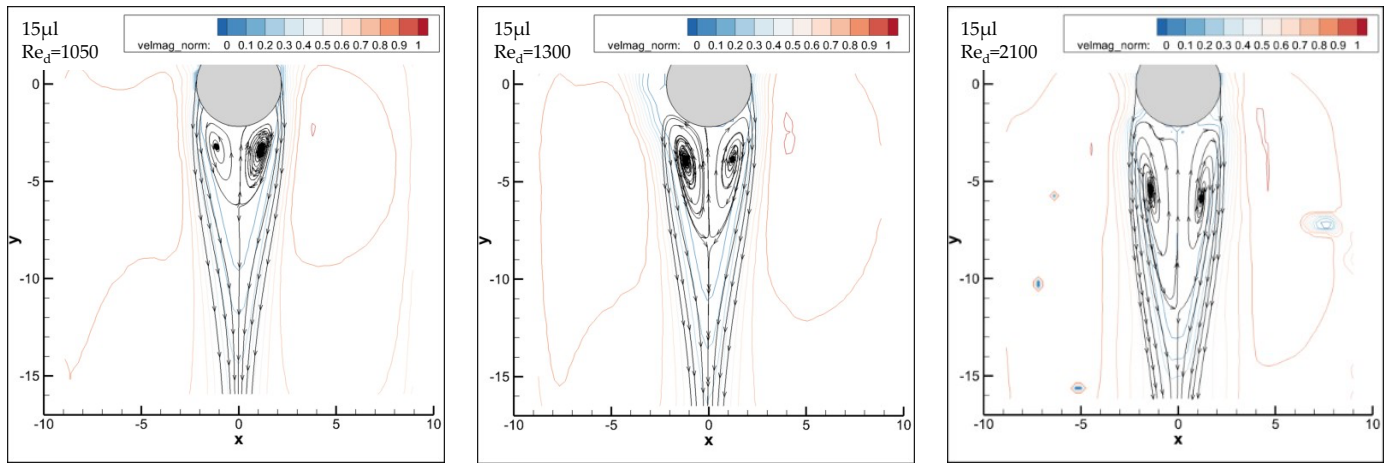


Figure. 5 Flow field around a pinned 15 μl drop for 45% (left), 56% (center) and 90% critical (right); shown via normalized velocity magnitude and streamlines

The following section therefore presents the results from the PIV measurements of the flow around the droplet, which show the formation of such structures. Figure 5 shows an example of the flow field for a 15 μl droplet at different flow velocities. The drop is still pinned in the velocity range shown here (up to $\text{Re}_d = 2100 = 90\%$ critical). A recirculation zone featuring two counter-rotating vortices forms in the wake of the droplet. This aligns with the flow behavior typically expected for rigid cylindrical structures at Reynolds numbers $\text{Re}_d < 90$. As illustrated in Figure 5, a recirculation

region with a vortex pair still develops even at $Re_d = 2100$, despite the fact that vortex street instabilities would be expected according to the literature (Schlichting & Gersten, 2016). It can therefore be assumed that the given aspect ratio leads to a stabilization of the flow. The extend of the recirculation zone in flow direction increases with increasing Reynolds number.

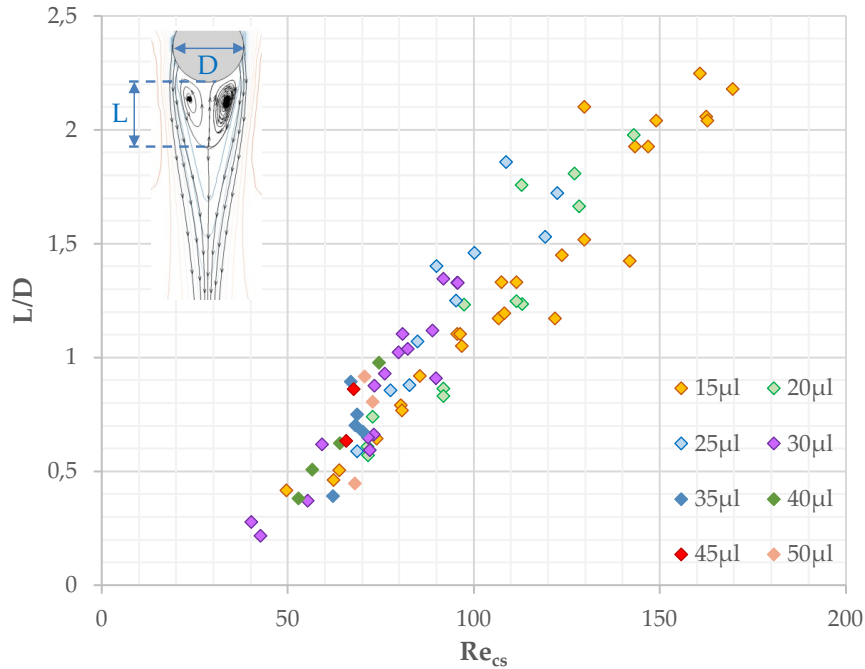


Figure. 6 Representation of the length of the recirculation zone in the wake, normalized to the diameter, as a function of the Reynolds number based on the free cross-section and the drop-volume.

Figure 6 summarizes the results regarding the extent of the recirculation area in the wake of drops. The increase in the normalized recirculation length with increasing Reynolds number can be seen. In this case, the Reynolds number is based on the free cross-section for each drop instead of the diameter. Based on that Reynolds number the normalized recirculation length only slightly depends on drop volume. It can be assumed that the movement of the phase boundary influences the extent of the wake region. It can also be assumed that for large drops, the greater blockage of the flow channel causes a corresponding change in the flow field (cf. the phenomenon of drop bursting for larger drops).

As can be seen in Figure 9, alternating vortex shedding can even occur under certain conditions for stationary droplets. While the counter-clockwise vortex propagates until detachment during the first time step, with a smaller new vortex already forming, the clockwise vortex moves only minimally along the flow.

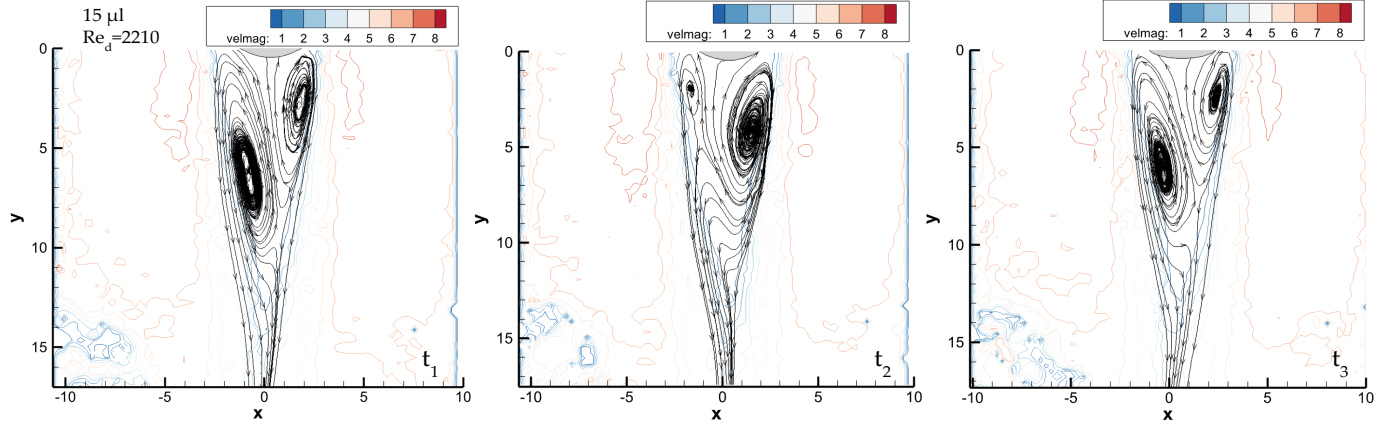


Figure. 9 Vortex Dynamics downstream of a 15 μ l droplet between consecutive frames (100 ms).

This dissolution of the counter-clockwise vortex also alters the orientation of the recirculation zone's wake region within the frame sequence. However, due to the low sampling rate of 10 Hz, the current measurement setup does not allow for a more precise determination of the shedding frequency and, consequently, the Strouhal number.

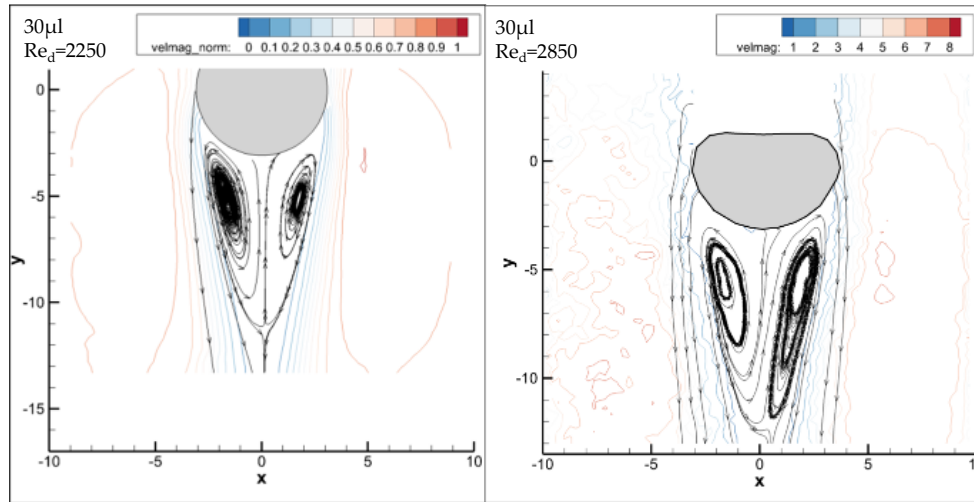


Figure. 7 Flow field around a 30 μ l drop initially pinned in place as a time average over 200 frames (left) and a 30 μ l drop just set in motion as a single frame (right); depicted using normalized velocity magnitude and streamlines.

If the Reynolds number or gas velocity is increased further, the drop detaches and moves (in a deformed state) downstream. Figure 7 shows an example of the flow field for a 30 μ l drop in its initially pinned state and at a point shortly after reaching the state of motion. It is clear that the recirculation area remains intact even in the motion phase (with very low drift speeds – see Fig. 4). It can be assumed that the high speeds at the edge and the fluid transport caused by the counter-rotating vortices inhibit the drop's downstream motion.

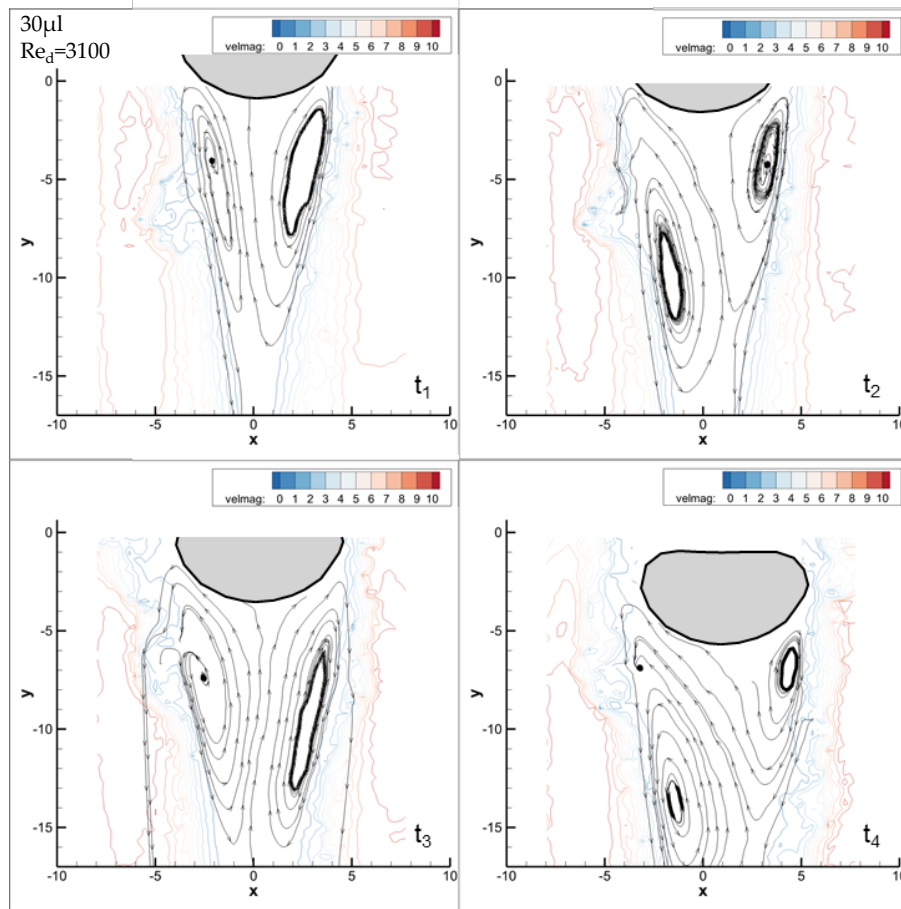


Figure. 8 Flow field around a 30 μl drop set in motion; represented by normalized velocity magnitude and streamlines

The results also show that in the case of the downstream-moving drop, the vortex pair in the wake can exhibit fluctuations in such a way that one of the two vortices temporarily dominates and displaces the other (see Figure 8) – however, this phenomenon of vortex oscillation for moving droplets needs to be analyzed further.

Further investigations into the variation of drop volumes and flow velocities are currently underway. In addition, investigations are being carried out with cylindrical glass plates, to assess the effect of the mobility of the interface on the flow structure. Further measurements on other channel configurations are also planned in order to consider different height-to-diameter ratios. In a further modification of the measurement setup, PIV measurements of the internal flow of the droplets will be carried out in order to demonstrate the correlation between the external and internal flow.

References

- Barwari, B., Burgmann, S., Bechtold, A., Rohde, M., & Janoske, U. (2019). Experimental study of the onset of downstream motion of adhering droplets in turbulent shear flows. *Experimental Thermal and Fluid Science*, 109, 109843.
- Barwari, B., Rohde, M., Wladarz, O., Burgmann, S., & Janoske, U. (2021). Motion of adhering droplets induced by overlapping of gravitational and periodical acceleration. *International Journal of Multiphase Flow*, 135, 103537.
- Burgmann, S., Dues, M., Barwari, B., Steinbock, J., Büttner, L., Czarske, J., & Janoske, U. (2021). Flow measurements in the wake of an adhering and oscillating droplet using laser-Doppler velocity profile sensor. *Experiments in Fluids*, 62(3), 47.
- Burgmann, S., Ehrhardt, B., Rosen, J., Janoske, U. (2025, May 12-16). Deformation and detachment of wetting drops in flat-channel flow. *12th International Conference on Multiphase Flow (ICMF 2025)*, Toulouse, France.
- Costalonga, M., & Brunet, P. (2020). Directional motion of vibrated sessile drops: a quantitative study. *Physical Review Fluids*, 5(2), 023601.
- Fan, J., Wilson, M. C. T., & Kapur, N. (2011). Displacement of liquid droplets on a surface by a shearing air flow. *Journal of colloid and interface science*, 356(1), 286-292.
- Fu, S. C., Leung, W. T., & Chao, C. Y. (2014). Detachment of droplets in a fully developed turbulent channel flow. *Aerosol Science and Technology*, 48(9), 916-923.
- Gupta, A. K., & Basu, S. (2008). Deformation of an oil droplet on a solid substrate in simple shear flow. *Chemical engineering science*, 63(22), 5496-5502.
- Luckey, S., Rauls, K., Rosen, J., Ehrhardt, B., Janoske, U., Burgmann, S. (2025, September 9-11). Mobilizing two-sided wetting drops in flat channel flow. *32th Conference Experimental Fluid Mechanics (GALA25)*, Darmstadt, Germany.
- Rohde, M., Barwari, B., Burgmann, S., & Janoske, U. (2022). Droplet motion induced by superposition of shear flow and horizontal surface vibration. *International Journal of Multiphase Flow*, 155, 104163.
- Rohde, M., Burgmann, S., & Janoske, U. (2024). The impact of a two-dimensional vibration excitation on the critical incident flow velocity of a sessile droplet. *International Journal of Multiphase Flow*, 171, 104663.
- Schlichting, H., & Gersten, K. (2016). *Boundary-layer theory*. springer.
- Zhu, L., & Gallaire, F. (2016). A pancake droplet translating in a Hele-Shaw cell: lubrication film and flow field. *Journal of Fluid Mechanics*, 798, 955-969.