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Deformation and movement of adhering droplets in shear flow

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Abstract

Droplets may appear on surfaces of machines etc. due to condensation or liquid sprays. Often there is an airflow over these surfaces, so that the droplet experiences a shear flow. If the critical velocity is exceeded, the droplet moves and may end up in a critical area influencing the functionality of the machine. However, there is no common definition for the initiation of a movement of a droplet, since advancing and/or receding contact line might move without a temporal mean movement of the droplet-center of gravity. Additionally, there is no generally accepted definition available to describe the critical velocity (e.g. bulk velocity or some shear flow velocity). In this work, a definition of the onset of a droplet movement is found based on a normalization of the position of the droplet-center of gravity. Furthermore, the effect of viscosity on the droplet behavior is studied. The influence of the droplet volume and fluid properties on the droplet detachment is analyzed in detail. The experimental results show that the critical velocity can be expressed by a mathematical correlation between the Reynolds number and Laplace number. The correlation provides the critical velocity very accurately.

1 Introduction

Droplet motion has great importance in several technical applications in the field of heat transfer, microfluid devices or process engineering. In general, droplet movement can be initiated through different mechanisms such as gravitation (Extrand et al., 1995), dielectric potential (Kuo et al., 2003), vibrational forces (Daniel et al., 2002) or shear flows (Dimitrakopoulos et al., 1997). In this paper we focus on droplets subjected to a velocity gradient induced by an airflow. For adhering droplet in a shear flow, a deformation of the droplet contour can be observed even for low Reynolds numbers in the order of O(100) (Seevaratnam et al., 2010). Droplets with a higher mass show a visible oscillating contour deformation in contrast to droplets with small volumes (Lin et al., 2006). Eventually, for increasing airflow velocity, the droplet starts to move. It is known that the onset of the droplet movement depends on the contact angle hysteresis and the droplet volume (Maurer, 2017). Furthermore, the material surface properties (Theodorakakos et al., 2006) and the fluid properties (Fan et al., 2011) determine the initiation of the droplet movement. However, the behavior of adhering droplets in airflow is not fully understood and there is no common definition available concerning the critical velocity and the beginning of a droplet movement. The behavior of droplets under the effect of an airflow is important to understand in order to avoid the loss of system performances and potential failures. Hence, a detailed experimental study is necessary to identify and understand the critical parameters.

The present paper deals with the experimental investigation of liquid droplet behavior in a shear flow within a Plexiglas-channel at different flow velocities. Liquid droplets of different volume (7.8 to 39.9 μl) and different ratio of water-glycerine (0 to 50 %) are placed on the bottom channel wall with a syringe. The droplet contour position is measured by transmitted light technique. The aim of this study is to analyze the influence of the fluid properties, in particular, the influence of viscosity on droplet detachment and behavior. A clear definition of the onset of a droplet movement is found and a unique criterion in order to determine the critical velocity is developed.

2 Experimental setup and methods

A main aim of this paper is to investigate the influence of fluid properties on the droplet behavior while being exposed to an airflow. Figure 1 shows a schematic representation of the test rig. The rectangular channel is made of Plexiglas to analyze the droplet behavior by camera technique. Droplets are placed with a microliter syringe on an acrylic glass plate. This section can be exchanged so that different material properties may be investigated. The volume flow of air is controlled by a mass flow controller. The droplet to be recorded is located between a high-speed camera and a LED light source. In this way, the camera captures the projection of the droplet shadow. For each experiment the velocity is increased linearly. Several different water-glycerine solutions were used for the droplet. The droplet analysis tool supplies geometrical and physical parameters.

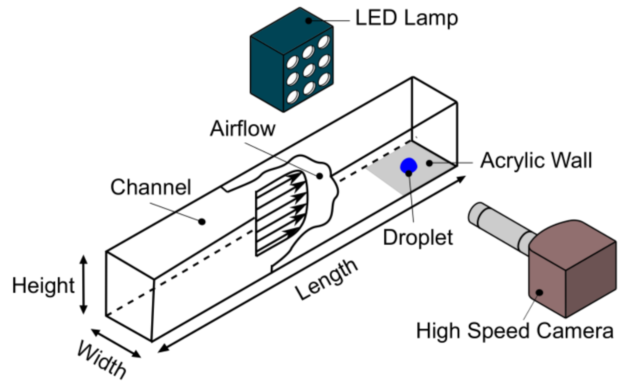

Figure 1: Schematic of the experimental setup.

The composition and the determined material properties at 25 °C can be found in table 1. The surface tension σ_d was measured by a tensiometer using Du Noüy's ring method. The dynamic viscosity μ_d was measured with a rotational viscometer. Rheological measurements of the listed water-glycerine solutions have shown that all liquids have a Newtonian behavior. The increase of the glycerine mass fraction Φ_g up to 50 % slightly changes the density ρ_d (+13 %), the surface tension σ_d (-9 %) and static contact angle Θ_s (74° to 68°) but significantly alters the dynamic viscosity μ_d (+477 %). Hence, the effect of the viscosity on the critical velocity is studied.

Table 1: Thermophysical properties and parameters values of selected liquids at 25 °C.

Φ_g	V_D	ρ_d	σ_d	μ_d	Θ_a	Θ_r	Θ_s	Bo
[%]	[µl]	[kg/m³]	[mN/m]	[mPa s]	[°]	[°]	[°]	[-]
0	7.8 – 39.9	997.05	71.96	0.89	74.5	74.2	74.4	0.73 - 2.16
10	7.8 – 39.9	1006.26	70.38	1.31	73.2	71.5	72.4	0.75 - 2.23
20	7.8 – 39.9	1031.38	69.82	1.76	70.8	71.5	71.2	0.78 - 2.30
30	7.8 – 39.9	1055.58	67.52	2.41	69.5	70.5	70.0	0.82 - 2.44
40	7.8 – 39.9	1083.63	66.77	4.25	68.2	68.7	68.5	0.85 - 2.52
50	7.8 – 39.9	1123.55	65.77	5.14	68.4	67.6	68.0	0.89 - 2.65

3 Contour of adhering and moving droplet

Figure 2 illustrates two examples of the motion path of pure water droplets (top left) and water-glycerine droplets (top right) as a function of the traveled distance. The water droplet is slightly deformed by the air flow and assumes a typical mean deformation. The center of gravity is shifted downstream and the droplet has a flat curved shape in the receding position, whereas in the advancing position the contour becomes steeper. In fig. 2, it can be qualitatively seen that the width of the moving droplet is smaller than that of the adhering droplet. However, the height of the moving droplet increases in comparison with the adhering droplet, thereby exhibiting a more compact shape. By introducing glycerine into water, the droplet deformation increases, as shown in fig. 2 (top right): The droplet flattens to a greater extent and a tail at the rear end appears. The greater the droplet volume, the longer the droplet tail becomes and the more the droplet deviates from the compact shape. Under certain conditions, a droplet separation can be observed at the rear end, i. e. small droplets detach from the main droplet. Figure 3 shows the movement of a 39.9 µl droplet of Φ_g = 50 % compared to a glycerine mass fraction of 70 %. As the amount of glycerine increases, the droplet spreads over a large area of the surface. In addition, the size of the separated droplets continues to increase. Additionally, the shape of the droplet deviates significantly from the compact shape. By further increasing the glycerine mass fraction, it has been observed that the contour differences become more apparent. The analysis of the droplet contour shows that the typical shape of the adhering droplet as well as the moving droplet is not significantly altered as long as glycerine mass fraction is kept below 50 %, as demonstrated in fig. 2 (top right). Since the behavior of the droplet movement changes considerably with glycerine mass fraction, the method for determining the critical velocity is specially developed for the compact shape, i. e. only for glycerine mass fraction up to 50 %.

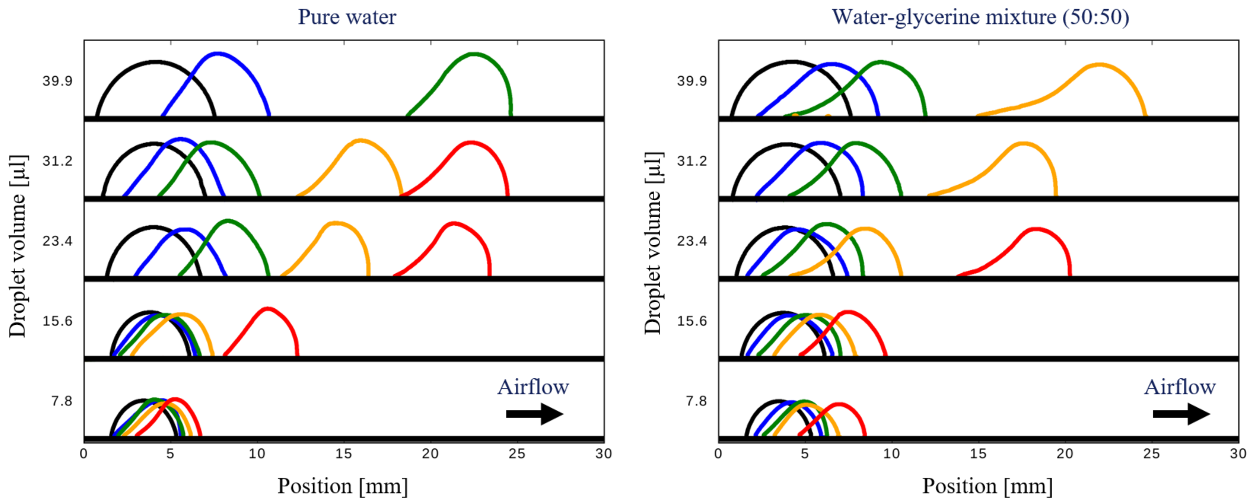

Figure 2: Typical patterns of adhering droplets in shear flow from non-moving to moving droplet (black to red contours correspond to time step: ● 0 s ● 15 s ● 18 s ● 21 s ● 24 s) for pure water (top left) and water-glycerine mixture of 50:50 (top right).

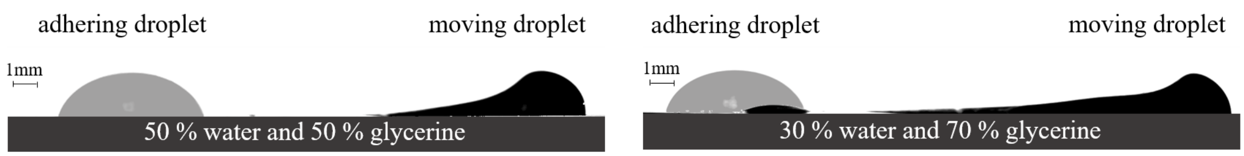

Figure 3: Typical shape of 39.9 µl droplets without and with airflow (from left to right) for a droplet of 50 % glycerine mass fraction (left) and 70 % glycerine mass fraction (right).

4 Definition of the onset of droplet movement and the critical velocity

A clear and universal definition of the droplet detachment has not yet been established. In (Hao et al., 2013), the authors chose the velocity at which the receding and advancing position are moved for the first time as the critical bulk velocity. But this definition is not really suitable for the global droplet movement. Even if a droplet detachment initially takes place, it is no indication that the droplet moves further downstream. Depending on the local fluid-surface system, a new wetting can occur and a new attempt to surpass the contact angle hysteresis is necessary. In (Maurer, 2017) a more accurate definition of droplet detachment is presented. The beginning of the global movement of a droplet is identified by the equivalence of the contact line velocity of the advancing and receding position. With our new method we can achieve better results; as demonstrated in fig. 4. On the x-axis, the distance covered by the droplet center of gravity x_c is adjusted to its current droplet width d_w. The ratio between the droplet velocity v_d and the airflow velocity v_f is plotted on the y-axis. For a better overview every 20th-time step is plotted. The graph can be divided into three sections that represent three different phases of movement. The first section (I) characterizes the oscillating movement of the droplet. A global movement downstream does not take place, whereas a droplet detachment has taken place several times. If the airflow continues to increase the distances between the individual points become greater (II). The droplet travels a greater distance in the same time span. In the third section (III), the droplet is in a uniform motion and has already traveled a long distance. The critical bulk velocity is detected at the transition from I to II. For this purpose, the red square in fig. 4 illustrates the possible range.

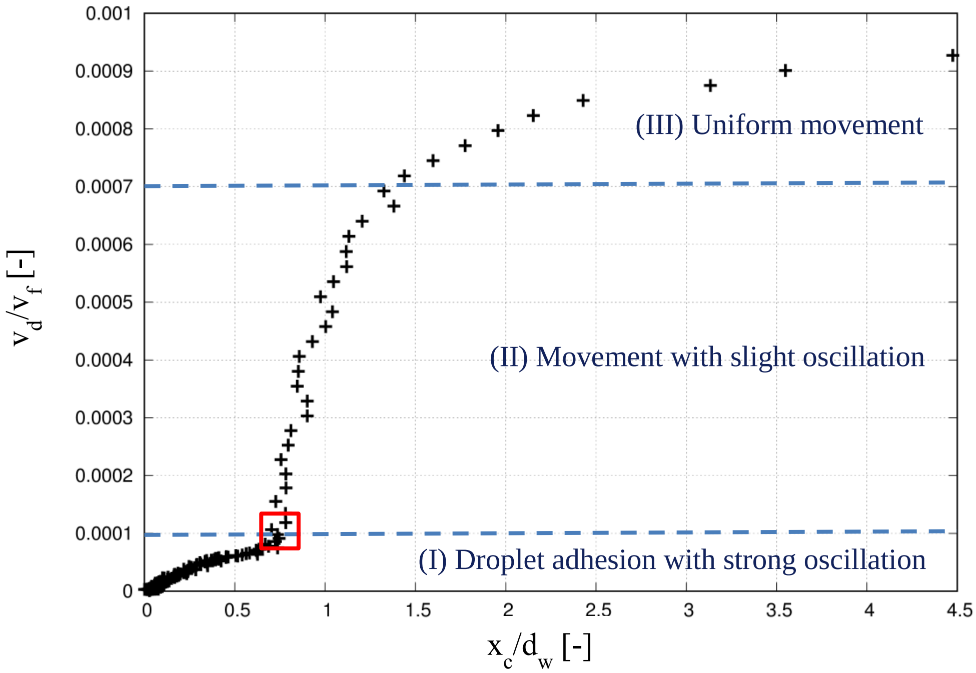

Figure 4: Dimensionless method for determining the critical bulk velocity v_{crit} depending on droplet velocity v_d, droplet width d_w and the distance covered by the droplet center of gravity x_c for a water droplet with 23.4 µl volume.

5 Influence parameters of the critical velocity

Figure 5 (left) illustrates that the required critical velocity v_{crit} decreases with an increase in droplet volume for all ratios of water and glycerine. Similar results can be found in the works of (Burgmann et al., 2017, Fan et al., 2011, Fu et al., 2014, Maurer, 2017) for other fluid-substrate systems. The main reason for this phenomenon is the influence of the droplet height. A large droplet experiences a higher local velocity due to the increase in the distance between the highest droplet point and the substrate surface. It is found that there is an increase of the critical velocity if the proportion of glycerine mass fraction grows. This is due to changes in the properties of the liquid caused by the admixture of glycerine in water. Additionally, an increase in glycerine mass fraction increases inertia and contact angle hysteresis, leading to an increase of the critical velocity. Furthermore, viscosity has a very big influence on the droplet detachment. As viscous damping and adhesion force become greater, higher drag force is needed to initiate a droplet movement.

For a correlation between the critical velocity and the reference parameters two important dimensionless numbers can be considered: the critical droplet Reynolds number, Re_{crit} and the Laplace number, La. The Reynolds number generally describes the ratio of inertial forces to viscous forces. The Laplace number is defined as the product of surface forces and inertial forces of a fluid divided by the square of the frictional force. Both dimensionless numbers are defined as follows:

$$Re = \frac{\rho_d v_{crit} d_h}{\mu_d} \tag{1}$$

$$La = \frac{\sigma \rho_d d_w}{\mu_d^2} \tag{2}$$

The fluid properties are related to the droplet. The droplet width d_w and the droplet height d_h are taken as the characteristic lengths. The curve of the critical Reynolds number versus the Laplace numbers can be characterized by an exponential approach.

$$Re_{crit} = 51.04 La^{0.434} \tag{3}$$

The results can be accurately well reproduced with the derived relationship, as demonstrated in fig. 5 (right). The coefficient of determination, R^2 is found to be 0.99. The authors want to point out that the critical velocity v_{crit} itself can only be used as a reference for the comparison to a limited extent. The reason for the limitation is the usage of different definitions for v_{crit}, geometrical dimensions, fluid properties, droplet volumes and wetting properties. Hence, in this study, the correlation between the Reynolds number and Laplace number is formulated which includes the droplet and geometrical dimensions and all the fluid properties. This relation will be further extended to include additional influencing parameters through experimental investigations. With the aforementioned relation, comparison with literature values becomes more consistent.

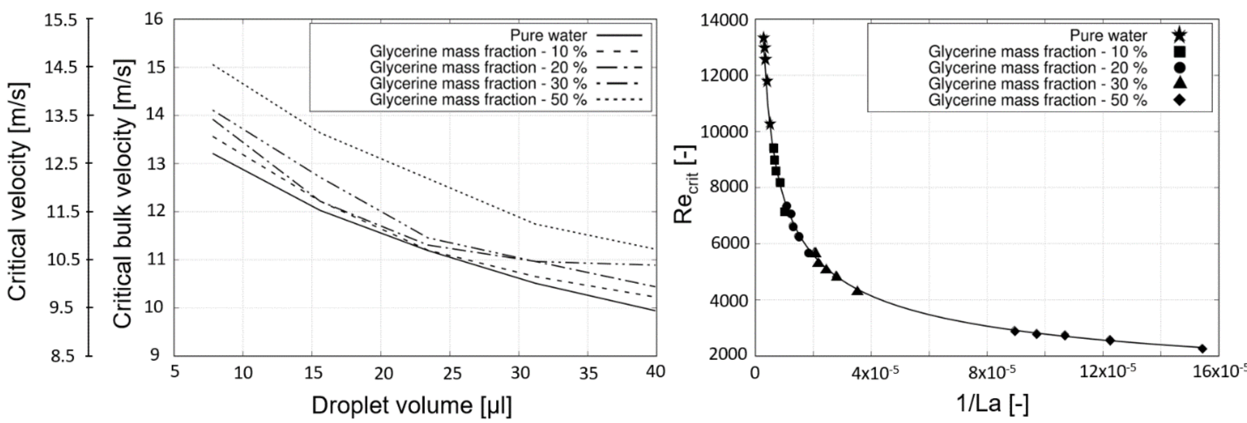

Figure 5: Critical velocity and critical bulk velocity for the onset of droplet movement for different ratios of glycerine and different droplet volumes (left) and dimensionless representation based on Reynolds and Laplace numbers (right).

6 Conclusion

The analysis of the droplet contour shows that the typical shape of the adhering droplet as well as the moving droplet is not significantly altered as long as glycerine content is kept below 50 %. It is found for all cases that the critical velocity decreases with increasing droplet volume, which is in agreement with literature. Measurements show the same trend of the critical velocity decrease for all ratios of water and glycerine. But there is an increase of the critical velocity that is needed to move the droplet if the amount of glycerine is increased, i.e. the increase of viscosity leads to an increase of the critical velocity. The critical velocity can be expressed by a Reynolds number based on droplet density and viscosity: $Re = \frac{\rho_d v_{crit} d_h}{\mu_d}$. Viscosity effects can be represented by the Laplace number, which is the ratio of surface and inertia forces to viscous forces: $La = \frac{\sigma \rho_d d_w}{\mu_d^2}$. The graph of the critical Reynolds number versus the reciprocal Laplace numbers (which represents the effect of viscosity) seems to show a good law. Further investigations are necessary to understand in detail the complex behavior of droplet. Therefore, different material surface properties will be analyzed and the influence of surface tension will be thoroughly examined. The aim of future investigations is to extend the mathematical correlation to include various other influencing factors in order to predict the initiation of the droplet movement more accurately.

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