Dispersion of Multiple Sessile Droplets on Surface by an Airflow

T. B. Sundaresan
Lecturer in Physics (Senior Grade)
P. A. C. Ramasamy Raja Polytechnic College, Rajapalayam 626108, India

Abstract— A droplet which is placed on a surface and is exposed to an airflow, can be shed, if the drag force overcomes the droplet's adhesion force. Presence of other sessile droplets, in proximity, changes the drag force, so the minimum airflow velocity required to shed the droplets (UCR) can vary. In this thesis, an experimental study on shedding of the multiple sessile droplets was performed on both hydrophilic and hydrophobic surfaces. The effects of the droplets' arrangement type, and the spacing on UCR were elucidate. For a pair of sessile droplets, a model was proposed to predict the UCR based on droplets' size, spacing, arrangement, and surface wettability. For three, or four sessile droplets arranged in triangle, square, reversed triangle, and diamond configurations, the effects of the droplets' interaction on variation of the UCR, was clarified. A critical value for spacing was determined beyond which multiple sessile droplets shed independently.

Key words: Chemical Synthesis; II–VI Semiconductors; X-Ray Diffraction; Elastic Properties

I. Introduction

The sessile drop technique is a method used for the characterization of solid surface energies, and in some cases, aspects of liquid surface energies. The main premise of the method is that by placing a droplet of liquid with a known surface energy, the shape of the drop, specifically the contact angle, and the known surface energy of the liquid are the parameters which can be used to calculate the surface energy of the solid sample. The liquid used for such experiments is referred to as the probe liquid, and the use of several different probe liquids is required.

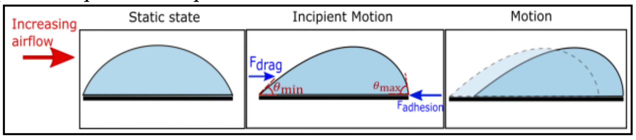

Fig. 1: Schematic of a Sessile Droplet

The drag force has a pressure drag component which is the integration of the pressure over the surface of the sessile droplet, and a shear stress components which depends on the airflow velocity magnitude [5]. Adhesion force is the summation of the surface tension force, distributed all around the contact line of the droplet [6]. As an airflow with increasing speed is introduced to a sessile droplet, the lateral adhesion force increases to resists the motion of the droplet baseline.

There are many experimental and numerical studies on shedding of a single sessile droplet. Dussan [7] conducted an experimental study on a sessile droplet which is exposed to shearing airflow; they provided an expression for the critical airflow gradient based on the contact angle hysteresis (the difference between advancing and receding contact angles), and droplet volume (V). They pointed that the viscosity of the droplet has no significant effect on the critical air flow, and the critical airflow gradient is proportional to the V −1 3 ⁄ . However, the model is valid only for the small contact angle hysteresis values. Fan et al. [8], experimentally studied the shedding of a sessile droplet for various droplet-surface systems (the static contact angles ranged from 50° to 90°).

Many studies can be found examining the sessile droplet shedding emerging into the gas diffusion membrane in fuel cells. Wu and Djilali [12] observed three different regimes in detachment of water droplet emerging through a pore inside a microchannel. The variable parameters in [12] are the airflow velocity and the rate of water injection into the pore. However, the pore size, and the pinning effects that it may have on the droplet's detachment, has not been clarified. Also, the observed regimes are limited to the hydrophobic substrate which were used in [12]; how the wettability of the substrate affects these regimes needs to be studied

Studies above indicate that the wettability of the substrate, size of the droplet, and properties of the liquid and flow are the main parameters in determining the minimum flow velocity for shedding. Most of the above mentioned studies, give a little attention to the adhesion force, or consider a single surface's wettability. Among all, [10] conducted a more systematic study in terms of defining a criteria for shedding, and considering the wide range of droplet's volume and surface wettabilities. In general, decreasing the wettability of the solid substrate results in reduction of the critical flow velocity. Also, critical flow velocity is a function of the inverse of the droplet's size. Still, all of the above studies consider shedding of a single droplet, which is not exactly the case of industrial, and biological applications where more than one droplet appear on the surface. As a conceptual example, consider the multiple droplets which condensate on the fin of a heat exchanger. Droplets which occupy the surface of the fin, result in reduction of the heat transfer rate, and reduce the efficiency of the heat exchanger. One possible way to remove these droplets is by airflow forces

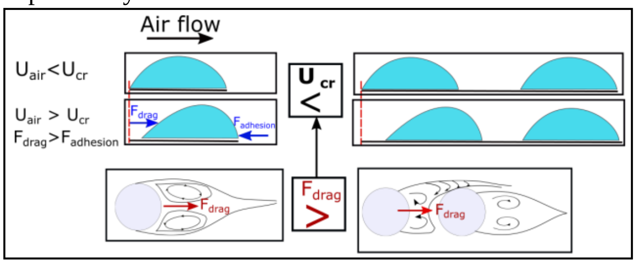

Fig. 2: Schematic View of the Shedding of a Single Sessile Droplet

II. Experimental Methods

The experiments were performed inside a closed-loop wind tunnel; the height, width, and the length of the test section are 6.4, 10.2, and 30.5 cm, respectively. Maximum airflow of 12 m/s is generated by a fan (EBM-Papst 4000 series fan), and to control the speed of the airflow, a voltage regulator was used to increase the speed of the fan. The level of turbulence in the tunnel is 0.2% (at 8.65 m/s), and at the maximum airflow velocity, the flow inside the test section is laminar. The speed of the airflow was measured using an EE75 hot film anemometer. The experiments were conducted for droplets' Re number ranging from 547 to 812 (Re=ρUcrH /μRe=ρUcrH μ, where U_{cr} is the air velocity at the incipient motion of upstream droplets and H is the height of the sessile droplet).

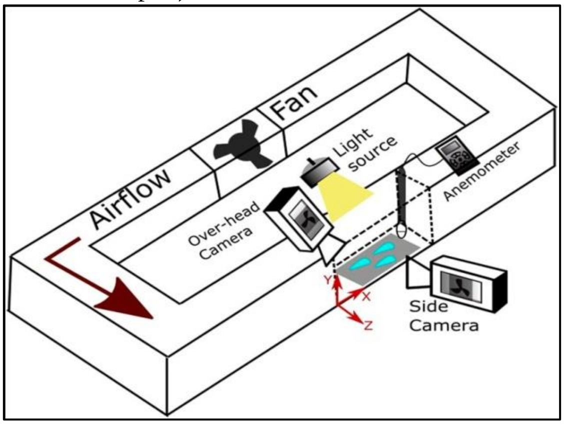

Fig. 3: Schematic View of the Experimental Setup

These arrangements can be considered as a repeating unit cell in a population of droplets (e.g., seen in dropwise condensation). All the sessile droplets within an arrangement had the same size, and experiments were conducted with 5 and 10 μl deionized (DI) water droplets. The droplets were placed on hydrophilic and hydrophobic surfaces by a syringe; immediately after the droplets were placed, air speed was increased at the rate of ~1 m/s^2 until the shedding was achieved. Image J software was used to measure that the desired spacing between the droplets was achieved (error for the spacing was ~4%). No significant evaporation was observed during the shedding process as the experiments typically took 10 s to complete after the start of the airflow. The hydrophilic surface was an aluminum substrate that was spin-coated using a PMMA solution [2% (w/w) PMMA in toluene]; advancing and receding contact angles were 74° and 58°, respectively. The hydrophobic surface was an aluminum substrate that was spin-coated using a Teflon solution [5:1 (v/v) FC-75, 3-M/Teflon AF]; advancing and receding contact angles were 122° and 107°, respectively.

Dimensionless spacing (S) is defined as the droplets' center-to-center length divided by a droplet's baseline length (as measured on the plane of the substrate). The baseline length of a 10 μl droplet on the hydrophilic and hydrophobic surfaces is 4.32 and 2.63 mm, respectively. For the other droplet volume, this information is provided in the supplementary material. For a constant droplet volume, given that S depends on droplet geometry and droplet geometry is affected by the surface wettability, the droplets' separation and wettability cannot be independent of one another. As will be shown later, taking S as a dimensionless parameter for different surface wettabilities will not affect the conclusion, but it will provide a more compact form of analyzing the problem.

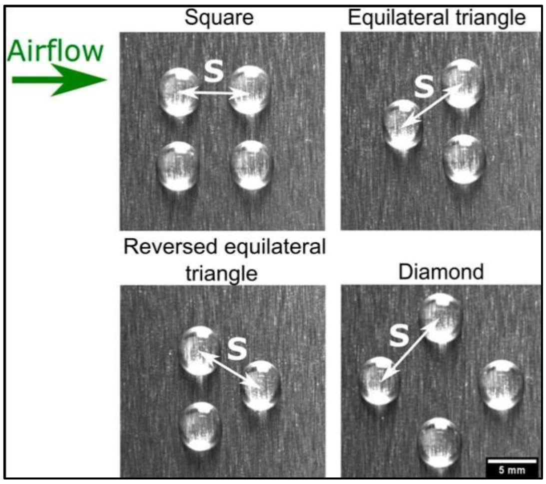

Figure 4. To Track the Shedding of the Sessile Droplets,

Two Phantom high-speed cameras (one for side view and one for overhead view) were operating synchronously, capturing images at 450 frames per second. The incipient motion is defined as the moment when the contact line of the upstream droplet(s) moved 5 pixels (220 μm) on the surface in accordance to our past practice. The air velocity at the incipient motion is the so-called critical air velocity (U_{cr}). Experiments were repeated three times and the standard deviation of the dataset is reported as the error.

III. RESULTS & DISCUSSIONS

In all the arrangements and any spacing, the upstream droplet(s) sheds first. At a spacing of S = 1.5, the common behavior seen was that the upstream droplet(s) hits the downstream droplet(s) and sheds as a larger unit. So, our focus in this study is on the comparison of shedding, and more specifically, the U_{cr} for the upstream droplets, in various arrangements. To provide an overall view of the findings, first, the $U_{cr}/(U_{cr})_{single}$ for the upstream droplet(s) in various arrangements on a hydrophilic (PMMA) surface. A figure similar to but for 5 μl droplets is provided in the supplementary material. The amount of change in $U_{cr}/(U_{cr})_{single}$ with respect to the type of arrangement and spacing is very similar for both the droplet sizes.

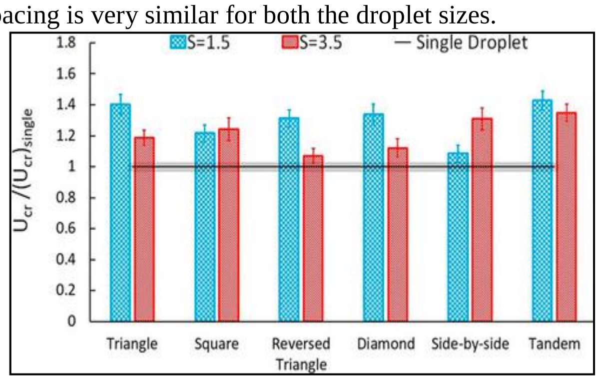

Fig. 5: Critical Air Velocity Ratio for the Upstream Droplet(s) in Different Arrangements at Two Spacing (S) Values

IV. COMPARISON OF THE ARRANGEMENTS

For a fixed number of sessile droplets, the type of the droplets' arrangement affects the U_{cr}. For three sessile droplets, within a small spacing, the upstream droplet in a triangle arrangement shows a higher U_{cr} compared with the upstream side-by-side droplets in a reversed triangle arrangement. Similarly, for four droplets, the upstream droplet in a diamond arrangement presents a higher U_{cr} compared with the upstream droplets in a square arrangement.

As it was discussed before, two side-by-side sessile droplets, at an intermediate spacing, have the maximum U_{cr}, probably due to the aforementioned oscillations of sessile droplets, which increase the interaction between them. However, by presence of one droplet (like reversed triangle arrangement) or two droplets (like square arrangement), at the downstream of the side-by-side droplets, U_{cr} decreases. As such, at S = 3.5, the upstream droplets in the reversed triangle and square arrangements have 22% and 5% lower U_{cr} compared with that of a pair of side-by-side droplets, respectively.

In general, there is a maximum ~40% increase in U_{cr} for the upstream droplet in tandem and triangle arrangements at S = 1.5 on both hydrophilic and hydrophobic surfaces. As the spacing increases to 3.5, U_{cr} decreases for the upstream droplets in triangle, reversed triangle, and diamond arrangements; whereas in square arrangement, the spacing does not affect the U_{cr}.

As the effects of the droplets' arrangement and the spacing on U_{cr} are identified, the next question to ask is when the droplets will shed independently from each other at the U_{cr} of a single droplet, regardless of the type of arrangement.

To answer this question, we start from our findings in shedding of a pair of sessile droplets; it was observed that when two droplets are at $S \geq 5.5$ on a hydrophilic surface and at $S \geq 3.5$ on a hydrophobic surface, they shed independently at the U_{cr} of a single droplet. This was true for both tandem and side-by-side arrangements. For side-by-side arrangement, both droplets also shed at the U_{cr} of a single droplet for $S \leq 1.5$ on both the surface wettabilities. To see if the "no interaction" spacings hold for shedding of three or four sessile droplets, the following arrangements were considered: triangle at S = 5.5 and rectangle at $S_{side\text{-}by\text{-}side} \times S_{tandem} = 1.5 \times 5.5$. One may hypothesis that the "no interaction" spacing can be the same for both triangle and tandem arrangements. Also, rectangle arrangement of four droplets consists of two pairs of side-by-side and tandem droplets, both within "no interaction" spacings, the droplets shed independently and at the U_{cr} of a single droplet. This means that as long as the droplets are placed at the "no interaction" spacing (found from experiments with a pair of droplets), they will shed independently, regardless of the type of the arrangement. The argument above is also true for 5 μl droplets;

It can be understood from the above discussions that depending on the surface wettability, there is a certain window of spacing where droplets are aerodynamically coupled. When the spacing between droplets falls within this window, both the arrangement type, and value of spacing affect the U_{cr} of the upstream droplets. Outside of the spacing window, regardless of the type of arrangement, all droplets shed independently with the U_{cr} of a single sessile droplet.

V. Conclusions

Shedding of three and four sessile droplets in proximity of each other and with different arrangements was investigated. At a specific airflow velocity (i.e., U_{cr} for each case), the flow structure over the droplets changes with the arrangement type of the droplets and the spacing between them. As such, for each case, the air velocity to overcome the adhesion force is changed. Upstream droplets in all the arrangements show a higher U_{cr} compared with a single droplet, with the highest value observed for triangle arrangement at S = 1.5 (~40% higher) and the lowest value for reversed triangle arrangement at S = 3.5 (same as the single droplet). Similar results were found for both surface wettabilities. Increasing the spacing for triangle, reversed triangle, and diamond arrangement leads to a decrease in U_{cr}; however, U_{cr} of the upstream droplets in square arrangement does not show sensitivity to spacing. When there are three droplets on a surface, the upstream droplet in triangle arrangement sheds at a relatively higher U_{cr} than the side-by-side droplets of reversed triangle arrangement. The same is true for comparison of the upstream droplet(s) in diamond and square arrangements for four droplets. The above change in U_{cr} was explained using simulations to understand the flow around the droplets. The change in U_{cr} is due to the change in the drag on the droplets as a result of changes in the vortex interaction at a given airflow speed. Finally, it was shown that when the droplets are placed far enough from each other (S = 5.5 for hydrophilic surface and S = 3.5 for hydrophobic surface), the configuration of the arrangement has no effect on the U_{cr}

References

[1] P. Dimitrakopoulos and J. J. Higdon, "On the displacement of three-dimensional fluid droplets from solid surfaces in low-Reynolds-number shear flows," J. Fluid Mech. 377, 189 (1998).

[2] P. Dimitrakopoulos and J. J. Higdon, "Displacement of fluid droplets from solid surfaces in low-Reynolds-number shear flows," J. Fluid Mech. 336, 351 (1997).

[3] A. D. Sommers, J. Ying, and K. F. Eid, "Predicting the onset of condensate droplet departure from a vertical surface due to air flow—Applications to topographically-modified, micro-grooved surfaces," Exp. Therm. Fluid Sci. 40, 38 (2012).

[4] H. Ding and P. D. Spelt, "Onset of motion of a three-dimensional droplet on a wall in shear flow at moderate Reynolds numbers," J. Fluid Mech. 599, 341 (2008).

[5] T. Cebeci and F. Kafyeke, "Aircraft icing," Annu. Rev. Fluid Mech. 35, 11 (2003).

[6] A. J. B. Milne and A. Amirfazli, "Drop shedding by shear flow for hydrophilic to superhydrophobic surfaces," Langmuir 25, 14155 (2009).

[7] J. Fan, M. C. Wilson, and N. Kapur, "Displacement of liquid droplets on a surface by a shearing air flow," J. Colloid Interface Sci. 356, 286 (2011).

[8] H. Ding, M. N. Gilani, and P. D. Spelt, "Sliding, pinch-off and detachment of a droplet on a wall in shear flow," J. Fluid Mech. 644, 217 (2010).

[9] S. Moghtadernejad, M. Tembely, M. Jadidi, N. Esmail, and A. Dolatabadi, "Shear driven droplet shedding and

coalescence on a superhydrophobic surface," Phys. Fluids 27, 032106 (2015).
[10] A. Razzaghi and A. Amirfazli, "Shedding of a pair of sessile droplets," Int. J. Multiphase Flow
[11] Y. Tsuji, Y. Morikawa, and Y. Fujiwara, "Pipe flow with solid particles fixed in space," Int. J. Multiphase Flow 11, 177 (1985).
[12] S. C. Liang, T. Hong, and L. S. Fan, "Effects of particle arrangements on the drag force of a particle in the intermediate flow regime," Int. J. Multiphase Flow 22, 285 (1996).