Colloids and Surfaces A: Physicochem. Eng. Aspects 522 (2017) 74–82

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Characteristics of drops on flat microplating surfaces from controlled upward longitudinal impact

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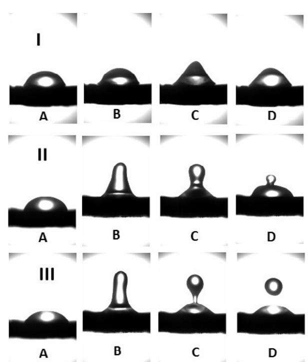
HIGHLIGHTS

- Repeatable upward impact momentums of up to 4.31×10^{-3} Ns on glycerol–water sessile drops was achieved.
- The propensity for the sessile drop to separate diminished with greater glycerol content in the mixture.
- The sessile drops were found to separate more readily when placed on scribed flat microplating surfaces.
- Additional pinning during the phase when the contact angle moved from receding to advancing facilitated separation.
- Finite element analysis indicated enhanced mixing when the separated liquid bodies coalesced.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 22 February 2017
Accepted 23 February 2017
Available online 27 February 2017

Keywords:
Impact
Microplate
Water–glycerol
Necking
Drops
Mixing

ABSTRACT

Sessile drops, based on water–glycerol mixtures at 40 μL, deposited on solid substrates were studied as they were accelerated upwards and then stopped suddenly to create an upward longitudinal impact effect. By varying the initial start positions of the platform in the setup, controlled impact momentums of up to 4.31×10^{-3} Ns could be attained. Three categories of drop behavior, labeled I to III, were uncovered. On the non-scribed substrate types I and II drop behavior were found, whereas all types of demeanor were exhibited by the scribed surface. On the scribed surface, the contact angle is able to recede more (by 20°) than on the non-scribed surface (by 15°). This is primarily due to the strong contact line pinning offered by the parapet and steep scarp formed around the groove. Since the liquid body is able to attain a lower receding contact angle on the scribed surface, this will allow higher adhesion effect of its lower portion even as the upper portion seeks to separate. This manifests in a greater propensity for the liquid body to neck and thus for separation to occur. Numerical simulations reveal the tendency of the separated drops to develop circulations that change direction as they coalesce. There is therefore potential for increased mixing using this mode.

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1. Introduction

Biochemical analysis using microfluidic technology continues to enjoy high levels of interest and development since its advent

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http://dx.doi.org/10.1016/j.colsurfa.2017.02.064
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over a decade ago [1,2]. There is now increasing interest to adopt alternative approaches that are easier to integrate and scale, and overcomes the issue of flow at any one location being dependent on the flow properties of the entire system that are endemic of continuous and closed flow devices. The use of discrete, independently controllable sample volumes [3], in particular with drops on open surfaces [4–6], is one option that is actively investigated. It has the advantage of having the microfluidic function assume a set of basic repeated operations, whereby one unit of fluid can be precisely moved over one unit of distance, thus facilitating the use of hierarchical and modular approaches that then make up flexible and scalable system architectures with high fault tolerance capabilities. Moreover, because sample volumes can be controlled independently, such systems offer greater potential to be reconfigured to change their functionality.

Standard microplates (micro titers) continue to be the tool of choice for liquid handling in analytical research and clinical diagnostic screening [7,8]. Their parallel architecture and standardized formats offer the ability for high throughput processing and easy instrumentation development, respectively. One aspect of microplate advancement has been to find more effective ways to dispense and manage the testing of increasingly smaller liquid volumes where poor well filling is a demonstrated problem [9]. An approach of using scribed transparency-based versions has been shown to overcome this problem [10,11]. They are also demonstrated to be able to sustain an appreciable degree of inadvertent sidelong impact without liquid sample spilling or displacement despite their seemingly less robust appearance in terms of handling stability [12]. In the process of this sidelong impact, capillary waves were found to travel toward the contact line at the opposite end. The scribed edges on the surface, through heightened pinning, could increase the amplitude of the wave to some extent, and would also multiply its resistance to spreading if the advancing contact angle condition was not exceeded [12]. These capillary waves are formed as a means to dissipate the mechanical energy supplied to the system. These perturbations understandably are not of the extent that they are able to offer strong bulk mixing of the liquid sample.

There are however, specific driving forces that can cause sessile drops to clearly exhibit resonance. In such a case, it may be possible for bulk mixing and even particle assembly to occur [13]. The need to provide a driving excitation to match the sessile drop's resonant frequency necessitates the availability of precision equipment to do so. However, if stochastic excitation is introduced such that it falls within the range the resonant frequency resides in, it is possible for the system to be set into resonance. This has been demonstrated with drops (i) rolling down a surface with asperities lithographically produced using fibrils of well-defined lengths, cross-sections and spacing [14], (ii) placed on a stationary tip coming in contact with a rotating SH drum, such that resonance is maintained primarily from stochastic stick-slip events between the liquid and SH surface [15], and (iii) dispensed on substrates that are created to have a circular hydrophilic region bound by superhydrophobicity so that they exhibited high contact angles, and then translated by a linear stepper actuator [16]. Yet, the extent of mechanical energy transferred from actuation of the liquid body will facilitate enhanced diffusion but not likely to the extent of significant bulk mixing.

In this work, we report findings in which sessile drops are accelerated upwards and then stopped suddenly to create a longitudinal impact effect. This contrasts sharply with previous studies made of drops released from heights and then impacted on solid substrates [17–20]. The tests were conducted on water–glycerol mixtures at varying volumes. These mixtures are routinely used to preserve the functionality of biological molecules during cooling and thawing processes, and to suppress intracellular ice formation, which can be harmful to cells and tissues [21,22]. Efforts are made to categorize the range of behaviors exhibited up to the point of liquid body separation. Careful attention is paid to the effects arising from the scribed or non-scribed scheme of the transparency. In the case of the liquid body detachment, numerical simulation is used to assess the liquid flow characteristics in order to deduce the extent of coalescent mixing.

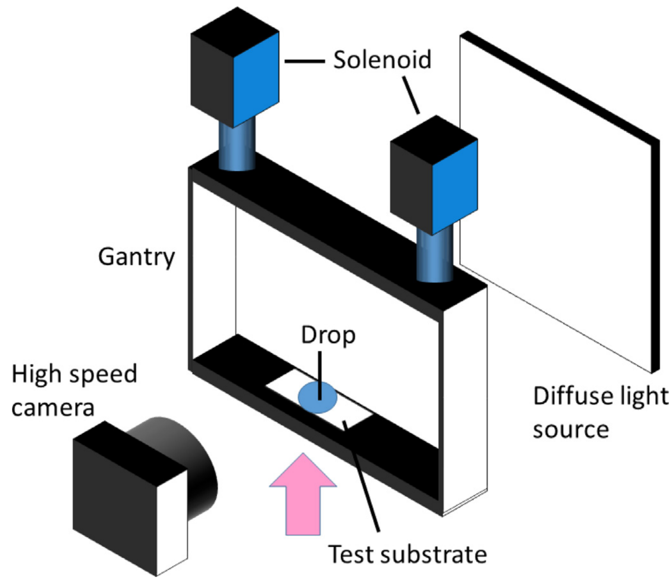

Fig. 1. Schematic description of the setup to conduct the experiments in which a pair of identical solenoids activated simultaneously actuates a gantry containing a substrate with drop dispensed on it. With diffuse illumination from the rear, high-speed camera video sequences of the drop as it was raised and stopped suddenly could be recorded for analysis.

2. Methods

The setup shown in Fig. 1 was used to conduct the experiments. Two pull-only solenoids (Techbrands, SS0902) are used to translate a gantry uniformly upwards. This is made possible by a 12 Volt DC power supply providing an electrical current to them simultaneously via a latching switch. The gantry is made by sawing off a rectangular 50 – 50 mm aluminum channel of 2.5 mm thickness with a depth of 20 mm. Aluminum was chosen because of its lightweight and rigid features. The test substrate is affixed to the lower surface of the gantry. During tests, specific volumes of liquid are dispensed using a manual pipette (Eppendorf) on the test substrate. Due to the architecture of the gantry, a diffused light source can be used to provide the background illumination to obtain good contrast images on a high-speed camera as the solenoid moves the gantry and stops at the end of each stroke. The movement stroke of the solenoid was adjusted to specific values to obtain different impact effects.

Prior to the experiments with drops being conducted, the gantry movement in relation to the stroke of the solenoids was characterized. This was done by tracking a selected position on the gantry using the high-speed camera video sequences recorded from the moment the gantry started to move to the time that it stopped. The impact momentum can be determined via this analysis. Its maximum value will be limited by the pulling power of the solenoid actuators and the frame rate of the high-speed camera. For the latter, the ability to accurately deduce higher impact momentums will be curbed if the frame-sampling rate is not rapid enough.

Glycerol–water mixtures (0–70% v/v) of 40 μL volume were used as test liquid drop samples. Glycerol is a simple colorless, odorless; polyol (sugar alcohol) compound widely used in agri-

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