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EXPERIMENTAL INVESTIGATION ON NEWTONIAN DROP FORMATION IN DIFFERENT CONTINUOUS PHASE FLUIDS

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ABSTRACT

In this work, formation water drops as a Newtonian fluid in different bulk fluids are investigated. A MATLAB code has been developed to process the images taken via a high speed camera in the lab to measure the contact angle of drop, as well as the drop's diameter and volume at different stages of formation. It is found that the water drop shows similar behavior when they shaped in the liquid phase bulk fluid with different properties while the drop formation's behavior is substantially different when water drops are formed in the gas bulk fluid. In addition, it is tried to predict the frequency of drop formation at different flow rates with regard to the inertial and surface tension forces applied to the dispread fluid.

INTRODUCTION

Drop formation has a huge number of applications in industry such as in-jet painting, combustion process, spray cooling, etc [1-10]. Optimization of these applications as well as the hope for designing new ones have been always very interesting field for researchers. Earlier studies in this field mostly intended to predict the drop volume at different flow rates in terms of fluid properties, flow rate, and nozzle geometry [11-15]. In recent years, new technologies have brought so many tools for researchers to observe and analyze the drop formation mechanism much better than before. Hauser et al. [16] have shown the complexities of drop formation phenomenon. In addition, using the photographs, Peregrine et al. [17] were able to conduct several experiments regarding droplet formation such as necking, bifurcation of the initial drop, vortex of the fluid due to capillary pressure and satellite drops. They, also, worked to demonstrate the effects of physical properties and flow rate on the satellite drops. Shi et al. [18] conducted experiments, revealing an increase in the fluid viscosity, liquid thread length would increase. The results also showed that one thread can break down to several other threads. Later, Zhang and Basaran [19] examined experimentally the dynamics of drop formation in ambient air in low flow rate by an 80 fps camera. In a more recent work by Wang et al. [20] using a high speed camera, the formation of a drop in low flow rate is studied. They measured various drop formation factor, namely contact angle, drop height, length of the neck, and wetted diameter however they have studied the drop formation in only liquid phase bulk fluid. Since the phase of the bulk fluid play a crucial role in the behavior of the drop formation, in this work, it is intended to draw a comparison between drop formations in existence of different Newtonian bulk fluids, namely, toluene, n-hexane and air. Using the developed code though MATLAB software, the contact angle, drop's diameter and the frequency of the formation are investigated.

NOMENCLATURE

Symbols	Discretion
Bo	Bond number
d	diameter, m
$d_{capillary}$	wetted diameter, m
F_B	buoyancy force, N
F_K	inertial force, N
F_σ	Interfacial tension force, N
g	gravitational acceleration, ms^{-2}
Q	flow rate of the dispersed phase, m^{3}s^{-1}
T	temperature, ˚C
u	dispersed phase velocity, ms^{-1}
ρ_d	density of the dispersed phase, kgm^{-3}
$\Delta\rho$	density difference, kgm^{-3}
θ	contact angle, deg

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σ	surface tension, Nm^{-1}
We	Weber number

EXPERIMENTAL METHOD

A Plexiglas tank with the cross section of 40 × 20 cm^2 and the height of 60 cm is filled with the bulk fluids. For the first part of the experiment air is the bulk fluid, still using the tank help the experimental setup to prevent the air flow in the lab environment to effect the formation of dispersed water drops. For the second and third part of the experiment, the tank is filled with toluene and n-hexane, respectively. A high speed camera which is capable of capturing 1000 images per second is utilized in this setup. A 1000 Watt projector is used for illumination. As shown in Fig. 1, the drops were released from a needle attached to a buret. Using a DIN 12700 buret, the flow rate of the falling drops are controlled and a hypodermic needle with inner and outer diameters of 1.8 and 2 mm, is tightly fitted to the end of the buret. The flow rate for measuring the contact angle remains constant. However the controlled flow rate for measuring drop formation's frequency and diameter changes. Since the drops fall from the needle as the result of the hydrostatic pressure of a column of fluid in the buret, we can change the level of the column of the fluid to produce different flow rate. Also, the temperature of the lab during the experiments is tried to be kept constant at 20 $\pm$2°C.

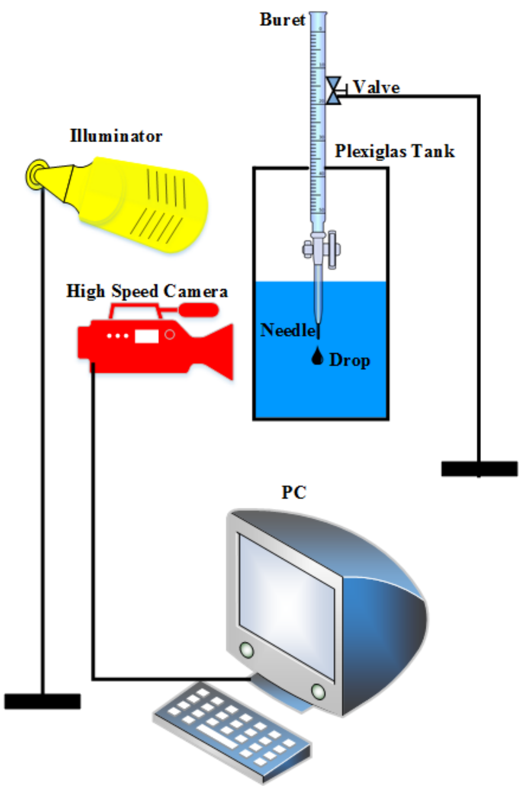

Figure 1. Experimental setup used to apply the air, toluene and n-hexane as bulk fluids

The properties of the materials used in the experiments are shown in Table 1. List of the effective force on droplet formation which is studied are provided in Table. 2.

Table 1. Properties of fluids used in the tests (at 20 ± 0.5 ˚C).

	Water	Toluene	n-Hexane
σ (mN/m) (in air)	72	28.5	18.4
γ (mN/m) (in water)	–	35.0	51.0
ρ (kg/m^3)	998	862	660
μ (cP)	1	0.62	0.33

Table 2. List of equations used for drop formation study.

Force	Equation
Buoyancy force	$F_B = \Delta\rho g V$
Interfacial tension force	$F_\sigma = \pi d_{capillary}\sigma$
Bond number	$Bo = \dfrac{\Delta\rho g d^2}{\sigma}$
Equivalent diameter	$D_{eq} = \sqrt[3]{(6 \times V/\pi)}$
Weber number	$We = \rho Q u/\pi D\sigma$

RESULTS AND DISCUSSION

To investigate the behavior of water drop, contact angles of the drops during formation in different continuous phases of Newtonian fluids, i.e. n-hexane, toluene, and air, are recorded. Fig. 2 shows the contact angle associated with water drop in air during formation. As it is shown in Fig. 3 scattered data is observed at the beginning of drop formation for all three kinds of bulk fluids which is the result of oscillations during and after the bifurcation of previous detached drops. These oscillations have significant effect on contact angle and behavior of the drop formation. The frequencies of these oscillations at the moment of pinch off are very high which make it difficult for the lab camera to capture all the details. As it is obvious in Fig. 3, at the beginning of drop formation, the contact angle is obtuse which 120° maximum contact angle is nearly the same for all cases. As the drop formation continues, its contact angle reduces very fast and changes to acute at middle of drop formation and remains roughly constant. Again, at the end of drop formation before detachment, the contact angle experiences a sharp increase which the angle becomes obtuse and the drop moves toward detachment. Water drops in n-hexane and water drops in toluene almost show the same behavior, however water drops in air show significantly different formation behavior which mainly caused by the different phase of bulk fluid. Also, the gravitational force and surface tension force are highly effective on duration of the drop formation which can be described in the shape of Bo number which is the ratio of gravitational force to surface tension force.

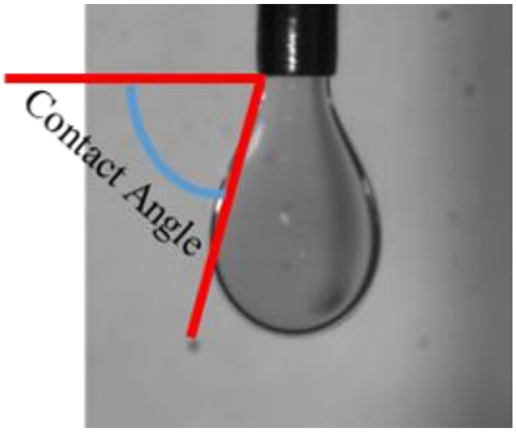

Figure 2. Contact angle associated with the water drop formation observed during the experiment.

The Bo number for water drop in toluene, n-hexane and air are 0.14, 0.23 and 0.49, respectively. In fact, it is shown that as the Bo number increases, the drops have more time to grow, as a result, at constant flow rate, the duration of the water drops formation in air is more than water drops in toluene and n-hexane.

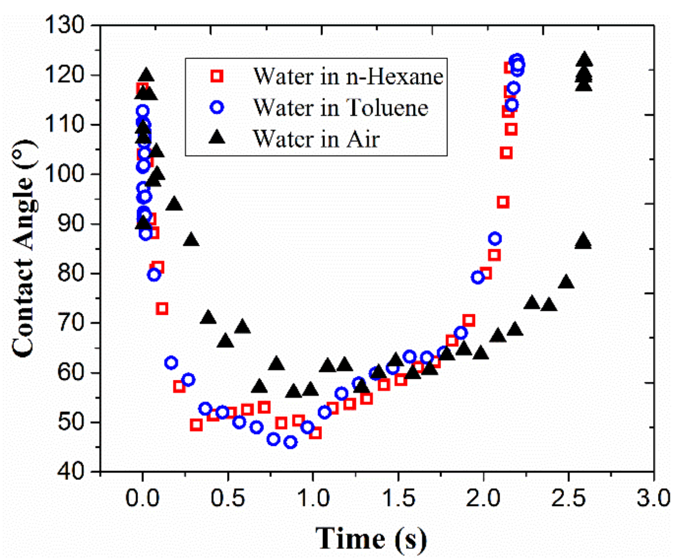

Figure 3. Results obtained showing the contact angle of water drop during the drop formation for water drops in n-hexane, toluene and air.

In next part of the conducted experiments, the flow rate of the dispersed fluid is changed in range of 100 to 300 mL/h. The goal of this section is to draw a conclusion between the diameters of drops against the flow rate. The diameter of formed drops against flow are is shown in Fig. 4. As it is obvious the drops' diameters in all three kind of bulk fluids increase with the flow rate. The drop diameter shown in Fig. 4 is the equivalent diameter ($ED = \sqrt[3]{v/\pi \times 6}$). The behavior of the dispersed drops in air is significantly different from behavior of the dispersed drops in toluene and n-hexane. According to the observed results, at the flow rate more than 50 mL/h the water drops in toluene and n-hexane have more time to grow before detachment. As a result, in the time interval between the start of drop formation and drop detachment, more fluid can be injected to the drops before detachment, leading to increase the drop diameter. This observation can be explained due to the fact that the bulk fluid viscosity plays a crucial role in the stability of the drops before pinch off. At the flow rate higher than 50 mL/h, as the viscosity of the bulk fluid increases, the water drops remain more stable and provide more time interval for the drops to form.

Since the drop formation frequency plays a crucial role is several industrial application [21], in this section the frequency of the formed drop is studied. Chaurasia et al. [15] divided the drop formation to two different regime.

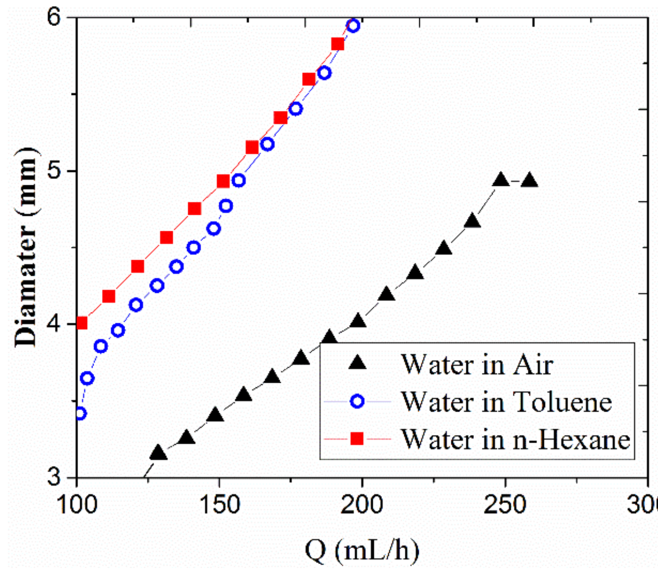

Figure 4. Experimental data for diameter of water drops in different bulk fluids against the flow rate.

They showed the variation in the rate of drop formation frequency with Weber Number can be interpreted as a simple reliable criterion for predicting the transition from the dripping to jetting regime. Also, they find a correlation between the drop formation frequencies against weber number for three oils at different surfactant concentrations. In this work, the flow rates are tried to keep low enough to make certain that Weber number associated with each case is less than 0.1. Accordingly, the drop formation does not enter jetting phase and remains at dripping phase during the experiments. As it is shown in Fig. 5, for water drops in air ($f \propto We^{0.5}$) and for water drops in toluene and n-hexane ($f \propto We^{0.7}$) the formation frequency is correlative with Weber number.

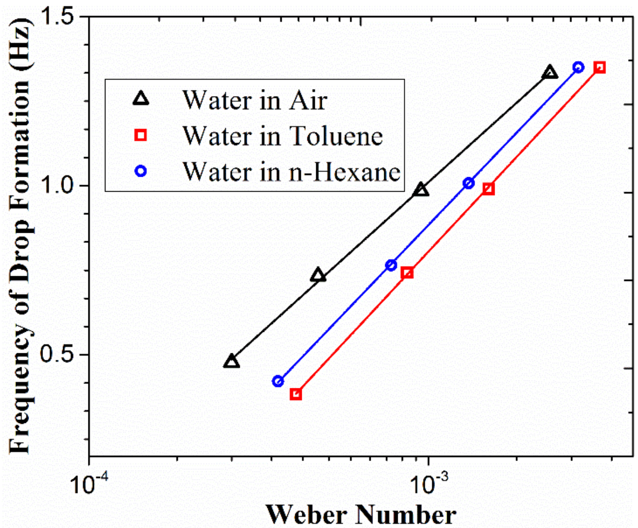

Figure 5. Drop formation frequency as a function of the Weber number for dispersion of water drop in air, toluene and n-hexane

As the flow rate increases, the frequency of the formation increases, as well. In addition, as the viscosity of bulk fluid increases, the frequency of water drop formation decreases which has agreement with previous studies [22]. From the observation, it is obvious that the interaction between the surface tension and inertial forces determines the drop formation with a very good estimation ($R^2 \geqslant 0.95$), shown in Fig. 5.

CONCLUSIONS

In this work, using experimental approach, the behavior of water drops as dispersed fluid in different bulk fluids namely, air, toluene and n-hexane is investigated. It is shown that for the contact angle and the drop's diameter, the drop formation is highly dependent on the phase of bulk fluid in which the water drops in toluene and n-hexane showed nearly similar behavior however showed significant different behavior in air. Also investigation of the formation frequency reveals that the drop formation frequency is highly function of interaction between the surface tension and inertial forces which is explained and estimated through Weber number.

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