Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(11) (2021) 751-752
DOI: 10.22060/mej.2019.15350.6101

An Analytical and Experimental Study on Dynamics of Newtonian Falling Drops in Inertia Regime with Low Reynolds Numbers

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ABSTRACT: Two phases flows particularly motion of droplets into a second fluid have a variety of application in different industries including oil and gas industry, medicine and pharmaceutical, extraction of metals, power plants as well as heat exchangers. In this paper, dynamic of a Newtonian drop falling into a laminar regime is studied. A fluid with viscosity of 340 cP is used in order to produce an inertia flow. In experimental section, de-ionized water and glycerin solutions with volume concentrations of 21:79 and 17:83 are used for drop phase. By increasing the volume of drop that leads to rising the inertia force, the drop shape is changed from sphere and a dimple at the rear end of the drop has appeared. Inertial forces, surface tension, and hydrodynamic tension play a significant role in drop shape. Increasing the drop volume causes expanding the dimple consequently drag force is enhanced and terminal velocity of drop is decreased as well. According to the experimental observations, variation of viscosity ratio does not have a profound effect on drop deformation. Moreover, increasing the Reynolds number leads to reduction of pressure coefficient. It is shown that the experimental observations have an appropriate agreement with analytical results.

Review History:

Received: 2018/11/27
Revised: 2019/07/07
Accepted: 2019/09/02
Available Online: 2019/09/10

Keywords:

Drop dynamics
Reynolds number
Terminal velocity
Drag force

1- Introduction

Measuring the velocity of a falling droplet is one of the most significant parameters in the oil industry. Also, drop dynamics is important in various technical applications including inkjet printing and spray coating so that different investigations are being conducted regarding drop size and its dynamics [1]. Hadamard [2] and Rybczynski [3] investigated an immiscible motion of a creeping drop in Newtonian regimes analytically and they found that the shape of a falling drop, in the absence of inertia, should be completely spherical and that the terminal velocity increases with an increase in the drop volume. Taylor and Acrivos [4] have indicated that at zero Reynolds number and limited capillary numbers condition, the drop remains exactly spherical and it loses its spherical shape and forms to be flattened, only at low Reynolds numbers. In the present study, an exact method has been used to calculate the drag force, as well as the impact of different parameters on drag coefficient, has been studied. The experimental results of this study have a suitable agreement with the previous investigations.

2- Methodology

In this experiment, two solutions consisting of twice-ionized (deionized) water and glycerin solution with 21:79 and 17:83 were used. Physical properties including density and viscosity for the first and second solution are $\tilde{\rho}=1.2\,\frac{\text{gr}}{\text{cm}^3}$, $\tilde{\eta}=60.1$ and $\tilde{\eta}=83.71$ respectively. The sign "~" denotes the interior fluid while the parameters with no sign are considered for exterior fluid. The viscosity of 340 mPa.s is used in order to create a low Reynolds number inertia flow. The surface tension at the interface between the two fluids is set as 21 mN/m. A high speed CMOS camera (pco.dimax S1) is used to capture the drop falling process. To measure fluids viscosities versus shear rate, a Brookfield viscometer is applied. The governing equations for both phases in this problem are the conservation of mass and momentum. For the droplet phase, these equations are presented as follows [5, 6]:

$$\nabla \cdot \tilde{u}^* = 0 \qquad (1)$$

$$\tilde{\rho}\frac{D\tilde{u}^*}{Dt} = -\nabla \tilde{P}^* + \tilde{\rho} g + \nabla \cdot \tilde{\tau}^* \qquad (2)$$

Where τ^* and u^* denote the dimensional tensors of stress and velocity vector, respectively. It should be mentioned here that the dimensional parameters are specified with an asterisk. In this paper, an exact method has been used to calculate the drag force based on Eq. (3):

$$F_D = 2\pi\int_{-1}^{1}[\mu(\tau_{rr} - \mu p - \left(1-\mu^2\right)^{1/2}\tau_{r\theta}]|_{r=1}\, d\mu \qquad (3)$$

Figs. 1 and 2 show the variation of viscosity versus shear rate for both of the fluids used in this experiment.

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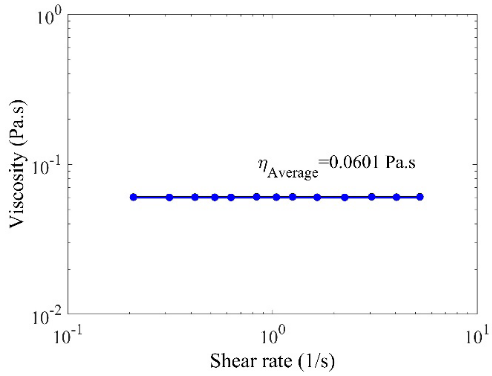

Fig. 1. Shear viscosity vs. shear rate of the first solution

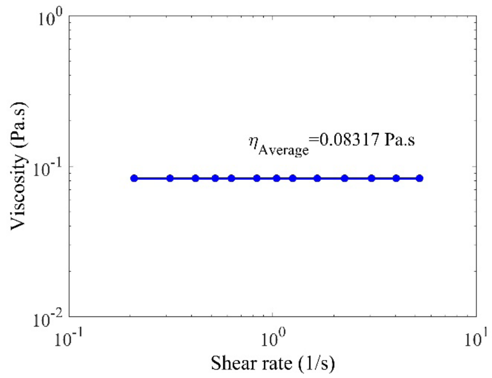

Fig. 2. Shear viscosity vs. shear rate of the second solution

3- Results and Discussion

As shown in Fig. 3, it can be seen that the experimental results of the current study have a suitable agreement with the results presented by Taylor and Acrivos [4]. Newtonian droplets can be seen in the Fig. 4 with different sizes. Both Reynolds and Capillary numbers increased by increasing the drop volume.

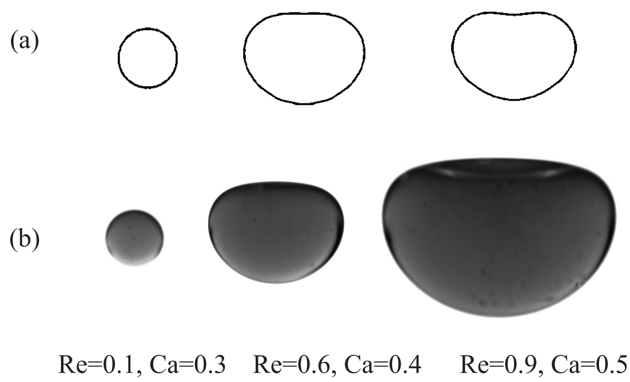

Fig. 3. A comparison between the steady shape of (a) the analytical solution of Taylor and Acrivos [4] (b) the experimental section at k=0.25

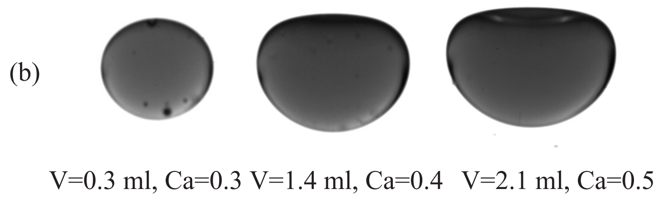

Fig. 4. Changes in the shape of Newtonian drop for (a) first solution (k=0.18) and (b) second solution (k=0.25)

Fig. 5 represents the drag force at the free surface versus the Reynolds number for various capillary numbers. It can be concluded that an increase in both inertia force and Capillary number leads to increasing the drag force in Newtonian drops.

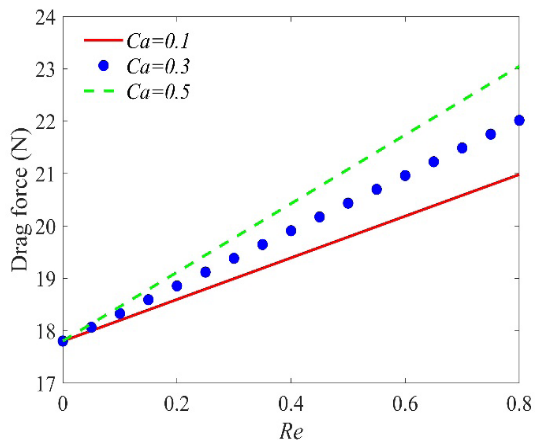

Fig. 5. Drag force at free surface against the capillary number

4- Conclusion

In this study, dynamics of Newtonian falling drops in inertia regime was investigated and by studying important parameters in the drop dynamics turned out that with an increase in Capillary number, due to the reduction of surface tension, a dimple at the rear of the drop has appeared which causes the rising the drag force.

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