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# Numerical Study of the Dynamics of Non-Newtonian Carreau Droplets under Electrowetting Phenomenon

R. Izadi, A. Moosavi*

Department of Mechanical Engineering, Sharif University Technology, Tehran, Iran.

**ABSTRACT:** Studying the dynamic behavior of droplets is very important in electrowetting phenomena. Due to the widespread application of non-Newtonian fluids, in the present study, the dynamics of non-Newtonian Carreau droplets have been investigated. The effects of the viscosity, the size and the applied voltage on the oscillations and the change in the height of the droplets have been inspected. The simulations have been conducted using the finite element method and in order to validate the method, the results have been compared with the available experimental and numerical results. The results indicate that by increasing the viscosity the amplitude of the oscillations increases but the frequency remains constant. These are similar to those of the Newtonian fluids with this difference that in Newtonian fluids the amplitude is larger but the frequency is smaller. Also, for Carreau fluids when the power index is smaller than one the results are similar to the Newtonian fluids but when the power index is larger than one the droplet reaches its final height faster and without any fluctuation. Increasing the height in the non-Newtonian fluid leads to an increase in the amplitude of the oscillations and decreases the amount of frequency in the fluid.

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## 1. INTRODUCTION

The electrowetting phenomenon operates on the basis of the electric capillary property that first was introduced by the French scientist Gabriel Lippmann. Accordingly, the wetting behavior of liquid droplets can be changed by applying the electric potential field. The droplet is placed on a hydrophobic surface. As a result of the applied voltage, the equilibrium surface tension changes [1]. In recent years there have been many studies that can be divided into numerical and experimental sections.

In the field of numerical research, an analytical model for calculating and analyzing the average droplet temperature in the electrowetting phenomenon was proposed by Oprins et al. [2]. In 2015, Izadpanahi et al. [3] investigated the movement of water droplets inside a microchannel under the electrowetting phenomenon. The simulation of electrowetting phenomena was carried out using OpenFOAM software applying the interfoam solver.

Experimental and laboratory studies are as follows. Hong et al. [4] in 2013 investigated the effect of droplet size and its viscosity on the dynamic droplet deformation including response time, maximum velocity and transmission pattern because of the direct current voltage in both the experimental and numerical methods . Experimental and laboratory studies of Ref. [5] showed that the frequency and amplitude of fluid droplet fluctuations under the electrowetting phenomenon depend on parameters related to the material such as density, viscosity and mass of the material. As has been already explained, the electrowetting phenomena have made great progress in scientific and industrial issues, particularly in the field of heat transfer and fluid drop motion. Therefore, the behavior of the fluid drop during its movement is very important due to the change of the contact angle of the fluid drop with the surface. In recent studies, the need for this study has been quite evident as many investigations have been done on the dynamics and motion of the drop. In general, fluids can be divided into Newtonian and non-Newtonian groups. Previous works have been focused on Newtonian fluids. Therefore, due to the expansiveness of non-Newtonian fluids and the increasing applications of this fluid in scientific and non-scientific fields, this study will investigate the dynamic behavior of a non-Newtonian fluid drops. The Carreau model is used to model non-Newtonian fluids. Since it is not intended to investigate a particular type of non-Newtonian fluid, the non-Newtonian properties of the blood will be considered as the basis and only the Carreau power index will be changed.

## 2. METHODOLOGY

In this section, applying the Finite Element Method (FEM) method will be studied to investigate the changes of electrowetting properties. The level set solver is used to solve the problem numerically. The geometry is two-dimensional with axial symmetry. According to the shape of the droplet,

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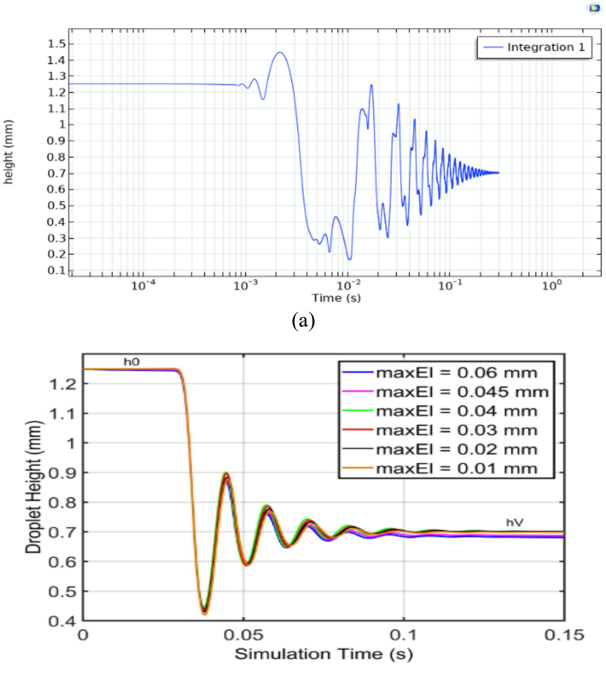
*Corresponding author's email: moosavi@sharif.edu



(a)

(b)

**Fig. 1. (a) Results of the present work; and (b) The results of Ref. [5].**

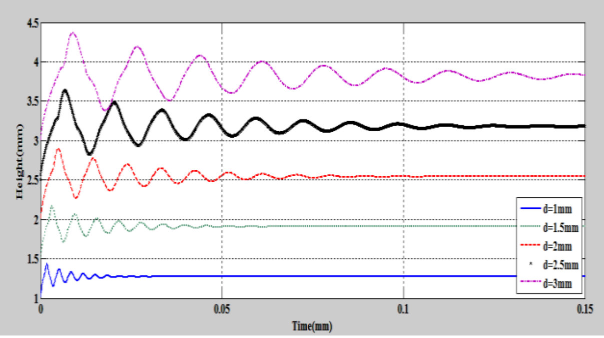


**Fig. 2. The fluctuation diagram of the height and final height of the non-Newtonian fluid drop (blood) as a function of the initial radius of the drop for the final contact angle of 60 degrees.**

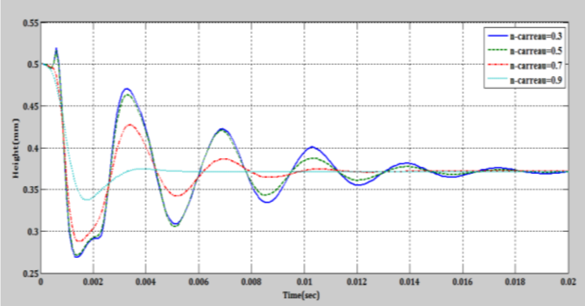


**Fig. 3. A comparison between the fluctuations of the height and final height of the non-Newtonian fluid drop by varying the coefficient *n* in the Carreau model for values of *n* smaller than one and with a contact angle of 60 degrees.**

only a quarter of a circle with an initial angle of 90 degrees and a radius *r* is considered. After applying the voltage, the contact angle of the drop begins to change.

The software solution interface is a level set method that can specify the interface between two fluids, so the Navier-Stokes equations are solved incorporating the Young-Lipman equation. The drop is initially at the height $h_0$ that stops after changing the contact angle and reaching the final height $h_v$.

All the solutions are carried out at 20 °C. Blood is used here as a non-Newtonian fluid, but its main purpose is to investigate the dynamic behavior of a non-Newtonian fluid based on the variation of the parameter *n* (Carreau power index). Therefore, assuming that the properties of the non-Newtonian fluid remain constant on the basis of its blood properties, only the parameter *n* (Carreau power index) is changed.

## 3. RESULT AND DISCUSSION

In this study, the structured and non-structured grids were used. To investigate the independence of the mesh, the results for different grid sizes are examined, namely, for 0.05, 0.1, 0.15 and 0.2 mm. One of the parameters discussed in this paper is the variation of the initial height of the fluid drop which can be referred to as the amplitude of the difference between the first wave and the second wave as the basis for the independence of the mesh, which is different for different values. This value is slightly different for different meshes that can be ignored.

For verification, the results of Ref. [5], which has been conducted experimentally and numerically for Newtonian fluids, will be used. In this study, the dynamic changes of water drop at 20°C were performed numerically and experimentally in the laboratory and the changes in drop height were recorded by a camera. In Fig. 1, we compare their numerical solution results which are checked by the experimental outcomes, with the results of the present work. The water drop is initially at a temperature of 20°C and a radius of 1.25 mm, which eventually reaches the final angle of 50°. The final drop height stabilizes after fluctuations of 0.7 mm. As can be seen, in both forms the final drop height is approximately the same, with very little error.

Increasing the fluid volume and, consequently, changing the drop height increases the amplitude of the oscillations. It can be seen from Fig. 2 that as the initial height of the non-Newtonian fluid drop increases, the amplitude of the oscillations increases but the damping vibrational frequency decreases. Another important parameter in droplet vibrations is the time that the final drop height is fixed. As can be seen in Fig. 2, the lower the drop height, is the lower this time.

Blood is a type of non-Newtonian fluid. As stated, this fluid has a viscosity proportional to the parameter *n* in the Carreau model. The changes in this parameter yield a nonlinear change in the viscosity. For blood, this value is 0.3. Here, to evaluate the dynamic behavior of non-Newtonian fluid droplets under the electrowetting phenomenon for different values of *n*, the effect of this coefficient is investigated for values of less and larger than one. Fig. 3

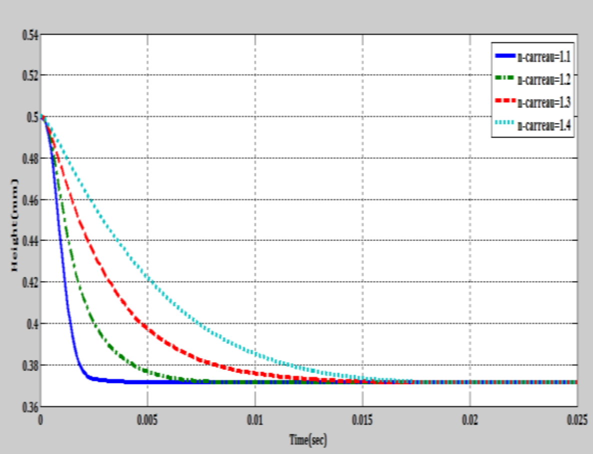


**Fig. 4. A comparison between the fluctuations of the height and final height of the non-Newtonian fluid drop by varying the coefficient *n* in the Carreau model for values of *n* greater than one and with a contact angle of 60 degrees.**

shows the behavior of this fluid for values of *n* less than one and Fig. 4 for values of *n* greater than one. It can be seen from Fig. 3 that as the value of *n* increases to one, the value of the maximum vibrational amplitude decreases. But the frequency of vibrations does not change appreciably. As shown in Fig. 4, it is concluded that by increasing this coefficient, the oscillation amplitude is constant but when the fluid reaches its final height, that is, in values greater than one for *n*, the fluid reaches its final height without oscillation.

If $n > 1$, the Carreau model can have a positive value; thus, by increasing the shear stress rate ($\gamma$), the viscosity of the fluid increases as the shear stress rate depends on the increase in the rate of the fluid velocity at the surface between the fluid and solid, $(\partial u / \partial y \;\; @y = 0)$. Therefore, there is a direct proportion between the fluid viscosity and the fluid velocity, but for the case $n < 1$, the viscosity value is inversely proportional to the shear stress rate (Eq. (1)) so the viscosity decreases with increasing the velocity.

$$\frac{\mu - \mu_{inf}}{\mu_0 - \mu_{inf}} = \frac{1}{\left[1+(\lambda\gamma)^2\right]^{\frac{1-n}{2}}} \qquad (1)$$

## 4. CONCLUSION

The convergence time in Newtonian fluids is much shorter than non-Newtonian fluids. This also means less oscillation in the non-Newtonian fluid.

The behavior of non-Newtonian fluids is completely dependent on the coefficient *n* in the Carreau equation. At values greater than one for this coefficient, the fluid converges very quickly without any oscillation, which also depends on the value of *n*.

For values less than a factor of *n*, the non-Newtonian fluid oscillations behave similar to the Newtonian fluid, but the convergence time and the number of oscillations until the fluid reaches equilibrium is less in the non-Newtonian fluid.

Increasing the viscosity of each type of fluid results in a decrease in the amplitude of the fluid oscillations individually, but the vibrational frequency of each of them remains constant.

It is shown that for non-Newtonian fluid at $n > 1$ the fluid velocity and its viscosity are directly related. However, for $n < 1$ the fluid velocity and its viscosity change indirectly.

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