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Experimental Study of non-Newtonian Falling Film Dynamics on Inclined Plate

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Abstract
In present work the dynamics of a falling film of CMC solution as a non-Newtonian fluid over an inclined surface has been studied experimentally. With rotational rheometer named POLYVISC Series L, the rheometry analysis of three different concentration of CMC solution (1.1, 1.5 and 2 weight percent) which is extensively utilized in industry have been reported. Fluid-air surface tension is also measured by the capillary method and dynamics of the falling film were studied with high speed imaging method. For different flow rate of fluid and different inclination angles of inclined plate a $(0 < a < p/2)$ time variation of falling film velocity have been recorded and an empirical correlation has been derived. The results show the effects of rheological properties, plate inclination and flow rate on dynamics of film flow of CMC solution.

Keywords: Inclined plate, non-Newtonian, high speed imaging, falling film

1-Introduction

The flow of thin films is relevant in a number of different fields, such as engineering (heating and cooling, coating, food, polymer and microchip production, etc.), biology (lining of mammalian lungs), and chemistry (flow of surface active materials). These flows can be driven by gravitational (flow down an inclined plane) or centrifugal (spin coating) forces. While the hydrodynamics of thin film flow of Newtonian liquids has been extensively studied for several decades [1], only modest attention has been devoted to gravity-driven films of non-Newtonian liquids. The flow of non-Newtonian liquid is not often fully understood in many processes and equipment units and so the designs are not properly optimized. Also in coating not understanding the shape of the film may cause in dry spots or other defects.

Only a few studies have experimentally investigated the flow of non-Newtonian fluids down inclined plates. Astarita et al. [2] measured the film thickness of non-Newtonian fluids in fully developed laminar flow down inclined plates for a range of flow rates and plate angles. Therien et al. [3] measured the film thickness for power law fluids flowing down inclined plates and compared the results with an analytical expression with good

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agreement. Sylvester et al. [4] compared experimental and predicted film thicknesses for power law fluids flowing down a vertical wall in the laminar and wavy fully developed regimes. Sutalo et al. [5] measured the film thickness of a power-law fluid and predicted the results by CFD methods. Wierschem and Aksel [6] studied the stability of liquid film down an inclined wavy plane. Miyara [7] used MAC method to simulate the flow of wavy liquid film down vertical and inclined planes and the results showed good agreement with experimental measurements. The hydrodynamics of developing power-law films has been studied by means of the integral method approach and similarity analysis. Anderson and Shang [8] recently devised a new similarity transformation for extensive studies of accelerating non-Newtonian film flow. Kamish [9] devised one-dimensional approximate equations governing the flow in a free coating and gas-assisted displacement of liquid in vertical and inclined tubes using asymptotic techniques.

In this work, dynamics of non-Newtonian falling film on an inclined plate has been investigated experimentally. The influence of rheological properties, surface tension, and inclination angle and flow rate of CMC solution with different concentration has been discussed clearly.

2-Experimental Setup

The experimental setup consisted mainly of a plate with adjustable angle of inclination which is shown in Fig. 1. Image acquisition and processing techniques were used to track the dynamic of fluid film and effects of different parameters. Whereas the fluid is highly viscous and the velocity of the falling film is very small an ordinary Canon EOS 400, 3fps, has been used in this work. After every run the plates were thoroughly washed and dried to minimize the possibility of contact angle changes. Also all experiments were carried out in ambient temperature$\left(24 \pm 2^{\circ} C\right)$. This setup was used to investigate the effect of different parameters on dynamics of falling film of a non-Newtonian fluid.

Food grade CMC solution with 1.1, 1.5 and 2 weight percent were prepared by solving required amount of CMC in double distilled Tehran city water. For better imaging 1% iodine solution was added to the prepared CMC solution. Although CMC’s power law parameters can be found in the literatures [10, 11] colored CMC apparent viscosity was measured by PolyVisc Visco Star Series L and power-law model has been fitted to the experimental data. Surface tension was measured in 24 °C and a single static contact angle was measured by the goniometry method and its variation was neglected. Being far from critical point and very minor changes in temperature corroborates the assumption of constant surface tension which is used throughout this paper.

3-Results and Discussion

3-1- CMC Properties

Table 1 illustrates the rheological properties and surface tension of three different concentrations of CMC solution (1.1%, 1.5% and 2%). The surface tensions for different concentrations are measured by the capillary and image processing methods. The capillary liquid height can be related to surface tension by following equation

$$\sigma_{la} = \frac{h\rho gr}{2\cos\theta} \qquad (1)$$

The results depict that surface tension increases by increasing CMC concentration. Liquid-solid, liquid-air and air-solid surface tensions can be related by following equation:

$$s_{lv} \cos q = s_{sv} - s_{sl} \qquad (2)$$

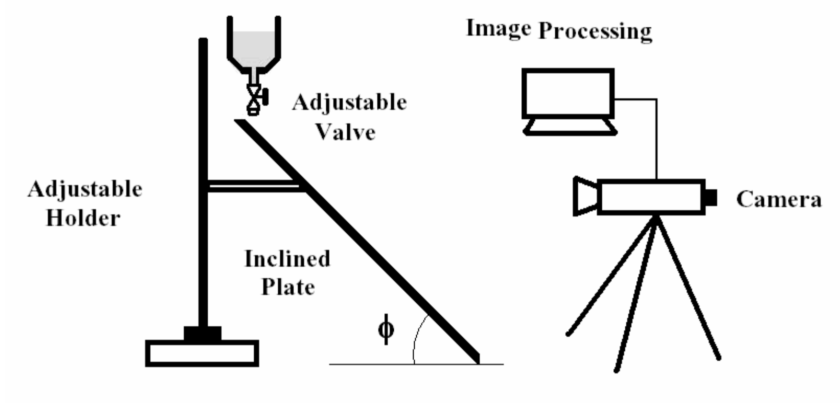

Fig. 1. Simple Schematic of experimental Setup

Where θ is contact angle, a single static contact angle was also measured by goniometry method (imaging and image processing) and changes in contact angle versus concentration are illustrated in Table 1. The results show that the contact angle is a weak function of CMC concentration which is neglected in further analysis. This simplification can cause 10% maximum error. To take into account contact angle effects, three different surfaces (glass, ceramic and aluminum) were used in our experiments. These were chosen to guarantee appreciable changes in contact angle. We observed a minimum contact angle of 31.5 degree on glass, 44.5 degree on ceramics and maximum contact angle of 58.5 degree was observed on aluminum plate.

Table 1. Rheological properties of three different CMC solutions

Concentration (%Weight)	Consistency Index (Pas^n)	Power-Law Index	Surface Tension (N/m)	Contact Angle (°)		
				*	**	***
1.1	5.051	0.462	0.07876	29.9	NA	NA
1.5	11.007	0.5294	0.08189	31.5	44.5	58.5
2	28.966	0.5427	0.08532	35.5	NA	NA

*Glass Surface, ** Ceramic surface, ***Aluminum surface, NA: Not available

3-2- Dynamics of Falling Film

Velocity of the falling film was calculated in every 5 second interval with analysis of the images. The time intervals were controlled by image acquisition program and real time was registered by the same program. Fitting different models to the acquired data shows that all dimensionless velocity profiles can be described by equations of general form as follows:

$$v^* = a\,t^{*^{-b}} \tag{3}$$

Despite gravitational acceleration this decelerating form is obtained in the developing stages of the film flow because of dispersion of fluid on the surface. This phenomenon is also visible in images of Fig. 2 i.e. less increase in film length in the same interval.
This means that part of the fluid accumulates especially in the width of the film. The velocity profile equation can be nondimesionalized by the velocity (velocity at same length) and time (time to reach the same length) of a corresponding inviscid fully developed flow [2]. The velocity and time of the corresponding inviscid flow are given respectively:

$$v_{inv} = \sqrt{2gx\cos\phi} \tag{4}$$

$$t_{inv} = \sqrt{\frac{2x}{g\cos\phi}} \tag{5}$$

Effect of various variables on the dimensionless velocity parameters, α and β, are investigated. Effects of different surfaces with different contact angles on dynamics of falling film are depicted in Fig. 3.

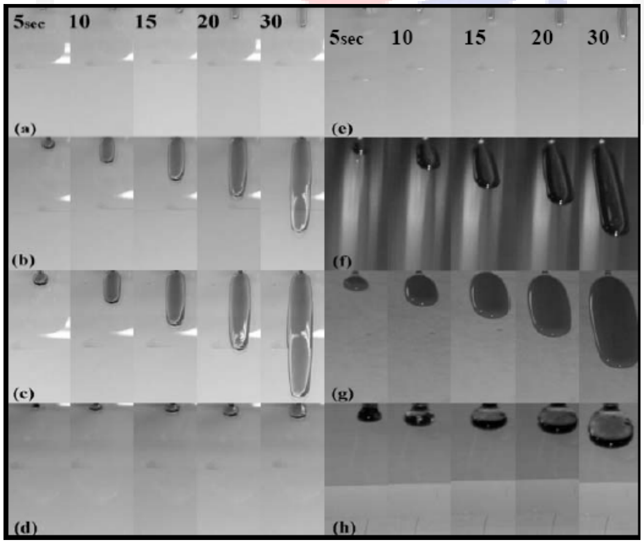

Fig. 2. Development of liquid film, (a): Q = 3ccpm- ϕ: 30° - 1.1% CMC - Surface: Glass. (b): 20ccpm - 30°-1.1% CMC - Glass. (c): 36ccpm - 30°- 1.1% CMC -Glass. (d): 3ccpm - 15° - 1.1% CMC -Glass. (e):3ccpm -45° - 1.1% CMC - Glass. (f): 10ccpm - 30° - 1.5% CMC -Aluminum. (g): 10ccpm - 30° - 1.5% CMC - Ceramics. (h): 11ccpm - 30° - 2% - Glass

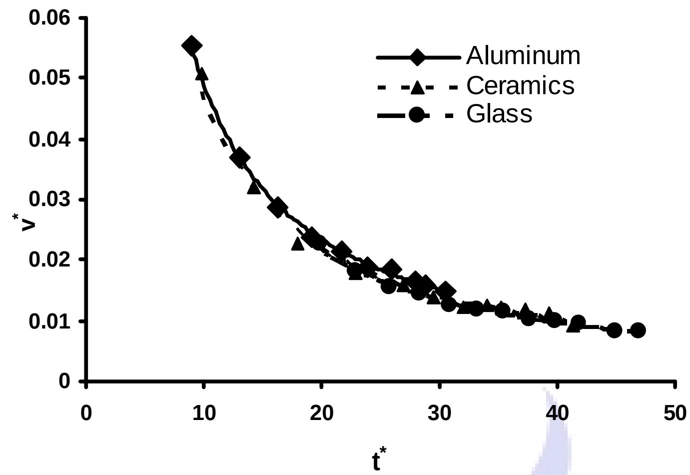

Fig. 3. Dimensionless velocity versus dimensionless time for different surfaces, Q=11, ϕ=30°

The results show, the first parameter α decreases by increasing contact angle and β shows the same but weaker trend. The dependence of β on contact angle is neglected which can cause 8% error in our analysis. Dramatic influence of input flow rate on the dynamics of falling film is shown in Fig. 4.

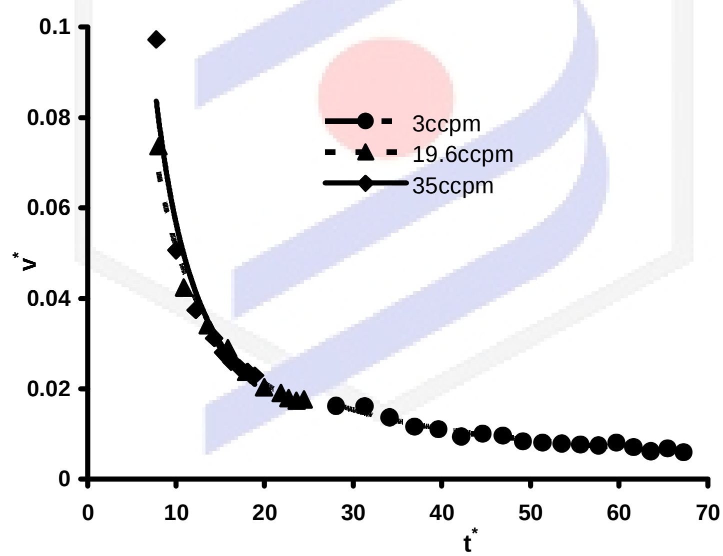

Fig. 4. Dimensionless velocity versus dimensionless time for different flow rates, Glass, ϕ=30°

In 3ccpm case the velocity of falling film is very slow and nearly constant so the dispersion takes place easier but as the flow rate is increased the film flows faster so it gives less time for dispersion which results in a steeper curve. Experimental results show that both parameters (α and β) increase with increasing inclination angle. By fitting curves like those of Fig. 3, 4 and 5 the effects of concentration were also studied. CMC concentration variation not only changes rheological properties of solution but also changes surface tension and contact angle which make the interpretation of results even harder. As discussed before, surface tension and contact angle are weak functions of concentration so further analysis are carried out based on the assumption of independence of this two parameters from CMC concentration. Experimental data shows the decrease of parameter α with concentration and minor changes of parameter β which is likely to be because of changes in surface tension and contact angle. The results show dimensionless velocity profile prefactor α, has depended to three dimensionless group Reynolds number Re, Froude number Fr, and Weber number We, but the other parameter β has depended strongly to Froude number[6]. An approximate value of fully developed film thickness is used as the characteristic length scale in these dimensionless groups [12]. This value is calculated by letting fluid to flow for relatively long time then by image processing methods the wetted surface is calculated and is divided to the total volume of fluid which is calculated by controlling the flow rate and registering the real time.

Several models were chosen by inspecting the way different variables influence parameters of equation (3). All three dimensionless groups were used to model α. Neglecting the effect of We on β a second order curve can adequately describe the dependence of β on Fr. We have devised following relationship to predict the parameter α:

$$a = 1.3162\left(\frac{\mathrm{Re}\,\mathrm{We}}{\mathrm{Fr}}\right)^{0.16} \tag{6}$$

95% confidence interval for pre factor is calculated to be in the $(-0.0734, 2.7058)$ interval. For dimensionless velocity profile exponent β, this interval is calculated to be in the $(-0.3487, 0.6681)$ interval.

$$b = 17.8970Fr^2 - 5.9691Fr - 1.0426 \qquad R^2 = 0.89 \tag{7}$$

4- Conclusion

In this research dynamics of gravity-driven film flow of non-Newtonian fluids was studied. Image processing and image acquisition methods were used to track the flow of the non-Newtonian solution. Different models were fitted to the data to study the velocity of falling film. And a simple equation described the velocity variations adequately. Effects of different parameters on coefficients of this equation are studied and a nondimensional equation is devised to predict the coefficients.

Nomenclature

Fr	Froude number, $u^2/\bar{\delta}g\cos(\theta)$
Fr_x	Froude number, $u^2/xg\cos(\theta)$
g	Gravitational acceleration
h	Liquid height in capillary tube
k	Consistency index
n	Power law index
Re	Reynolds number, $r u^{2-n}\bar{d}^{\,n}/k$
Re_x	Reynolds number at x, $r u^{2-n}x^{n}/k$
r	Capillary tube radius
t	time
v	Velocity profile
u	Inlet velocity
We	Weber number, $r u^2\bar{d}/s_{sl}$
We_x	Weber number, $r u^2 x/s_{sl}$
x	Location on inclined plate

Greek Symbols

α	Pre factor for velocity profile, Eq. (2)
β	Exponent for velocity profile, Eq. (2)
δ	Film thickness
ϕ	Inclination angle
θ	Contact angle
ρ	Density
σ	Surface tension

Subscripts

al	Air-liquid
inv	Invicide flow
sl	Solid-liquid
sv	Solid-vapor

Superscripts

*	Dimensionless variable
-	Mean variable

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