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Some experiences with the numerical simulation of Newtonian and Bingham fluids in dip coating

Abdelkader Filali [a], Lyes Khezzar [a,*], Evan Mitsoulis [b]

[a] Department of Mechanical Engineering, The Petroleum Institute, P.O. Box 2533, Abu Dhabi, United Arab Emirates
[b] School of Mining Engineering & Metallurgy, National Technical University of Athens, Zografou 157 80, Athens, Greece

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ABSTRACT

The dip-coating process is simulated numerically for Newtonian and Bingham fluids with a particular emphasis on finding the free surface location under different sets of conditions. The main focus of the simulations is the evaluation of the Finite-Volume Method (FVM) combined with the Volume-Of-Fluid (VOF) technique embedded in the commercial code (Fluent), while some results are also obtained with the Finite-Element Method (FEM) using another commercial code (Polyflow). The objective is to check how well the results compare with previous results regarding the free surface location for both axisymmetric and planar geometries, and also provide new results. The numerical results were first validated against previous experimental data for the Newtonian limit case. Then numerical results were compared favourably with previous simulations available in the literature for both Newtonian and Bingham fluids. The influence of the coating fluid properties as well as surface withdrawal speed for Newtonian fluids and of the yield stress for Bingham fluids are discussed. The effect of inertia for the planar case is investigated, and the formation of the cusp and wavy shape of the free surface is analyzed.

1. Introduction

Coating flows are liquid flows forming on solid surfaces. Dip-coating is a process that belongs to the family of self-metered coating processes, wherein a substrate is dipped into a liquid coating solution and then is withdrawn from the solution at a controlled speed (Fig. 1). The combination of substrate speed, liquid properties (such as density, viscosity, and surface tension), and the process geometry influence the thickness of the coated film. The produced film has to satisfy thickness and uniformity requirements of the final product design.

Dip-coating processes are found in a wide field of practical applications. These coatings are used for decorative, protective and functional applications that include galvanized steel, magnetic information storage systems and manufacture of semi-conductor components. Although coating processes have been developed mainly through empirical means, see Ruschak [1] and Weinstein and Ruschak [2], appropriate design and manufacture calls for a detailed understanding, knowledge and ability to predict the coating flow process. Computational Fluid Dynamics (CFD) methods, based on the solution of the governing conservation equations, combined with interface-tracking techniques, such as the Volume-Of-Fluid (VOF) technique of Hirt and Nichols [3], are in principle not limited in their range of applicability, and offer a strong viable alternative. The present work uses such techniques in the study of dip-coating flows with the objective of finding their limitations and of gaining experience in applying them in cases where the free surfaces are highly curved.

Three non-dimensional numbers emerge to describe this flow. These are:

(i) the capillary number, *Ca*, which represents the ratio of viscous to surface tension forces and is defined by:

$$Ca = \frac{\mu V_0}{\sigma}, \tag{1}$$

where μ is the viscosity, σ is the surface tension, and V_0 is a characteristic speed (in dip coating the substrate speed);

(ii) the Reynolds number, *Re*, which represents the ratio of inertia to viscous forces and is defined by:

$$Re = \frac{\rho V_0 l_c}{\mu}, \tag{2}$$

where l_c represents the characteristic length, defined as $l_c = (\sigma/\rho g)^{1/2}$, where g is the acceleration of gravity;

(iii) the fluid property number, P_0, which is equal to the square root of the ratio *Ca*/*Re* with the capillary rise $(\sigma/\rho g)^{1/2}$ used as the length scale, is defined by:

* Corresponding author. Tel.: +971 50 820 1536.
E-mail address: lkhezzar@pi.ac.ae (L. Khezzar).

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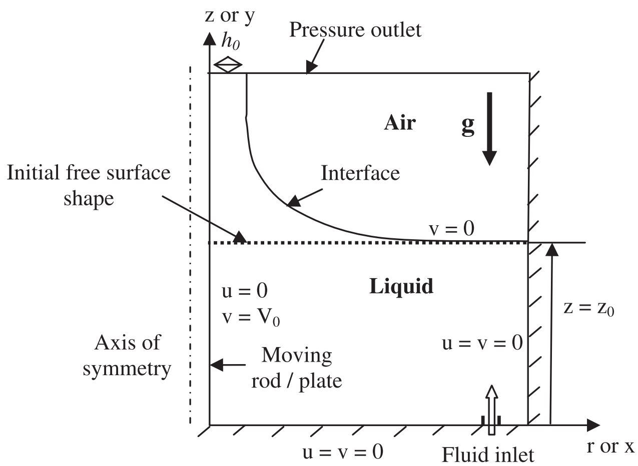

Fig. 1. Schematic representation of the dip-coating problem with reference axes and boundary conditions.

$$P_0 = \mu\left(\frac{g}{\rho\sigma^3}\right)^{1/4} = \sqrt{\frac{Ca}{Re}}. \tag{3}$$

It is to be noted that the fluid property number is related to the Morton number, $Mo = P_0^4$.

The dip-coating flow is usually laminar in nature, initially transient and tends towards a steady state, and has a free surface the dynamics and final shape of which need to be predicted accurately, first during the transient and then steady-state periods. The location of the free surface and the fluid rheology in the case of non-Newtonian fluids presents particular challenges to the numerical simulation of such flows.

Following the initial pioneering work of Landau and Levich [4] and Derjaguin [5], several experimental investigations were carried out, such as by Lee and Tallmadge [6], Tallmadge and Soroka [7], Groenveld [8], and Spiers et al. [9]. Kizito et al. [10] carried out experiments in a broad parametric range, including extended *Ca* and *Re* numbers. Using laser-induced fluorescence, they identified the phenomena leading to the formation of an asymptotic meniscus profile, which eventually develops a *cusp* at the interface when inertia forces are important ($Re > 7$). Based on the property number, P_0, two phenomena of free coating are identified. When P_0 is larger than about 0.5, the non-dimensional final film thickness becomes constant beyond $Ca \approx 1$. For $Ca < 1$, the data shows that the effect of *Re* is negligible and the film thickness depends only on the capillary number. However for $Ca > 1$, the viscous force predominates, and surface tension has a negligible influence in that situation. When P_0 is less than about 0.1, the non-dimensional final film thickness depends on *Ca* and *Re* but it becomes constant beyond a Weber number ($We = Ca\ Re$) of about 0.2. In that case *Re* is important, and the surface tension force becomes negligible compared with the inertia force. In both cases, the non-dimensional final film thickness becomes constant as the effect of surface tension on the meniscus becomes relatively unimportant.

Numerical simulations based on the Finite Element Method (FEM) have been carried out by Tanguy et al. [11,12], who modeled the dip-coating process for Newtonian and non-Newtonian fluids. Numerical results were presented for both flat-plate coating (planar geometry) and wire coating (axisymmetric geometry), and compared successfully with experimental data by Lee and Tallmadge [13]. Most previous numerical works used FEM. Tanguy et al. [12] used the Augmented Lagrangian Method developed by Fortin and Glowinski [14]. An iterative solution based on FEM was used by Reglat et al. [15] to predict the free-surface flow displacement of a Newtonian fluid by a cylindrical substrate. The method was based on a prediction/projection fixed-point iterative scheme and a combination of an original nodal displacement scheme in combination with B-spline smoothing and remeshing to update the free surface. Hurez and Tanguy [16] carried out a FEM analysis using Newtonian and non-Newtonian Bingham fluids with an iterative method based on the Arbitrary Lagrangian–Eulerian (ALE) approach in conjunction with mesh smoothing. It was shown that the influence of the viscosity and the withdrawal velocity must be studied separately, and that the capillary number is not sufficient to describe the meniscus flow dynamics, so that as mentioned above, a fluid property number P_0 is also needed. Yamamoto et al. [17] used FEM to simulate transient viscoelastic dip-coating flows around a rod with three Phan–Thien–Tanner (PTT) fluids that differ in the stretch-thickening property. Recently, Jin et al. [18], using the FIDAP software (Ansys, Inc.), confirmed the asymptotic Newtonian value of the flow rate of 0.582 for large capillary numbers ($Ca \to \infty$) and observed wavy wiggles on the free surface for large values of capillary number ($Ca \sim 3.5$) with the property number $P_0 = 0.83$. Jenny and Souhar [19] used FEM with a semi-implicit front-tracking method for the moving free surface and identified steady and wavy regimes based on the property P_0 and capillary numbers *Ca* for high Reynolds number $Re > 1$. It was concluded that beyond a critical $Re \approx 5$, the flow becomes wavy producing fluctuations of the order of 10% of the mean value of the film thickness.

It can be said that on the experimental side, most of the previous studies were based on flow-visualization techniques and consisted of observing and measuring the free-surface conditions. These efforts, successful as they were, were limited in the amount of quantitative information that can be obtained. On the other hand, CFD as a simulation tool allows access to useful quantitative information on such flows, which would be difficult to obtain using experimental tools. It transpires also from the above literature review that most numerical studies used FEM with remeshing techniques. Present-day numerical methods based on the Finite Volume Method (FVM) and combined with an interface tracking technique, such as VOF, are capable of simulating dip-coating flows and can be used for analysis and design purposes.

In the present work, an analysis of the dip-coating process for a vertical plane and a cylindrical rod is carried out using FVM embedded in ANSYS – FLUENT® code version 12.1 [20]. Both Newtonian and non-Newtonian Bingham fluids are used. The location of the free surface at equilibrium, in the presence of surface tension and external gravity force, is predicted starting from an initial liquid bath at rest with a horizontal free surface, using VOF for interface capturing. The present study provides an evaluation of the VOF algorithm and FVM in predicting the behavioral details of such flows. The numerical work is contrasted with the results obtained in the works by Kizito et al. [10] and Hurez and Tanguy [16]. Particular attention is given to the existence of cusps on the free surface under certain flow conditions and the resulting flow field structure for dip coating in planar geometries.

2. Mathematical modeling

Since the focus of this study is an evaluation of the technique based on the FVM-VOF combination, its mathematical model is described in some detail, while a short description of the FEM modeling approach is also given for completion.

2.1. Governing equations

The field conservation equations for mass and momentum for transient, incompressible, laminar flow are given below and are shared by the liquid and gas phases: