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Thin film flow on a vertically rotating disc of finite thickness partially immersed in a highly viscous liquid

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HIGHLIGHTS

- The film formation is investigated experimentally and modelled numerically.
- A correlation equation has been proposed to predict the film thickness.
- The experimental measurements were conducted using the laser scan method.
- Numerical modelling was performed using the Volume of Fluid method.
- The rim thickness of the disc was found to have a measurable effect on the film profile.

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ABSTRACT

The entrainment and flow of a thin film of liquid on a vertically rotating disc partially immersed in a liquid bath has been investigated experimentally and modelled numerically. The Volume of Fluid (VOF) Computational Fluid Dynamics (CFD) modelling approach has been employed to characterise the shape and stability of the thin film thickness profile. The thickness of the rotating disc plays a significant role in the thin film profile and this is confirmed through the comparison of simulation with the experimental results. Other factors determining the film thickness were identified as the rotational speed and the fluid viscosity where the film thickness profile increases with the increase of the rotational speed and also the viscosity. A correlation equation to predict the film thickness as a function of angular position, radius, rotating speed, viscosity and surface tension is proposed. The results given in this study specifically report on the thin film thickness variation with the angular direction and the film entrained into the liquid. In both the simulation and experimental results, it is noted that the film thickness stabilises following a rotation of 15° after drag out of the liquid, and remains so until 10° before being dragged back in.

1. Introduction

Thin film flows on vertical rotating discs are extensively used in the extrusion coating process, in which a polymeric material is extruded on to another polymeric material to form a composite laminate (Parmar et al., 2009). Other typical examples include that of the oil disc skimmers, which are used for oil recovery as an alternative to toxic chemical dispersants in case of an offshore oil spill. In the synthesis of polyethylene terephthalate (PET) in polycondensation reactors (Cheong and Choi, 1995), a series of vertically rotating discs are partially immersed in highly viscous polymer liquid, where the melt is picked up and spread, in the form of a thin film, onto the surface of the discs. This achieves an enhanced mass transfer from melt to film, enabling the low-cost production of plastic bottles and food packaging boxes.

While there have been many studies of thin film flows on horizontally rotating discs (Mouza et al., 2002; Thomas et al., 2010), there have been limited studies (Zhang et al., 2008; Yu et al., 2009) on the vertical case. Unlike the horizontal case, the film flow in a vertically rotating system is always associated with a meniscus region, where the liquid is dragged out of the tank by the rotation of the disc. As a result, an unstable oscillating region is set up, where the film formed on the disc is dragged back into the liquid tank. The fluid dynamical aspects are still not fully investigated, although there are some discussions and general solutions of film

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thickness profiles for the problem of liquid drag out (Landau and Levich, 1942; Wilson, 1982).

In the present study there are two aims: to formulate a relationship for thickness as a function of position on the disc, and to examine the effect of disc rim thickness on the film formation process. It is important to recognise that as a result of the film formation process, the film thickness distribution in different radial and angular positions on the disc surface is not uniform (Afanasiev et al., 2008). The simulation results of this study confirm that the flow entrained onto the rim of the disc has a non-negligible effect on the film formation on the disc surface leading to a change in the film thickness profile relative to that of an idealised "thin" disc. Results for two disc rim thickness are presented here.

The computational model for the liquid thin film flow consists of expansive tank of liquid, partially bounded by a solid substrate with a free surface (the rotating disc), where the liquid is exposed to another fluid, usually a gas and most often air in applications (Sadighi et al., 2008). To describe the physical phenomena of the liquid film flow, the Navier–Stokes equation is used, which presented here in cylindrical coordinate form (Afanasiev et al., 2008; Idowu and Adewuyi, 2010; Bird et al., 2007). The mathematical model proposed by Afanasiev et al. (2008) is extended to define the film pattern formation. The mathematical model must be solved numerically, but simplifications can be applied on the basis of non-dimensional analysis. In this study the CFD code employed is ANSYS Fluent 6.3 (Aubin et al., 2005), and the Volume of Fluid (VOF) method is employed for tracking and locating the free surface.

In the modelling of the film formation, it is important to consider the force balance, as the shape and stability of the thin film is controlled by the forces acting on it: viscous, inertial, surface tension, centrifugal, Coriolis and gravitational forces. For a vertically rotating disc with low rotational speeds in the order of 1–6 rpm, the Coriolis force can be neglected at the leading order, as the Coriolis force term is of the same order as the inertial force terms, following lubrication theory (Myers and Charpin, 2001; Myers and Lombe, 2006).

The numerical simulations data have been validated through a comprehensive experimental investigation. The experiments were conducted in a laboratory scale experimental device as described in the experimental section and the measurements were performed using the laser scan method (Sung et al., 2004). The experimental and numerical simulation results obtained illustrate a good agreement.

2. Mathematical modelling

The physical set up for the vertically rotating disc partially immersed in liquid is shown in Fig. 1. A disc of radius R is rotating at rotating speed Ω about its horizontal axis, which is a distance d above the liquid bath. For most thin film flows on vertically rotating discs, the flows can be treated as incompressible (Afanasiev et al., 2008).

For the problem of the vertically rotating disc, the cylindrical coordinate system is employed for convenience. Let the liquid velocity vector to be represented by $(u_r,\ u_\theta,\ u_z)$ and ω denotes the angular velocity vector with components $(0, 0, \Omega)$.

2.1. Governing equations

The Navier–Stokes equations used to describe the thin film flow on a vertically rotational disc can be expressed in cylindrical coordinates as (Afanasiev et al., 2008):

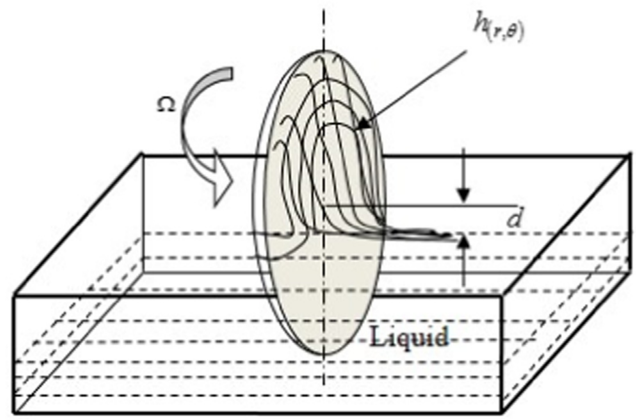

Fig. 1. Configuration of a rotating disc partially immersed in liquid.

$$\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta^2}{r}+u_z\frac{\partial u_r}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial r}$$
$$+\nu\left[\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}+\frac{\partial^2 u_r}{\partial z^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r}{r^2}\right]-g\sin\theta \tag{1a}$$

$$\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_r u_\theta}{r}+u_z\frac{\partial u_\theta}{\partial z}=-\frac{1}{\rho r}\frac{\partial p}{\partial \theta}$$
$$+\nu\left[\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_\theta}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}+\frac{\partial^2 u_\theta}{\partial z^2}+\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r}{r^2}\right]-g\cos\theta \tag{1b}$$

$$\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}$$
$$+\nu\left[\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right] \tag{1c}$$

where ρ, μ, ν and p denote, respectively, the density, dynamic viscosity, kinematic viscosity and the pressure of the liquid. The only external force assumed to be acting on the thin film liquid is gravity g. Thin film flows on the rotating discs, like other flows, should also satisfy the continuity condition, which states the law of conservation of mass and again expressed in cylindrical coordinates (Afanasiev et al., 2008)

$$\frac{1}{r}\left[\frac{\partial}{\partial r}(ru_r)\right]+\frac{1}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial u_z}{\partial z}=0 \tag{2}$$

2.2. Boundary conditions and simplifications

At the surface of the disc, i.e. $z=0$, the no-slip boundary condition is imposed and the disc surface is assumed to be impermeable. As the sides of the disc are symmetrical, only one side is considered here. Flow on the rim of the disc will be discussed later. Thus,

$$u_r=0,\quad u_\theta=r\Omega,\quad u_z=0 \tag{3}$$

The total rate of change of the thin film thickness should be equal to zero, which results in the following kinematic condition (Afanasiev et al., 2008)

$$\frac{\partial h}{\partial t}=u_z-u_r\frac{\partial h}{\partial r}-\frac{1}{r}u_\theta\frac{\partial h}{\partial \theta} \tag{4}$$

Considering the film coating on one surface of the disc, Eq. (2) is integrated over the film thickness to obtain

$$u_z=-\int_0^h\left\{\frac{1}{r}\left[\frac{\partial}{\partial r}(ru_r)\right]+\frac{1}{r}\frac{\partial u_\theta}{\partial \theta}\right\}dz$$