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Thin film flow over spinning discs: The effect of surface topography and flow rate modulation

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Abstract

We examine the effect of disc topography and time modulation of the liquid flow rate at the inlet on the dynamics of a thin film flowing over a spinning disc. We use a combination of boundary-layer theory and the Kármán–Polhausen approximation to derive coupled equations for the film thickness, and radial and azimuthal flow rates. Substrate patterning is taken into account in the limit of small-amplitude topography. Our numerical results indicate that the combined effects of flow rate modulation at the inlet and disc patterning can lead to a significant increase in interfacial waviness, which greatly exceeds that associated with the constant flow rate, smooth disc case.

Keywords: Spinning disc; Fluid mechanics; Interfaces; Process intensification; Mass transfer; Topography; Waves; Hydrodynamics

1. Introduction

Thin liquid films falling under the action of gravity or subjected to centrifugal forces exhibit complex dynamics characterised by the formation of large-amplitude waves (Chang and Demekhin, 2002; Matar et al., 2006). These waves give rise to intense mixing on the surface of the disc and substantial increase in the heat and mass transfer rates, commonly referred to as ‘process intensification’. In the case of thin films flowing over spinning discs, the body force is controllable, which allows the process-intensifying nature of these flows to be exploited in industrial applications; recently, so-called ‘spinning disc reactors’ (SDRs) have been used as compact devices for the manufacturing of fine chemicals and pharmaceuticals (Aoune and Ramshaw, 1999; Boodhoo et al., 2004, 2006; Matar and Lawrence, 2006a). It may indeed be possible for SDRs to replace batch reactors as the reactors of choice for the large-scale production of speciality chemicals.

Due to their importance in applications such as reaction engineering, thin film flows over spinning discs have received considerable attention. Experimental work has identified the presence of different flow regimes depending on the flow rate (Espig and Hoyle, 1965; Butuzov and Puhovoi, 1976; Rifert et al., 1982; Thomas et al., 1991) and the development of three-dimensional flow structures from axisymmetric waves (Woods, 1995). Previous work has also shown that a local decrease of the local time-averaged thickness, below the waveless so-called ‘Nusselt’ solution, results from the formation of waves (Charwat et al., 1972; Leneweit et al., 1999), and that inertia is important near the inlet while viscous forces are significant near the disc periphery (Burns et al., 2003). The latter work demonstrated the development of a ‘spin-up’ zone near the inlet and a ‘synchronisation’ zone further downstream; in the former region, the liquid experiences significant torque and is then accelerated by centrifugation to higher radial velocities. In addition to the above studies, the experimental work of Aoune and Ramshaw (1999), who examined the absorption of oxygen by thin water films on spinning discs, demonstrated the process-intensifying effect of the waves: the mass transfer rates in the presence of the waves were found to be considerably larger than in their absence.

Advances have also been made in terms of modelling work. A significant number of studies have focused on

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determining steady, axisymmetric waveless solutions (Emslie et al., 1958; Dorfman, 1967; Rauscher et al., 1973; Shkadov, 1973; Miyasaka, 1974; Lepekhin et al., 1981; Sisoev et al., 1986; Needham and Merkin, 1987; Shvets et al., 1992; Woods, 1995; Myers and Charpin, 2001) using boundary-layer theory and the Kármán–Polhausen method or lubrication theory. The stability of these solutions was also investigated (Charwat et al., 1972; Eliseev, 1983; Needham and Merkin, 1987; Sisoev and Shkadov, 1987, 1990). Models based on the combination of boundary-layer theory and the Kármán–Polhausen approximation (with an appropriate closure for the velocity profiles) have also been introduced recently in order to account for large-amplitude wave formation (Sisoev et al., 2003; Matar et al., 2004, 2005; Matar and Lawrence, 2006a). These models, which constitute extensions of the work of Shkadov on falling films and thin film flows over spinning discs (Shkadov, 1967, 1973), comprise coupled, highly nonlinear evolution equations for the radial and azimuthal film flow rates and the film thickness.

Numerical solution of these equations over periodic domains demonstrated the presence of 'families' of axisymmetric, 'regular' waves, as well as solution non-uniqueness (Sisoev et al., 2003). Using the concept of 'dominating waves', initially formulated for the falling film (Sisoev and Shkadov, 1997a,b; Sisoev and Shkadov, 1999; Shkadov and Sisoev, 2004), this issue is addressed by observing that the family of waves with maximal height (or maximal speed) would correspond to the one observed in physical experiments (and numerical experiments involving the solution of an initial value problem); this facilitated comparisons with measured wave profiles and propagation speeds yielding excellent agreement (Woods, 1995; Sisoev et al., 2003). Numerical simulations over extended domains were also successful in capturing the onset and evolution of large-amplitude waves as well as their interaction leading to coarsening and the emergence of long-wave, coherent structures (Matar et al., 2004, 2005).

The above models have also been extended to account for mass transfer effects (Matar et al., 2005; Sisoev et al., 2005) (as well as the presence of surfactants Matar and Lawrence, 2006a and electric fields Matar and Lawrence, 2006b). The numerical predictions of these models demonstrated that the substantial wave-induced increase in mass transfer rates is strongly dependent on the structure of the 'dominating waves' which, for a given flow rate (and liquid properties), is a function of the wave frequency. These findings further suggest that it may be possible to maximise the degree of process intensification by using periodic 'forcing' at the disc inlet.

The above studies have all involved smooth discs; the effect of disc topography on the dynamics has remained largely unexplored. This is surprising since it is well-known that substrate topography can exert a significant influence on the behaviour of thin film flows, giving rise to capillary waves and ridges. This effect can be detrimental to the uniformity of coating layers in the manufacturing of microelectronics, optical and magnetic devices using spin-coating techniques (Stillwagon and Larson, 1988, 1990; Kalliadasis et al., 2000; Kalliadasis and Homsy, 2001). It is also well-established that the flow over highly corrugated surfaces, or so-called 'structured packings' results in an increase in mass transfer rates; this effect is employed widely in gas–liquid contacting operations, e.g. distillation and absorption columns (see, for instance, Shetty and Cerro, 1998; Valluri et al., 2002 and references therein). Recent work on falling film flows at moderate flow rates indicated that doubly sinusoidal topography can lead to the replacement of the regular, large-amplitude waves present in flow over smooth substrates by standing waves; this is accompanied by a concomitant increase in mass transfer rates.

In this paper, we study the flow of thin films over spinning discs and focus on aspects of the flow, whose effects have not been studied in the literature: disc topography and time modulation of the liquid flow rate at the inlet. We extend the models derived by Matar et al. (2005) to account for the presence of a patterned disc and conduct numerical simulations of the flow in the presence and absence of inlet 'forcing' and substrate topography. We explore the possibility of using inlet 'forcing' and/or disc topography to yield a substantial increase in interfacial waviness above that associated with the 'unforced', smooth disc case.

The rest of this paper is organised as follows. In Section 2, we provide details of the problem formulation. In Section 3, we discuss our numerical results and show how a combination of inlet forcing and substrate topography can lead to a significant increase in interfacial waviness. Finally, concluding remarks are provided in Section 4.

2. Formulation

We consider the axisymmetric dynamics of a thin film of a Newtonian fluid with viscosity μ and density ρ flowing over a disc spinning with rotational speed Ω, as shown in Fig. 1. The film is bounded from above by an essentially inviscid gas and from below by a rigid and impermeable disc; the gas–liquid interface is endowed with a constant surface tension, σ. The surface of the disc is textured. The characteristic vertical and radial scales are H_0 and R_0, which are defined below. We use local tangent-normal cylindrical coordinates (ξ, θ, η) to

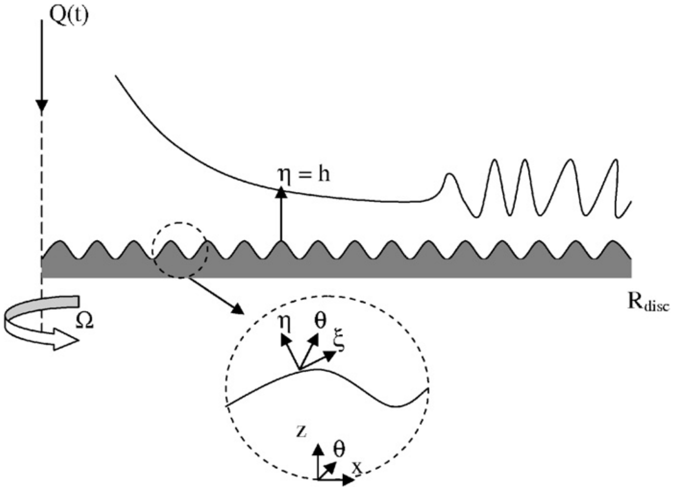

Fig. 1. Schematic representation of the flow.