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Analysis of squeeze flow of fluids between solid and porous surfaces

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ABSTRACT

Squeeze flow of fluids between surfaces is important in rheology, material processing, lubrication and biomedical applications. The surfaces for squeezing can be solid and/or porous. In this work, the squeeze flow between a porous surface and a solid surface is examined with Newtonian model fluids and model fabrics used in composite processing. Given that the fluid is expected to impregnate the fabric, the permeability and the wettability of the fluid–fabric combination are of utmost importance. Constant velocity squeeze flow experiments were carried out with polyester and polyol resins, while glass fabrics with different sizings were used as the porous surfaces. To understand the variation of the normal force during squeeze flow, its scaling with squeeze gap is evaluated. The scaling is observed to vary from −3 to −1 for different squeeze flow experiments. Squeeze flow theories are used to examine the normal force variation for different fluid–fabric combinations. It is shown that a slip based squeeze flow model and a permeability based squeeze flow model can be used to understand the wettability and the permeability of a fabric with a specific fluid.

Introduction

Squeeze flow is a type of flow in which a fluid is compressed between two parallel plates approaching each other and thus, squeezed out radially, and has applications in rheology, lubrication and material processing (Engmann et al., 2005; Servais et al., 2002; Li et al., 2004; Huang et al., 2002). An example schematic diagram of squeeze flow between solid surfaces is shown in Fig. 1(a). It is conducted mainly in two modes; at constant squeezing velocity or at constant squeeze (normal) force (Meeten, 2004; Alexandrou et al., 2013). In a constant squeezing velocity mode, the normal force varies with time, whereas in a constant normal force mode, the squeezing velocity varies with time. Therefore, the normal force or the squeezing velocity is measured as a function of the distance between the solid surfaces (referred to as the squeeze gap).

The earliest study on squeeze flow was done by Stefan in 1874 (Bird et al., 1987) leading to an expression relating normal force and squeeze gap, referred to as Stefan equation. More recently, this flow is being investigated for different types of fluids and geometries (Laun et al., 1999; Meeten, 2001; Lian et al., 2001; Li et al., 2004; McIntyre and Filisko, 2010; de Vicente et al., 2011; Guo et al., 2013). For example, analytical expressions relating normal force and squeeze gap between rigid spheres have been derived for power-law fluid and Bingham fluid (Lian et al., 2001; Li et al., 2004). The normal force is derived from the pressure distribution during squeeze flow. Several others such as Laun et al. (1999) derived analytical solutions for squeeze flow of both Newtonian and power-law fluids considering Navier slip at the walls of the solid surface. Similarly, analytical expressions for normal force during squeeze flow of Herschel–Bulkley fluids were developed by Lawal and Kalyon (1998). Stick-slip as well as bi-viscosity models have been used to describe the squeeze flow of Bingham fluid (Estellé et al., 2006; Estellé and Lanos, 2007; Yang and Zhu, 2006).

Squeeze flow between a porous medium and a solid surface is schematically shown in Fig. 1(b), and is relevant for lubrication and biomedical applications (Hlaváček, 2010; Ruggiero et al., 2011). In this case, the squeeze gap is the distance between the porous medium and the lower solid plate (as shown in the Fig. 1(b)). Generally, the porous medium in squeeze flow is referred to as the porous surface. It should be noted that flow in this porous surface is actually three-dimensional. Squeeze flow between a porous surface and a solid surface was studied by Prakash and Vij (1973); they derived relations between normal force, time and squeeze gap for different geometries such as circular, annular, elliptic and rectangular. The circular geometry and lower porosity were shown to lead to higher normal force.

This work examines the squeeze flow with porous fabric relevant in composite processing, as it involves impregnation of polymeric resins into fibrous reinforcements (Strong, 2007).

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Permeability of the fibrous medium is an important parameter which needs to be determined. Several models have been used for the measurement of permeability, but the results obtained by different methods vary significantly (Mekic and Bakke, 2013). Permeability generally depends on various processing parameters such as infusion velocity, infusion pressure, resin temperature, fabric temperature, micro-structural parameters such as fabric porosity, lay-up and orientation (Yazdchi et al., 2011).

In this work, squeeze flow of a polymeric resin between a porous fabric (porous surface) and a solid surface was studied using model porous surfaces such as glass fabrics and Newtonian model fluids such as polyester and polyol resins. The experimental results for normal force variation with squeeze gap are fit to available theoretical models. An attempt is made to relate the model parameters with different combinations of fluids and porous surfaces. In the next section, the theoretical models are summarised. After describing the materials and methods, we present the experimental results followed by analysis based on the models.

Background

For squeeze flow of Newtonian fluids between solid surfaces, normal force as a function of squeeze gap is given by Stefan equation (Bird et al., 1987; Laun et al., 1999) which is as follows:

$$N = -\frac{3\pi\mu v R^4}{2d^3} \tag{1}$$

where N is the normal force acting on the top surface in the positive z-direction, μ is the viscosity of the fluid, v is the squeezing velocity in the negative z-direction, R is the radius of the circular surface and d is the squeeze gap (Fig. 1(a)).

Stefan equation (Eq. (1)) is derived assuming no-slip at the solid surfaces. For certain fluids and solid surfaces, a slip at the solid surfaces may exist. The modified expression incorporating slip is referred to as the Hassager equation (Laun et al., 1999), and is given by:

$$N = -\frac{3\pi\mu v R^4}{2d^3}\left[\frac{1}{1+\frac{6\beta\mu}{d}} + 2\left(\frac{d}{R}\right)^2\right] \tag{2}$$

where β is the slip coefficient related to the slip velocity (v_s) as follows,

$$v_s = \beta\tau_{zr} \tag{3}$$

where τ_{zr} is the shear stress at the solid surface. $\beta = 0$ corresponds to no-slip, while $\beta = \infty$ applies for complete slip. Intermediate values of β correspond to partial slip. For no-slip case, the second term can be neglected in comparison to the first term as $d \lll R$ and the equation reduces to Eq. (1). In the case of complete slip, only the second term remains.

Relation between normal force and squeeze gap has also been derived in the case of porous bearings, where squeezing of the lubricant occurs between a porous surface and a solid surface. Here, permeability of the porous surface is an important parameter (Prakash and Vij, 1973). The relation is:

$$N = -\frac{3\pi\mu v R^4}{2\left(d^3 + 12KH\right)} \tag{4}$$

where d is the squeeze gap (Fig. 1(b)). K and H are the permeability and the thickness of the porous surface. For $K = 0$ (impermeable surface), Eq. (4) reduces to Eq. (1). Large values of K imply highly permeable porous surface, and in this case N becomes independent of d. Very small values of d also imply that N is independent of d. As discussed later, variation of H is not considered in the present work.

Experimental details

Materials

Materials, which are commonly used in the composites industry, were chosen as the Newtonian model fluids and fabrics for the experimental work.

1. General purpose polyester resin supplied by Millennium Polymers Pvt. Ltd., Bangalore (India). Viscosity at 25 °C is 6.411 Pa s.
2. Polyol: An alcohol having many hydroxyl radicals including polyethers, glycols, polyesters and castor oil. Polyol is also known as Polyhydric alcohol. Conventional Polyether Polyol MW3000 was selected for experiments. Specifications are as follows:

Hydroxyl number (mg KOH/g)	53–59
Acid values (mg KOH/g) max	0.1
Water (max)	0.1
Viscosity at 25 °C (Pa s)	0.554
Density at 25 °C (g/cm^3)	1.00–1.02
Color (Pt-Co), Hazen degrees, max	50
Sodium and potassium content (ppm) max	5

   Polyester was diluted with n-Butyl phthalate to get diluted polyester whose viscosity is equal to that of polyol. Both the model fluids (polyester and polyol) were characterised in steady shear at different strain rates, and were found to be Newtonian.
3. Woven glass fabrics supplied by Urja Fabrics, Ahmedabad (India).

- Phenolic compatible glass fabric.
- Epoxy compatible glass fabric.

Both the fabrics have the same weaving pattern and same physical properties such as thickness and weight in grams

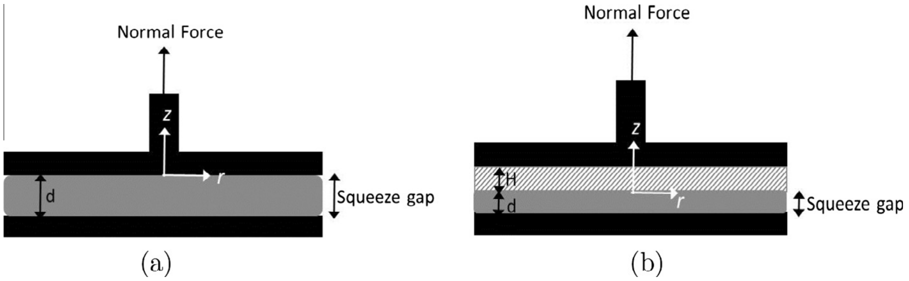

Fig. 1. Schematic diagram of squeeze flow between (a) circular solid surfaces and (b) a circular porous medium and a circular solid surface. Black regions represent the solid surfaces, grey regions represent the fluid and hatched regions represent the porous medium.