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Numerical modeling of anisotropic drag for a perforated plate with cylindrical holes

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HIGHLIGHTS

- Numerical simulation of laminar flow in a perforated plate is performed at pore scale.
- Effects of porosity, hole diameter, plate thickness, and hole pitch are discussed.
- Correlations of directional permeabilities and Forchheimer coefficients are proposed.
- Validity of proposed formulations is assessed with their application to cavity flow.

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ABSTRACT

Direct numerical simulations of an incompressible laminar flow past a perforated plate are carried out at the pore scale. With the aim of evaluating the anisotropic drag of a perforated plate, two simple flow tests have been conducted: i) transpiration flow through a perforated plate with a regular array of cylindrical holes and ii) a linear shear flow over the plate. In the transpiration flow test, the dependence of the pressure drop on the transpiration velocity is discussed for porosities of 0.1–0.4 and hole depth to diameter ratios of 1–3 at pore-level Reynolds numbers of up to 25. The linear shear flow problem is then investigated along with a discussion of the effects of porosity, plate thickness, and pore distribution on the slip velocity at a clear fluid/perforated plate interface. Simple correlations of directional permeabilities and non-Darcy coefficients are also proposed for the perforated plate, with their application to a lid-driven cavity flow.

1. Introduction

A fluid flow across a perforated plate has been of great interest, being encountered in a variety of engineering applications such as mechanical, chemical, civil, and nuclear industries. More specifically, it has received great attention in the design of fluidic devices to regularize the flow distribution (Sahin and Ward-Smith, 1987; Spearman et al., 1991), control the shear flow over the bluff body (Patil et al., 2006; Bae et al., 2012), and reduce aerodynamic noise (Hayden, 1976; Yahathugoda and Akishita, 2005).

The flow resistance of a perforated plate has long been the subject of earlier studies, most of which were focused on the effects of geometric and flow parameters. Using eigenfunction expansion, Wang (1994) analyzed the Stokes flow through a thin screen with holes in a regular array, showing that the pressure drop induced by a transpiration flow in direction perpendicular to the plate surface is primarily dependent on the porosity and hole shape, but is less affected by the perforation pattern. A similar observation was also obtained by Tio and Sadhal (1994). Concerning the turbulent flow through perforated plates, Malavasi et al. (2012) investigated experimentally the effects of hole diameter, plate thickness, and distribution of the holes on the pressure losses at high Reynolds numbers. They reported that, in addition to open area ratio (or porosity), the ratio of plate thickness to hole diameter also plays an important role in the pressure drop, while the impact of hole arrangement is insignificant. Recently, Guo et al. (2013) performed numerical simulations of a turbulent flow in a relatively thin perforated plate with circular holes, discussing the effects of surface roughness and plate inclination angle. It was demonstrated that the pressure loss coefficient is influenced by the impact angle of the flow, while the angular effect may change with the plate thickness. Furthermore, Idelchik (1986) proposed some empirical correlations for predicting the pressure loss coefficient through perforated plates with sharp, beveled, and rounded edges over a wide range of Reynolds numbers.

The slip velocity at a clear fluid/porous medium interface is

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Nomenclature

Δa	hole pitch in the transverse direction [m]
Δb	hole pitch in the lateral direction [m]
D	hole diameter [m]
H	cavity height [m]
K	permeability [m^2]
K_x	permeability in the x direction [m^2]
K_y	permeability in the y direction [m^2]
K_z	permeability in the z direction [m^2]
P	pressure [Pa]
ΔP	pressure drop [Pa]
P_0	stagnation pressure [Pa]
Re	Reynolds number [–]
Re_p	pore-level Reynolds number [-]
$\boldsymbol{U}$	velocity [$m\,s^{-1}$]
U	velocity component in the x direction [$m\,s^{-1}$]
U_s	slip velocity [$m\,s^{-1}$]
U_t	transpiration velocity (superficial) [$m\,s^{-1}$]
U_w	wall velocity [$m\,s^{-1}$]
V	velocity component in the y direction [$m\,s^{-1}$]
x, y, z	Cartesian coordinates [m]

Greek letters

α	non-Darcy coefficient [m^{-1}]
α_y	non-Darcy coefficient in the y direction [m^{-1}]
γ	shear rate [s^{-1}]
δ	plate thickness [m]
δ_i	interface boundary layer thickness [m]
ε	porosity [–]
μ, μ_0	dynamic viscosity of fluid [$kg\,m^{-1}\,s^{-1}$]
μ_e	effective viscosity of porous medium [$kg\,m^{-1}\,s^{-1}$]
ν	kinematic viscosity of fluid [$m^2\,s^{-1}$]
ρ, ρ_0	density of fluid [$kg\,m^{-3}$]

Superscript

$\bar{}$	superficial average

another major concern in technological applications of a perforated plate, because of its relevance to the heat transfer and flow characteristics. Tio and Sadhal (1994) investigated theoretically the linear shear flow over a zero-thickness plate with parallel slits, and expressed the relation between the shear stress and average slip velocity at the plate surface as a function of porosity. Pozrikidis (2004, 2005, 2010) solved numerically the shear flow past a permeable interface and discussed the effects of pore structure, plate thickness, and Reynolds number on the slip velocity. Regarding the boundary conditions for the fluid velocity and shear stress at the interface, Beavers and Joseph (1967) proposed a semi-empirical correlation for the interfacial velocity at a permeable wall. Later, Pozrikidis (2001) derived an expression for the slip velocity at the perforated surface of low porosities, based on the analytical solution for Stokes flow over an infinite plane wall with slits and holes (Smith, 1987). Ochoa-Tapia and Whitaker (1995a, 1995b), Kuznetsov (1996), Chandesris and Jamet (2007), and more recently Tan and Pillai (2009) analyzed the dependence of the velocity profile inside the porous medium on the porosity and permeability, emphasizing the influence of a discontinuity in the stress (or stress-jump) at the permeable interface with small solid fractions (or high porosities). However, most of these researches have been conducted for given porosities, permeabilities, and stress-jump coefficients typically varying with the configuration of pores, and determination of these parameters still remains a challenging issue (Goyeau et al., 2003).

Under most situations, the flow resistance in a porous medium can be modeled by Darcy's law (Darcy, 1856), which provides a linear relationship between the pressure drop and transpiration velocity

$$-\nabla P = \frac{\mu}{K}\bar{\mathbf{U}} \tag{1}$$

where the overbar denotes the superficial average, P is the pressure, $\boldsymbol{U}$ is the velocity, μ is the dynamic viscosity of a fluid, and K is the permeability of the porous medium. This linear model describes well the drag in porous media, being applied to a wide range of engineering problems, especially when the pore-level Reynolds number is sufficiently small, i.e., for cases where the flow in porous media can be modeled as a Stokes flow (Scheidegger, 1974; Coulaud et al., 1988; Chai et al., 2010; Bae et al., 2012). However, in many practical applications of perforated plates, the flow resistance exhibits a highly anisotropic and non-linear behavior containing the inertial effect, thus making it problematic to model the fluid flow through a perforated plate with linear drag only. Moreover, the linear Darcy model fails to take into account the boundary layer development in the porous medium and the associated viscous effect. To cope with these limitations, some corrections to Darcy's law have been proposed in the literature (Forchheimer, 1930; Ergun, 1952; Vafai and Tien, 1981). For instance, Vafai and Tien (1981) established a momentum equation for the interstitial flow in porous media using the local volume averaging method

$$-\nabla P = \frac{\mu}{K}\bar{\mathbf{U}} + \rho\alpha|\bar{\mathbf{U}}|\bar{\mathbf{U}} - \mu_e\nabla^2\bar{\mathbf{U}} \tag{2}$$

where α is the so-called non-Darcy coefficient, ρ is the fluid density, and μ_e is the effective viscosity of the porous medium. The above equation is often referred to as the Brinkman–Forchheimer equation, and is considered a more general description of the flow resistance in porous media because the diffusion term (or Brinkman term) accounting for the boundary effect and the non-linear drag term (or Forchheimer term) representing the inertial effect are additionally included. The permeability, non-Darcy coefficient, and effective viscosity in Eq. (2) are usually thought of as material properties depending on the micro-structural configuration of the pores, differing significantly between the types of porous materials. With this matter, various expressions simply relating these parameters to porosity and solid particle dimension are available for a Cartesian grid of cubes, packed beds, a bank of circular cylinders, fibrous porous media, and so on (Lee and Yang, 1997; Guo and Zhao, 2002; Papathanasiou et al., 2001; Irmay, 1965; Bird et al., 2002; Yazdchi et al., 2011; Clearman et al., 2008; Gervais et al., 2012; Bae et al., 2013). However, despite its practical significance, less effort has been devoted to perforated plates.

In the present study, we investigate the steady, laminar, and incompressible flow past a perforated plate with a regular array of cylindrical apertures. By conducting direct numerical simulations of the transpiration flow through a perforated plate at the pore scale, we first demonstrate the impacts of porosity, plate thickness to hole diameter ratio, and pore distribution on the flow resistance. The dependence of slip velocity at a clear fluid/perforated plate interface on the pore configuration is then analyzed for the linear shear flow over the plate. Based on the numerical results, we also provide simple correlations of directional permeabilities and non-Darcy coefficients for a perforated plate. Finally, the