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Numerical modeling of flow around and through a porous cylinder with diamond cross section

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ABSTRACT

Fluid flow across a porous cylinder has various engineering applications. In this paper, a two-dimensional, steady, and laminar flow around and through a porous diamond-square cylinder is studied numerically. The governing equations are written for two zones: the clear fluid zone and the porous zone. For the clear fluid zone, the regular Navier–Stokes equation is used; and the Darcy–Brinkman–Forchheimer model is used for simulating flow in the porous zone. The governing equations, together with the relevant boundary conditions, are solved numerically using the finite-volume method (FVM). In this study, the ranges of Reynolds and Darcy numbers are 1–45 and 10^{-6}–10^{-2}, respectively. The effects of the Darcy and Reynolds numbers on several hydrodynamics parameters such as pressure coefficient, wake structure, and streamlines are explored. Finally, these parameters are compared with the solid and porous diamond-square cylinders. The numerical results indicate that the wake length and pressure coefficient decrease when Darcy number increases.

1. Introduction

The mathematical modeling and analysis of flow in porous media have attracted considerable attention during past three decades due to their different practical applications. As most of the published papers focus on flow past a circular cylinder or a rectangular cross section, in this study, flow past a porous diamond-square cylinder will be investigated, for which there is little previous study. The practical applications for such cylindrical structures are similar to that of a square cylinder with incident flow at 45°. Examples of such applications are flow past buildings, bridges, and electronic components, bioreactors with porous microcarriers [1], and porous scaffold [2].

Recently, a number of investigators have studied flow around and through a porous cylinder. For example, Adler [3] obtained streamlines through and around porous spherical particles, using the velocity profile calculated by Neale et al. [4]. Bhattacharyya et al. [5] investigated the fluid motion around and through a porous circular cylinder. Their results indicate that the drag coefficient on the porous cylinder reduces monotonically with the increase in the Reynolds and Darcy numbers. They also found that as the Darcy number increases, the angle of separation and wake length reduce.

In another research, fluid flow around and through a porous square cylinder was studied by Yu et al. [6] They also investigated fluid flow around and through a porous circular cylinder (Yu et al. [7]). Their results revealed that by increasing the Darcy number, the wake behind the cylinder will disappear. They also found that the recirculating wake exists downstream of the porous cylinder, which resembles that of the solid cylinder for small Darcy numbers. Yu et al. [8] investigated steady flow around and through a porous sphere. Yu et al. [6–8] found that at small Darcy numbers, the recirculating wake initially occurs outside of the porous square cylinder. However, for the porous circular cylinders, the wake initially occurs inside of the cylinder.

The vortex shedding behind a porous square cylinder was studied by Jue [9]. His results revealed that the vortex shedding is delayed with increasing Darcy number. Chen et al. [10] presented the flow past a porous square cylinder based on the stress-jump interfacial conditions. They found that the drag coefficient decreases with increasing porosity. They also investigated the flow past a porous trapezoidal cylinder by considering the stress-jump interfacial conditions [11].

Dhinakaran and Ponmozhi [12] investigated numerically the fluid flow and heat transfer around and through a porous square cylinder. They found that the drag coefficient and wake length for

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Nomenclature

C_F	Forchheimer coefficient
C_p	Pressure coefficient
D	Cylinder diameter (m)
Da	Darcy number $= K/D^2$
K	Permeability (m^2)
L_R	Length of recirculation region (m)
p	Pressure (Pa)
P'	Cell pressure correction (Pa)
P^*	Guessed pressure field (Pa)
Re	Reynolds number $= \rho_f U_\infty D/\mu$
U	Velocity ($m\ s^{-1}$)
u, v	Velocity components in x, y directions ($m\ s^{-1}$)
$\bar{u}, \bar{v}$	Velocity components in $\bar{x}$, $\bar{y}$ directions ($m\ s^{-1}$)
x, y	Rectangular coordinates (m)
$\bar{x}, \bar{y}$	Rectangular coordinates parallel and normal to the cylinder surface (m)

Greek symbols

α_P	Under-relaxation factor for pressure
μ	Dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	Density ($kg\ m^{-3}$)
ε	Porosity

Subscripts

f	Fluid
eff	Effective
w	Wall
∞	Free stream
1	Clear fluid domain
2	Porous domain

the porous square cylinder approaches the corresponding case of a solid square cylinder for very low Darcy numbers, typically at values around 10^{-6}. Works on flow past a cylinder wrapped with a porous layer are very abundant in the open literature [13–15]. Valipour et al. [15] studied the MHD flow and heat transfer around a solid cylinder wrapped with a porous ring. They used the least square method [16,17] and suggested two empirical equations for the average Nusselt number that the effect of a magnetic field and the Darcy numbers are taken into account.

In this study, fluid flow around and through a porous diamond-square cylinder is investigated, for which there is little previous study. The main motivation of this study is to estimate the effects of the Reynolds and Darcy numbers on pressure coefficient, wake structure, velocity distribution, and streamlines. Moreover, these parameters are compared with solid and porous diamond-square cylinders.

The rest of this paper is organized as follows: In Section 2, the governing equations, relevant boundary conditions, numerical solutions, grid-independent study, and validation are presented. This is followed by a presentation and discussion of the numerical results in Section 3. Finally, Section 4 provides some summarized conclusions.

2. Analysis

2.1. Conceptual model and governing equations

As indicated in Figs. 1 and 2, a diamond-square cylinder with the diagonal length D (normal to the incident flow) and equal side lengths is considered. It is similar to flow with an incidence angle equal to 45°. The uniform fluid flow with free stream velocity (U_∞) from left to right is considered to pass around and through the cylinder. In order to make the problem amenable to numerical simulations, the following assumptions were made:

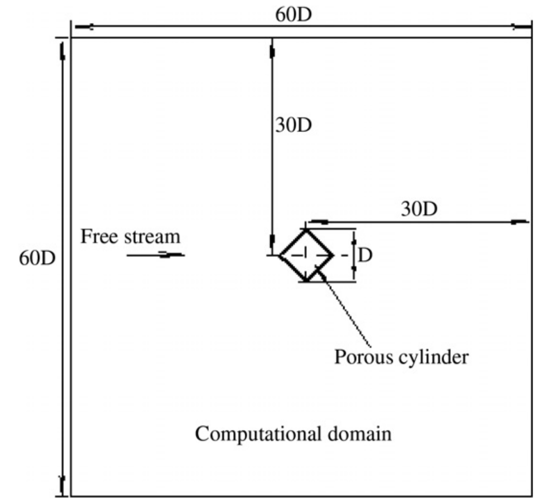

Fig. 1. Computational domain and geometry of a cylinder.

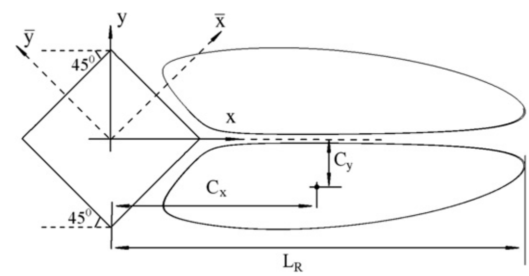

Fig. 2. Schematic of the recirculation zone for a cylinder.

- The porous matrix is assumed to be homogeneous and isotropic with uniform porosity and tortuosity.
- The fluid flow is steady and laminar. In addition, the cylinder is very long, such that the problem can be modeled as a two-dimensional flow.
- All the fluid properties are assumed to be constant, and the body forces are negligible.

Governing equations, momentum and continuity equations, are derived to simulate this problem. The governing equations must be solved for two zones: the clear fluid zone and the porous zone. Hence, two sets of equations were considered here, one set for the clear domain that is indicated by subscript 1 and a second set for the porous medium denoted by subscript 2. Following the above assumptions, the governing equations can be written as given below:

2.1.1. Governing equations for clear domain

Mass conservation:

$$\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y} = 0. \quad (1)$$

Momentum equations in x and y directions:

$$\rho_f \left(u_1 \frac{\partial u_1}{\partial x} + v_1 \frac{\partial u_1}{\partial y} \right) = -\frac{\partial p_1}{\partial x} + \mu \left(\frac{\partial^2 u_1}{\partial x^2} + \frac{\partial^2 u_1}{\partial y^2} \right) \quad (2)$$

$$\rho_f \left(u_1 \frac{\partial v_1}{\partial x} + v_1 \frac{\partial v_1}{\partial y} \right) = -\frac{\partial p_1}{\partial y} + \mu \left(\frac{\partial^2 v_1}{\partial x^2} + \frac{\partial^2 v_1}{\partial y^2} \right). \quad (3)$$