Computers & Fluids 92 (2014) 188–198

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical simulation of the flow around and through a hygroscopic porous circular cylinder

Qingyong Zhu [a,*], Yaoqin Chen [a], Huaizhong Yu [b]

[a] School of Engineering, Sun Yat-sen University, Guangzhou 510275, China
[b] The University of Queensland, Brisbane St Lucia, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 18 May 2013
Received in revised form 16 December 2013
Accepted 18 December 2013
Available online 2 January 2014

Keywords:
Hygroscopic porous circular cylinder
Adsorption effects
High order accurate compact difference schemes
Heat transfer

ABSTRACT

The flow around and through a hygroscopic porous circular cylinder was studied numerically in this paper. The cylinder is placed horizontally and exposed to a uniform flow of air. The effects of the important parameters, the hygroscopicity, the porosity, the Reynolds and Darcy numbers, on the flow are investigated in detail. A single-domain model is introduced to describe the flow around and through a porous circular cylinder with consideration of the adsorption effects. The flow is simulated by solving time-dependent Navier–Stokes equations in the homogenous fluid region and Darcy–Brinkman–Forchheimer extended model in the inner region. High order compact finite difference schemes are constructed for better simulation of this problem. Detailed numerical simulation results indicate that the effects of adsorption may have a significant effect on the flow behind the porous cylinder and suppress the occurrence of recirculating wake.

1. Introduction

The flow over bluff bodies, such as cylinders, has been the subject of numerous experimental and numerical studies for a long time, especially from the fluid mechanics point of view. This flow not only exhibits many fundamental mechanisms, some of them still not satisfactorily explained, but also has many practical applications. Most of the studies on flow around cylinders concentrate on circular and square shapes. For the steady flow past a circular cylinder, the flow behavior is determined by the Reynolds number. The numerical and experimental data on velocity distribution, pressure coefficient and separation angle, etc. have been studied [1,2]. The incidence angle is another important factor which affects the flow for the flow past a square cylinder [3,4]. Zhou et al. [5] investigated the vortex structures and particle dispersions in flows around a circular cylinder by lattice Boltzmann method (LBM), with non-equilibrium extrapolation method (NEM) dealing with the computational boundaries. However, these studies dealt with an impermeable circular or square cylinder.

One of the early investigations on flow around porous bluff body can be found in the work of Joseph et al. [6], in which the low Reynolds number flow of viscous fluid around a porous sphere was examined. In their studies, the Darcy law and the asymptotic equation of Stokes were used to govern the flow in porous and non-porous regions. The analytical solutions of velocity, pressure fields as well as drag on the sphere were obtained. Wolfersdorf [7] investigated the steady potential flow past a circular cylinder with porous surface. They [8] evaluated the solutions obtained. Later, Heier et al. [9] have studied the potential flow past a porous circular cylinder. Masliyah et al. [10–14] have studied the flow past an isolated porous cylinder or sphere. In most of those studies the flow field is described by the Darcy equation inside the porous bodies and the Navier–Stokes equations under creeping flow conditions to govern the flow outside the porous bodies. Noymer et al. [15] have numerically studied the flow around a permeable circular cylinder by using commercial software PHOENICS. The Darcy and Navier–Stokes equations were used to govern the porous and homogenous flows and the pressure and mass flow were matched at the interface of the two regions. They found the drag on a porous cylinder is significantly higher than that for a comparable impermeable cylinder at $Re = 100$ and 1000. This finding was substantiated by their wind tunnel tests. Bhattacharyya et al. [16] numerically investigated the steady flow around and through a porous circular cylinder, in which the porous flow was governed by a generalized model including the Brinkman term, the Forcheimmer term, and a nonlinear convective term. It was found that the drag coefficient, the wake length and separation angle decrease with increasing Darcy number. The separation point shifts towards the rear stagnation point as Darcy number is increased. Nazar et al. [17] analyzed mixed convection boundary layer flow from a horizontal circular cylinder embedded in a fluid-saturated porous medium using the Brinkman model in detail.

* Corresponding author. Tel./fax: +86 20 84036235.
E-mail address: mcszqy@mail.sysu.edu.cn (Q. Zhu).

0045-7930/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compfluid.2013.12.022

More recently, Yu et al. [18,19] analyzed the flow structure around a permeable square/circular cylinder using the stress-jump boundary condition. They presented the flow structure around the permeable cylinder, with the help of streamlines, for different Reynolds numbers, Darcy numbers and porosity. They presented plots of the coordinates of wake center as a function of Reynolds number for different Darcy number along with the length of the wake formed behind the porous cylinder.

It is evident that many studies concentrated on the fluid flow characteristics of a porous cylinder in the steady/unsteady flow regime. In fact, if the permeable cylinder is made up of hygroscopic materials such as fibers, the hygroscopicity of the permeable cylinder should be considered. However, it was not presented in previous studies. The effects of adsorption due to the hygroscopicity of the porous cylinder are exactly the focus of the present work. The remainder of this paper is organized as follows: The mathematical model and governing equations of the problem are presented in Section 2. This is followed by the numerical method in Section 3. The results and discussion are made in Section 4. In Section 5, we provide the conclusion.

2. Mathematical model

The computational domain is presented schematically in Fig. 1(a). We consider a cylinder of radius a placed in a uniform flow of a vapor–air mixture. Unlike most similar heat and mass transfer models in which the hygroscopicity of the material is ignored, we consider the influence of the hygroscopicity, which more accurately represents the actual conditions presented in the model. A single-domain model is introduced to describe the process of the flow around and through a porous circular cylinder with consideration of the adsorption effects.

2.1. Governing equations

The problem we considered here is the flow around and through a hygroscopic porous circular cylinder, which consists of the flow outside the porous cylinder governed by the classic continuity and Navier–Stokes equations, and the flow for porous region based on Darcy–Brinkman–Forchheimer extended model.

The governing equations in the homogenous fluid region are written as:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial(\rho_m u)}{\partial x} + \frac{\partial(\rho_m v)}{\partial y} = 0 \tag{1}$$

$$\rho_m \frac{\partial u}{\partial t} + \rho_m(\vec{V} \cdot \nabla)u = -\frac{\partial p}{\partial x} + \mu_m \nabla^2 u \tag{2}$$

$$\rho_m \frac{\partial v}{\partial t} + \rho_m(\vec{V} \cdot \nabla)v = -\frac{\partial p}{\partial y} + \mu_m \nabla^2 v \tag{3}$$

where u and v are the x and y components of velocity, p is the pressure. ρ_m is the fluid density and $\mu_m = \frac{\mu_1}{1+(x_2/x_1)\psi_{12}} + \frac{\mu_2}{1+(x_1/x_2)\psi_{21}}$ is the dynamic viscosity according to the formula of Wilke [20], here, $\psi_{ij} = \frac{\left[1+(\mu_i/\mu_j)^{1/2}(M_j/M_i)^{1/4}\right]^2}{\left[8(1+M_i/M_j)\right]^{1/2}}$, x_i is the mole fraction of the ith component.

In the inner region, the governing equations for porous region based on Darcy–Brinkman–Forchheimer extended model can be expressed as:

$$\frac{\partial \rho_m}{\partial t} + (1-\varepsilon)\dot{M} + \frac{\partial(\rho_m u)}{\partial x} + \frac{\partial(\rho_m v)}{\partial y} = 0 \tag{4}$$

$$\rho_m \frac{\partial u}{\partial t} + \frac{\rho_m}{\varepsilon}(\vec{V} \cdot \nabla)u = -\varepsilon\frac{\partial p}{\partial x} + \mu_m \nabla^2 u - \frac{\mu_m \varepsilon}{K}u - \frac{\rho_m G\sqrt{u^2+v^2}}{\sqrt{K}}u \tag{5}$$

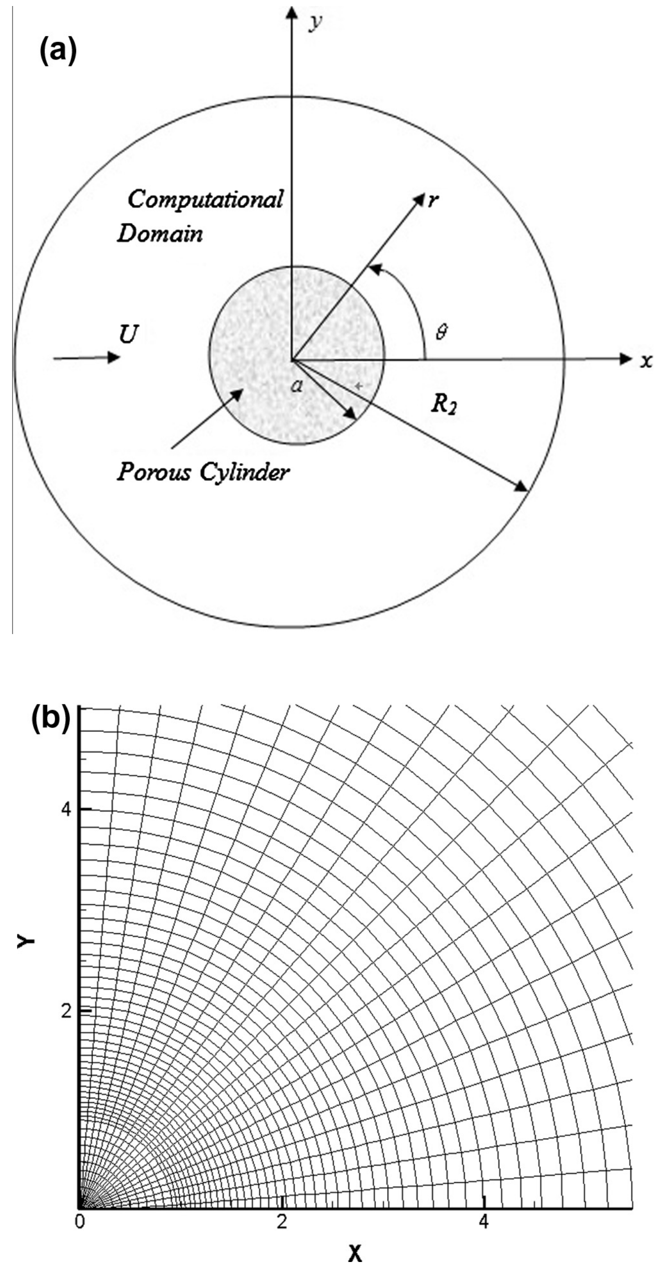

Fig. 1. (a) Schematic of flow around and through a porous circular cylinder. (b) Grid resolution in and around the cylinder.

$$\rho_m \frac{\partial v}{\partial t} + \frac{\rho_m}{\varepsilon}(\vec{V} \cdot \nabla)v = -\varepsilon\frac{\partial p}{\partial y} + \mu_m \nabla^2 v - \frac{\mu\varepsilon}{K}v - \frac{\rho_m G\sqrt{u^2+v^2}}{\sqrt{K}}v \tag{6}$$

where $\dot{M}$ is the water condensation rate in the fibers, ε is the porosity, K is the permeability and $G = \frac{1.75}{\sqrt{150}}\frac{1}{\varepsilon^{3/2}}$ is Forchheimer coefficient. The permeability (K) and the porosity (ε) could be related through the Carman–Kozeny relation [21]

$$K = \frac{1}{K_0 S_0^2}\frac{\varepsilon^3}{(1-\varepsilon)^2}$$

where K_0 is the Kozeny constant, S_0 is a shape factor.

As the solution technique, a single-domain approach is used which consider the porous layer as a pseudo-fluid and the