Journal of Non-Newtonian Fluid Mechanics 246 (2017) 21–30

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

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

Flow resistance of viscoelastic flows in fibrous porous media

Hai Long Liu[a], Junfeng Wang[a], Wook Ryol Hwang[b,*]

[a] School of Energy and Power Engineering, Jiangsu University, Zhenjiang, China, 212-013
[b] School of Mechanical Engineering, Research Center for Aircraft Parts Technology (ReCAPT), Gyeongsang National University, Gajwa-dong 900, Jinju, Korea, 660-701

ARTICLE INFO

Article history:
Received 23 April 2016
Revised 17 May 2017
Accepted 22 May 2017
Available online 23 May 2017

Keywords:
Porous media
Flow resistance
Viscoelastic fluid
Extensional stretch of polymer
Finite-element method

ABSTRACT

In this work, we present flow simulations of viscoelastic (Oldroyd-B and Leonov) fluids in the unidirectional fibrous porous media to investigate effects of the elasticity on the flow resistance. Extensive numerical simulations were carried out for the Oldroyd-B and Leonov fluids to investigate the flow resistance in some typical geometries of unidirectional fibrous porous media: square, hexagonal, as well as randomly aligned arrays of unidirectional fibers. To the best knowledge of the authors, we report for the first time the stiff increase of flow resistance through numerical simulations above a certain Weissenberg number. Considerable growth in the flow resistance has turned out to be closely associated with microstructure of porous media through the extensional stretch of polymers. For the hexagonal and randomly aligned fibers, where there are enough spaces behind fibers, significant amount of polymer stretch is observed along with substantial growth of the corresponding flow resistance. On the other hand, only minor change in flow resistance and negligible polymer stretch are observed in case of square-packing porous media.

1. Introduction

There are diverse applications of polymeric flows through porous media in engineering fields such as the chemical enhanced oil recovery, reactions in fixed beds, filtration in chemical engineering and manufacturing of thermoplastic composites [1]. In such processes, an excessive pressure drop (or flow resistance) has been observed above a certain flow rate for moderately concentrated solutions of high molecular weight polymers. Experimental measurements of the flow resistance for polymeric flows in aligned arrays of cylinders or undulating flow channels also reported the remarkable increase in the flow resistance for the Weissenberg number beyond a critical value [2–9].

The elastic instability is considered to be responsible at least partly for such a steep increase of flow resistance: i.e., the observations of transition from 2D steady flow to three-dimensional time dependent structure with unsymmetrical flow patterns, secondary flows (vortices) and pressure fluctuations through experiments of purely elastic fluids and these flow structures would transfer the energy from the mean flow to the disturbance flow and dissipate it continuously [10–12]. Newly study by De and co-workers [13] modeled unsteady viscoelastic flows through a continuous array of cylinders. And they observed the presence of vortices and the development of asymmetry flow structure numerically in porous space with the increase of elasticity. On the other hand the extensional stretching of the viscoelastic flows, which leads to a large extensional viscosity, has been also considered for a major factor of the increase in the flow resistance [9]. Chimielewski and co-authors [7,8] conducted flow experiments of poly(isobutylene) solutions through arrays of cylinders and pointed out that the converging-diverging geometry of the pores could create extensional flow regions and thereby lead to increase in the flow resistance. By employing the flow-induced birefringence (FIB) measurement and computational study to polymer melt past a confined cylinder, Baaijens and co-workers [14] reported the evident birefringent tail at the wake of cylinder that is dominated by elongation effects, as well as the fringe pattern between cylinder and walls where a shear-elongational flow is present. However, little increase of drag coefficient (flow resistance) has been reported due to the strong shear-thinning behaviors of polymer melts. Recently, Moss and Rothstein [15,16] compared a series of viscoelastic wormlike fluids flows past a confined cylinder, and a periodic array of cylinders. Interestingly, they found instable asymmetric flow patterns for just one of the test fluid above a critical Deborah number, the other remained stable for all Deborah number tested. They showed that observed instability originates in the extensional flow in the wake of the cylinder by means of the particle image velocimetry (PIV) measurements and flow-induced birefringence. On this approach, a number of studies hypothesized that the stress-

* Corresponding author.
E-mail address: wrhwang@gnu.ac.kr (W.R. Hwang).

http://dx.doi.org/10.1016/j.jnnfm.2017.05.004

conformation hysteresis is responsible for the pressure drop (flow resistance) enhancement in the extensional flow [17–23]. That is, the curve of polymer stress versus polymer molecular conformation evolves along distinct paths during the stretching period from its relaxation back to equilibrium, and this difference represents a net dissipation of energy between the externally imposed flow and the internal chain dynamics which appears to be significant only when the fluid is subjected to large Hencky strains [18,22]. Nonetheless extensional flow effect on the viscoelastic flows in porous media has not been examined intensively and clearly.

There are a considerable number of contributions to the numerical modeling of the viscoelastic flows in the porous media which attempted to understand the relationship between macroscopic response of the flow behaviors in terms of pressure drop (flow resistance) and the flow kinematics of viscoelastic fluids. Unfortunately those computational efforts have failed to predict the experimentally observed growth of the flow resistance. Souvaliotis and Beris [24,25] developed a domain-decomposition/spectral-collocation method to simulate an Oldroyd-B fluid through a square array of cylinders, and reported no increase of the flow resistance. Talwar and Khomami [26,27] employed a higher-order finite element scheme to solve the same problem by using various constitutive models (e.g., Upper-convected Maxwell (UCM), Phan–Thien–Tanner (PTT) and Giesekus models). They concluded that the elasticity reduces the flow resistance, which is opposite to the experimental findings. Moreover, a similar problem solved by Hua and Schieber [28] using a combined finite-element and Brownian dynamics technique (CONNFFESSIT) with several kinetic theory models showed no increase of the flow resistance with the elasticity as well.

Possible interpretation for the discrepancy between numerical predictions and experimental observations might be due to the restricted porous architecture (simple packing structure) of the previous numerical approaches and a limited range of achievable Weissenberg numbers. It was already pointed out by Liu et al. [29] that there is no increase of flow resistance in viscoelastic flow through a periodic array of cylinders confined between walls due to the absence of elongation.

In this work, we present flow simulations of viscoelastic fluids through the porous media to investigate effects of the elasticity on the flow resistance or pressure drop. We begin with briefly introduction of the modeling strategy and the definition of the Weissenberg number in typical fibrous porous geometries. A brief description of the finite element techniques is also present in the Section 2, employing (i) DEVSS/DG (Discrete Elastic-Viscous Stress Splitting/Discontinuous Galerkin) finite element scheme combined with the mortar-element method for the bi-periodic boundary condition; (ii) the fictitious domain method for a proper representation of fibers in a fluid; and (iii) the matrix logarithm to achieve stable solutions at relatively high Weissenberg number. In Section 3, by introducing Oldroyd-B and Leonov models as constitutive equations, we present the flow resistance in typical fibrous porous microstructures: square, hexagonal, as well as randomly aligned arrays of unidirectional fibers. The effects of the elasticity on the flow resistance are discussed.

2. Modeling and numerical methods

2.1. Problem formulation

In this work, transverse flow through a porous media is modeled as a flow through unidirectional fiber filaments with circular cross sections. By distributing fibers in desired configurations, one may mimic the fiber bed with various microstructures. A general configuration of fibers in the bi-periodic domain has been described in Fig. 1. The Cartesian x and y coordinates are selected to parallel and normal to the flow direction. The computational domain, denoted by Ω, has four boundaries, which are denoted by Γ_i $(i = 1, 2, 3, 4)$. We use the symbol B_i $(i = 1, 2, 3\ldots, N)$ to denote a region occupied by the ith fiber with N being the number of fibers and the symbol B for the collective regions occupied by fibers. The periodic boundary conditions in the horizontal and vertical direction allow a unit cell description in fiber arrangement, minimizing finite-size domain and avoiding unwanted effects of boundary condition such as fluid-wall interactions. In our model, the constant pressure drop is imposed in the horizontal direction.

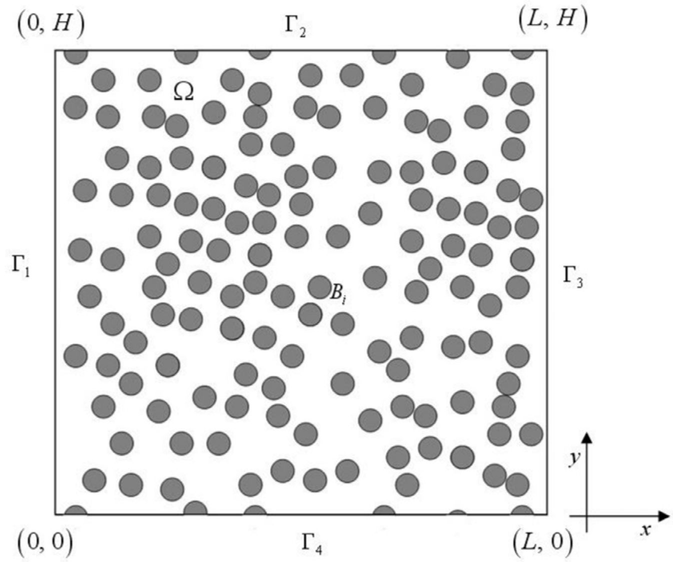

Fig. 1. The bi-periodic representative unit computational domain for modeling cross-sectional microstructure in unidirectional fibrous media.

For the viscoelastic flow across the porous bed, the onset of viscoelastic effects can be conveniently represented in terms of a normalized flow resistance *fRe*:

$$fRe = \frac{Q_{Newtonian}}{Q_{Viscoelastic}}, \tag{1}$$

where $Q_{Viscoelastic}$ is the flow rate of viscoelastic flow which pass through the porous specimen under a given pressure drop, and $Q_{Newtonian}$ is the corresponding flow rate yielded with a Newtonian fluid.

The Weissenberg number *Wi* for measuring the elasticity in viscoelastic flows is defined as the characteristic shear rate times the relaxation time and the characteristic shear rate is closely related with the local porous architecture. Fig. 2 shows two different regular arrangements of fibers (square and hexagonal packing), which will be studied intensively throughout this work. One can define the Weissenberg number in these two typical regular packing structures as:

$$Wi = \lambda\dot{\gamma} = \lambda\frac{Q}{2\delta^2}, \tag{2}$$

where the λ is the relaxation time. The characteristic shear rate $\dot{\gamma}$ in the porous media is expressed in term of the flow rate Q and the characteristic pore length δ. As for the problem of square and hexagonal packing structure as indicated in Fig. 2(a) and (b), the typical pore length δ is:

$$\delta = \frac{1}{2}H - \sqrt{\frac{V_f HL}{N\pi}}. \tag{3}$$

V_f is the fiber volume fraction; L and H are the dimensions of the computational domain. The symbol N denotes the number of fibers in the unit cell where $N = 1$ for the square packing