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Pore-scale modeling of viscoelastic flow in porous media using a Bautista–Manero fluid

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ABSTRACT

This article examines the extensional flow and viscosity and the converging–diverging geometry as the basis of the peculiar viscoelastic behavior in porous media. The modified Bautista–Manero model, which successfully describes elasticity, thixotropic time dependency and shear-thinning, was used for modeling the flow of viscoelastic materials which also show thixotropic attributes. An algorithm, originally proposed by Philippe Tardy, that employs this model to simulate steady-state time-dependent flow was implemented in a non-Newtonian flow simulation code using pore-scale modeling. The simulation results using two topologically-complex networks confirmed the importance of the extensional flow and converging–diverging geometry on the behavior of non-Newtonian fluids in porous media. The analysis also identified a number of correct trends (qualitative and quantitative) and revealed the effect of various fluid and flow parameters on the flow process. The impact of some numerical parameters was also assessed and verified.

1. Introduction

The study of the flow of non-Newtonian fluids in porous media is of immense importance and serves a wide variety of practical applications in processes such as enhanced oil recovery from underground reservoirs, filtration of polymer solutions, and soil remediation through the removal of liquid pollutants. Viscoelasticity and thixotropy are two of the main features of non-Newtonian behavior. They are usually associated with the polymeric substances that are widely used in petroleum industry, chemical engineering systems, and many other scientific and industrial applications. Despite the fact that a massive amount of literature on these subjects do exist, there are few attempts to model these phenomena in connection with the flow through porous media. This is partly due to the mathematical complexity of these fluid models. Further difficulties are usually encountered in modeling the flow through porous media especially morphologically-complex ones.

In the recent years, a number of researchers have used pore-scale network modeling to describe the flow of complex fluids in porous media. In this context, Lopez et al. (2003), Lopez and Blunt (2004) investigated single- and two-phase flow of shear-thinning fluids in porous media using Carreau model in conjunction with network modeling. Sochi and Blunt (2008) followed a similar approach in their investigation of single-phase flow of Ellis and Herschel–Bulkley fluids through porous media. Balhoff and Thompson (2004, 2005) used a network model extracted from a computer-generated random sphere packing to investigate various aspects of non-Newtonian flow in packed beds. In this article we adopt pore-scale network modeling using two random networks to simulate the flow of Bautista–Manero fluids in porous media. Bautista–Manero is a reasonably-sophisticated model that is capable of describing various aspects of viscoelasticity and thixotropy among other non-Newtonian attributes.

1.1. Non-Newtonian fluids

Non-Newtonian fluids are commonly divided into three broad groups: time-independent, viscoelastic and time-dependent

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Nomenclature

Note: Units, when relevant, are given in the SI system. Vectors and tensors are marked with boldface. Some symbols may rely on the context for unambiguous identification.

$\dot{\gamma}$	strain rate (s^{-1})
$\dot{\boldsymbol{\gamma}}$	rate-of-strain tensor
λ	structural relaxation time in Fredrickson model (s)
λ_1	relaxation time (s)
λ_2	retardation time (s)
μ	viscosity (Pa s)
μ_0	zero-shear viscosity (Pa s)
μ_∞	infinite-shear viscosity (Pa s)
τ	stress (Pa)
$\boldsymbol{\tau}$	stress tensor
f_e	scale factor for the entry of corrugated tube (–)
f_m	scale factor for the middle of corrugated tube (–)
G	geometric conductance (m^4)
G'	flow conductance ($m^3\ Pa^{-1}\ s^{-1}$)
G_o	elastic modulus (Pa)
k	parameter in Fredrickson model (Pa^{-1})
L	tube length (m)
P	pressure (Pa)
ΔP	pressure drop (Pa)
Q	volumetric flow rate ($m^3\ s^{-1}$)
r	radius (m)
R	tube radius (m)
R_{eq}	equivalent radius (m)
R_{max}	maximum radius of corrugated capillary
R_{min}	minimum radius of corrugated capillary
t	time (s)
$\mathbf{v}$	fluid velocity vector
$\nabla\mathbf{v}$	fluid velocity gradient tensor
V	fluid speed ($m\ s^{-1}$)
δx	small change in x (m)
$\overset{\triangledown}{}$	upper convected time derivative
$(\cdot)^T$	matrix transpose
x_l	network lower boundary in the non-Newtonian code
x_u	network upper boundary in the non-Newtonian code

(Skelland, 1967; Chhabra and Richardson, 1999). The first group is characterized by the fact that the strain rate at a given point is solely dependent upon the instantaneous stress at that point. The second group includes the fluids that show partial elastic recovery upon the removal of a deforming stress. The third group consists of those fluids for which the strain rate is a function of both the magnitude and the duration of stress and possibly of the time lapse between consecutive applications of stress. A large number of models have been proposed in the literature to model all types of non-Newtonian fluids under various flow conditions. Most these models are basically empirical in nature and arise from curve-fitting exercises (Barnes et al., 1993).

1.2. Viscoelastic fluids

Viscoelastic substances exhibit a dual nature of behavior by showing signs of both viscous fluids and elastic solids. Polymeric fluids often show strong viscoelastic effects, which can include shear-thinning, extension thickening, viscoelastic normal stresses, and time-dependent rheology. The equations describing the flow of viscoelastic fluids consist of the basic laws of continuum mechanics and the rheological equation of state describing a particular fluid and relates the viscoelastic stress to the deformation history. Many differential and integral viscoelastic constitutive models have been proposed in the literature to describe the the observed viscoelastic phenomena. What is common to all these is the presence of at least one characteristic time parameter to account for the fluid memory (Larson, 1988, 1999; Keunings, 2004; Owens and Phillips, 2002).

The behavior of viscoelastic fluids is drastically different from that of Newtonian and inelastic non-Newtonian fluids. This includes the presence of normal stresses in shear flows, sensitivity to deformation type, and memory effects such as stress relaxation and time-dependent viscosity. These features underlie the observed peculiar viscoelastic phenomena such as rod-climbing (Weissenberg effect), die swell and open-channel siphon (Boger, 1987; Larson, 1988).

The behavior of viscoelastic fluids at any time is dependent on their recent deformation history, that is they possess a fading memory of their past. Indeed a material that has no memory cannot be elastic, since it has no way of remembering its original shape. Many materials are viscoelastic but at different time scales that may not be reached. Therefore the concept of a natural time of a material is important in characterizing the material as viscous or elastic. The ratio between the material time scale and the time scale of the flow is indicated by a non-dimensional number: the Deborah or the Weissenberg number (Barnes et al., 1993; Boger, 1987; Bird et al., 1987; Larson, 1988).

A common feature of viscoelastic fluids is stress relaxation after a sudden shearing displacement where stress overshoots to a maximum then starts decreasing exponentially and eventually settles to a steady-state value. This phenomenon also takes place on cessation of steady shear flow where stress decays over a finite measurable length of time. A defining characteristic associated with stress relaxation is the relaxation time which may be defined as the time required for the shear stress in a simple shear flow to return to zero under constant strain condition (Bird et al., 1987; Deiber, 1978; Larson, 1988).

1.3. Important aspects for viscoelastic flow in porous media

In the last few decades, a general consensus has emerged that in the flow of viscoelastic fluids through porous media elastic effects should arise, though their precise nature is unknown or controversial. Strong experimental evidence indicates that the flow of viscoelastic fluids through packed beds can exhibit rapid increases in the pressure drop, or an increase in the apparent viscosity, above that expected for a comparable purely viscous fluid. This increase has been attributed to the extensional nature of the flow field in the pores caused by the successive expansions and contractions that a fluid element experiences as it traverses the pore space. Even though the flow field at pore level is not an ideal extensional flow due to the presence of shear and rotation, the increase in flow resistance is referred to as an extension thickening effect (Phan-Thien and Khan, 1987; Plog, 2002; Deiber and Schowalter, 1981, Pilitsis and Beris, 1989).

There are two major interrelated aspects that have strong impact on the flow through porous media. These are extensional flow and converging–diverging geometry.

1.3.1. Extensional flow

One complexity in the flow in general and through porous media in particular usually arises from the coexistence of shear and extensional components; sometimes with the added complication of inertia. Pure shear or elongational flow is very much the