Chemical Engineering Science 99 (2013) 81–88

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

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

Redirection and channelization of power-law fluid flow in a rough-walled fracture

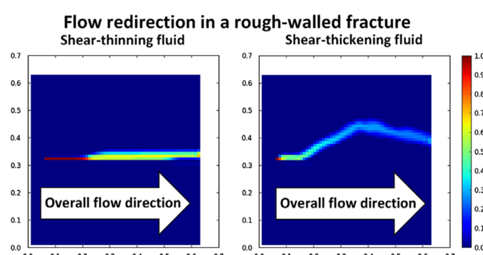
Alexandre Lavrov *

SINTEF Petroleum Research, Formation Physics Department, Trondheim, Norway

HIGHLIGHTS

- Flow of a non-Newtonian fluid in a rough-walled fracture is modeled numerically.
- Varying the exponent of the power-law fluid changes the flow field.
- Reducing the exponent of the power-law fluid leads to channelization of flow.
- This has implications for dye transport and geometric dispersion in the fracture.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form
15 May 2013
Accepted 23 May 2013
Available online 4 June 2013

Keywords:
Non-Newtonian fluids
Petroleum
Transport processes
Porous media
Computation
Fracture

ABSTRACT

Flow of non-Newtonian fluids in rough-walled rock fractures is common in many technological processes in oil and gas industry. A numerical study of power-law fluid flow in rough-walled fractures is carried out under the assumptions of the lubrication theory approximation. It is shown that, in a self-affine fracture, varying the exponent of the power-law fluid may lead to a redirection of flow compared to a Newtonian fluid flow field. This effect is observed even though the fracture landscape is isotropic, i.e. no preferential flow paths have been created in the model by e.g. relative displacement of the fracture faces. In another fracture, one that contains an obstacle represented by a spot of zero aperture, the spread of the flow around the obstacle is again controlled by the power exponent of the fluid. The fluid being more shear-thinning leads to a channelization of the flow in such a fracture. "Channelization" here refers to the fluid velocity component in the direction of the applied pressure gradient becoming larger as compared to the velocity component in the direction normal to the overall flow direction as the fluid becomes more shear-thinning. A channelization is also observed in a fracture containing a local zone of an elevated aperture. The effects of rheology on the spread and redirection of flow in a fracture of variable aperture are crucial for optimization of transport and placement of particles or tracers in natural and man-made fractures.

1. Introduction

Flow of non-Newtonian fluids (either yield-stress or power-law) in rough-walled fractures is common in many processes in petroleum and drilling engineering as well as in nature. Examples include flow of drilling fluids into geological fractures during drilling in naturally-fractured reservoirs (e.g. carbonates); flow of polymer solutions into artificially induced hydraulic fractures during well stimulation; flow of heavy oils (Lavrov, in press-a). In particular, liquids of power-law rheology are commonly used in hydraulic fracturing in oil and gas industry. Hydraulic fracturing is a well stimulation technique. The fracturing fluid is injected from the wellbore into the rock in order to create fractures that would provide high-permeability conduits for reservoir fluids to flow

* Tel.: +47 73591181.
E-mail address: Alexandre.Lavrov@sintef.no

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.05.045

toward the well. The fracturing fluid also delivers a granular material (proppant) that is placed in the fracture in order to prevent it from closing after the pumping stops. After the fractures have been created and propped, the polymer breaks and the fluid is flown back into the well. The fractures are then ready to produce hydrocarbons from the reservoir. The dimensions of hydraulic fractures can be tens or hundreds of meters in length, with the aperture measuring typically millimeters. “Aperture” here refers to the fracture opening, i.e. the distance between fracture surfaces in the direction perpendicular to the nominal fracture plane. This parameter is sometimes also called “fracture width” in hydraulic fracturing literature.

The multi-scale nature of hydraulic fractures becomes a challenge when fluid flow and particle transport in these systems are simulated numerically. The productivity of a well stimulated by the described technology is largely determined by the outcome of the hydraulic fracturing that, in turn, depends on how accurately the flow of non-Newtonian fluid in the fracture can be predicted at design stage. It is therefore essential to understand the flow of non-Newtonian fluids in rough-walled conduits such as rock fractures in order to be able to optimize hydraulic fracturing and other processes involving polymer flow in oil and gas industry.

Surfaces of natural or man-made fractures in rocks have generally irregular self-affine landscapes characterized by a fractal dimension (or Hurst exponent) and the rms variation of the aperture [see e.g. Amitrano and Schmittbuhl (2002) and references therein]. The average opening of the fracture is represented by the average fracture aperture, i.e. the aperture averaged over a representative area of the fracture surface. Both the average fracture aperture and the rms of the fracture aperture control the hydraulic permeability of the fracture (Brown, 1987). A great deal of experimental and numerical efforts have been invested into the studies of Newtonian fluid flow in geological fractures (e.g. Brown, 1987; Oron and Berkowitz, 1998; Zimmerman et al., 1991; Pyrak-Nolte and Morris, 2000; Koyama et al., 2008). A recent review by Lavrov (in press-a) reveals that only a few such studies have been performed on non-Newtonian power-law fluids flowing in conduits of varying aperture in general and even fewer in conduits with irregular wall profiles typical of fractures in rocks, in particular. Typically, regular (e.g. sinusoidal) wall profiles have been assumed in the earlier numerical studies of power-law fluid flow in conduits of varying aperture (Yalamanchili et al., 1995; Hron et al., 2000; Di Federico, 1997; Shankaran, 2007). Such conduits are of interest for e.g. blood flow but are hardly representative for rough-walled fractures in rocks. Only a few studies touched upon power-law fluid flow in rough-walled fractures, e.g. Auradou et al., 2008, 2010. In the experiments by Auradou et al. (2008, 2010), fracture faces were two identical self-affine surfaces displaced relative to each other, thereby providing a variation in the local aperture. The aperture distribution was thus anisotropic in the fracture plane in these studies. In a recent numerical study on power-law fluid flow by Lavrov (2013b), fractures with isotropic self-affine surfaces were employed to evaluate the effects of fracture geometry and fluid rheological properties on the equivalent hydraulic aperture of a rough-walled fracture.

The objective of this study is to take a closer look at details of power-law fluid flow in a rough-walled fracture, by means of numerical modeling.

The novelty of this work is as follows. Channelization and redirection of power-law fluid flow in a conduit with irregular rough self-affine walls is shown for the first time numerically, to the best of the author's knowledge. “Channelization” here refers to the fluid velocity component in the direction of the applied pressure gradient becoming larger as compared to the velocity component in the direction across the overall flow direction as the fluid becomes more shear-thinning. “Redirection” here refers to redirection as compared to the flow field obtained with a Newtonian fluid. It should be emphasized that a Newtonian fluid flow itself is redirected by asperities (e.g. Koyama et al., 2006). As an extreme example, if an asperity protrudes so as to block the flow, the fluid will be redirected and will go around it, no matter if it is non-Newtonian or Newtonian. The present study does not imply that a Newtonian fluid is not redirectd when it flows on a rough landscape, but that the power-law fluid is redirected as compared to its Newtonian counterpart.

In an earlier work by Auradou et al. (2008, 2010), where channelization of a shear-thinning fluid was observed experimentally, an anisotropic fracture landscape was employed. The present study is, to our best knowledge, the first attempt to numerically investigate details of power-law fluid flow in irregular rough-walled conduits with isotropic landscapes. It is recognized that some less detailed studies were carried out earlier, in particular studying the equivalent hydraulic aperture of such conduits (Di Federico, 1997; Lavrov, 2013b).

In Section 2, the numerical model is described. The results are presented and discussed in Section 3. Conclusions are provided in Section 4.

2. Numerical model

Steady incompressible flow of a pure-power-law fluid in a fracture of variable aperture is considered. The fracture has a square shape in its nominal plane (Fig. 1); gravity is neglected, which can be interpreted as the fracture plane being horizontal, with the gravity vector normal to page in Fig. 1. The fluid rheology is given by

$$\tau_{ij} = C\dot{\gamma}^{n-1}\dot{\gamma}_{ij} \tag{1}$$

where τ_{ij} is the shear stress; $\dot{\gamma}_{ij}$ is the shear rate; C is the consistency index; n is the power exponent; and

$$\dot{\gamma} = \sqrt{2\mathbf{D}:\mathbf{D}} \tag{2}$$

where $\mathbf{D}$ is the strain rate tensor. At $n<1$, the fluid is shear-thinning; at $n>1$, the fluid has shear-thickening behavior. Eq. (1) has been commonly employed to describe the rheology of polymer solutions in hydraulic fracturing (e.g. Clifton and Abou-Sayed, 1979; Adachi et al., 2007; Eskin, 2009; Lakhtychkin et al., 2012; Wong et al., 2013) even though some other models e.g. Carreau fluid or Cross fluid, might provide a more accurate description of the fluid behavior at low shear rate (Shah and Yortsos, 1995).

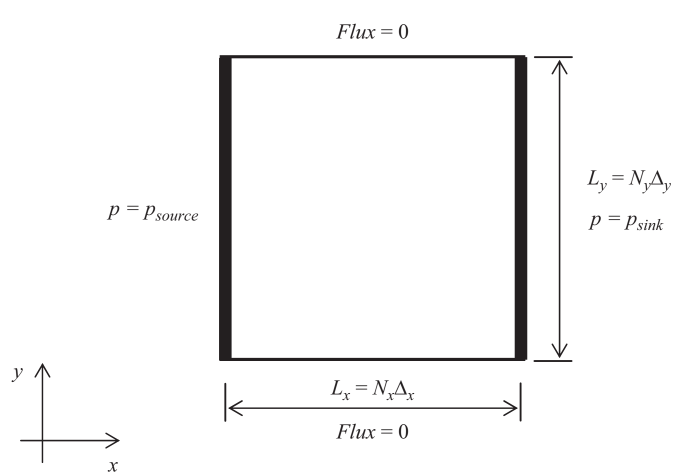


Fig. 1. Geometry of the fracture used in numerical simulations. Pressure boundary conditions are applied on the highlighted boundaries.