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Engineering performance of additives in water floods

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ABSTRACT

The viscosity of a chemically modified injector fluid measured in a rheometer is a poor indicator of behaviour in the reservoir i.e. pressure driven permeable flow. The three classical types of viscosity assessment are only linked for a rather restricted set of conditions. Increasing use of non-Newtonian injection fluids involves additional permeable flow resistance components over and above that attributable to shear viscosity. The main two sources are viscoelastic and extensional viscosity effects. We review these and show how extra effects can also be observed in aperture flow. Undeveloped conduit flow as observed in fractures is the linking feature between resistance to flow in pipes and resistance to flow in porous media.

1. Introduction

Secondary oil recovery is limited by the “sweep” – the ability of injected water to uniformly permeate all regions of the reservoir and displace oil towards a production well. In regions of high permeability, water can break through to the production well. Such regions of high permeability consist either of enhanced permeability rock matrix or fractures giving rise to “short circuits” between the injector and producer wells.

Rheological additives are used to overcome such problems. These change the viscosity of injected water to optimise various hydrocarbon production mechanisms. The oil-displacing fluid (usually water based) should restrict flow in high permeability regions. This leaves the lower permeability regions more accessible for banks of water to displace oil there (Lake, 1989). Near the well bore low viscosity is required in order to aid injection. A recent development has been fluids which selectively thicken in regions of high permeability while remaining thin in regions of low permeability (Golombok and van der Wijst, 2013; Golombok et al., 2008).

The behaviour of such non-Newtonian fluids cannot, strictly speaking, be described by the Darcy equation. Nonetheless, for application, the independent controlled variable is still that associated with Darcy flow: the pressure drop (Δp) which determines the fluid flow (Q) so that transport is described by a resistance factor (R_{tot})

$$\Delta p = R_{tot}(R_{geo},\ R_{fl})\,Q \tag{1}$$

for both flow through a porous medium or a fracture or a combination of both. This total resistance is a function of a geometric structure factor (R_{geo}) and a fluid resistance factor (R_{fl}). For Newtonian fluids, the total resistance is a product i.e. $R_{tot}=R_{geo}\bullet R_{fl}$. The geometric resistance factor (R_{geo}) can be identified with the inverse of the medium conductivity i.e. $R_{geo} = L/A\kappa$ where L is the length of the medium, A the cross sectional area and κ is the permeability. The fluid resistance factor (R_{fl}) located in the second flow resistance term is, for example in Darcy flow, associated with the (shear) viscosity. However, more generally, these fluid properties can consist of a number of components

$$R_{fl} = R_{fl}(R_{vis},\ R_{ex},\ R_{el}) \tag{2}$$

where R_{vis} is a viscous component traditionally associated with the shear viscosity, R_{ex} an extensional (also called elongational) viscous term and R_{el} an elastic component associated with continual changes in pore dimensions.

These extra fluid properties are not normally considered in discussions of rheological additives to injection fluids. Nonetheless they are a considerable component of the resistance which such a fluid experiences during flow through a permeable medium particularly for materials such as polymers or even novel non-polymeric additives. The application aim is to engineer a particular desired response from a fluid when it flows through a 3 D structure of spatially varying permeability (such as in the water based displacement of oil in reservoirs). These parameters (R_{ex}, R_{el})

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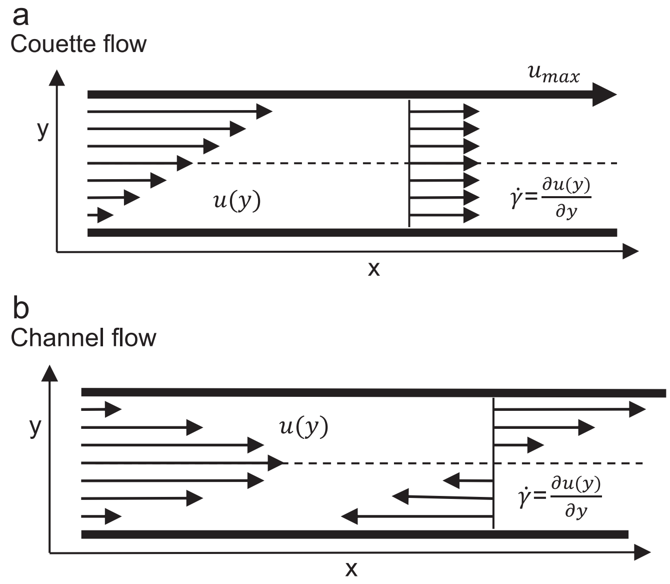

Fig. 1. Two types of fluid velocity profiles. (a) Velocity profile and shear rate for Couette flow. The width is in the *y*-direction. (b) Velocity profile and shear rate for Poiseuille flow. The width is in the *y*-direction, the length in the *x*-direction and the height of the conduit is perpendicular to the plane of the drawing.

provide extra levers for controlling this flow and yield better conformance. The challenge is to “tune” the fluid to have maximum resistance at the highest permeability regions of the reservoir. This may require different formulations depending on whether the main problem at regions of high permeability is fractures or highly permeable porous matrix. A fluid flow resistance which has these extra resistance components above the shear viscosity thus displays an “apparent” viscosity better characterised as a fluid resistance to flow. This apparent viscosity is equal to the shear viscosity in the case of a Newtonian fluid (Gonzalez et al., 2005; Rojas et al., 2008).

In this paper we discuss the problem of applying classical Couette cell measurements to predicting the viscous effects in permeable media including fracture flow. It is not obvious why the Couette cell is so widely used as it is clearly of limited utility for predicting pressure driven flow, particularly for non-Newtonian fluids (Delshad et al., 2008; Lake, 1989). A Couette cell has a single unique shear rate imposed by the movement of the wall (Fig. 1(a)). In contrast, in a pressure driven flow such as in a conduit, the shear rate varies across the opening (Fig. 1(b)). Non-Newtonian fluids can have a shear rate–viscosity dependence. Therefore, the variability of shear across the opening of a conduit leads to a variation of viscosity across the opening. In a reservoir the shear within a pore or fracture also changes due to constant varying aperture size. A pressure induced flow then leads to a spatial variation of viscosities within the pores or fracture.

The motivation for comparing the apparent viscosity in each of these cases is to be able to better predict the viscosity (fluid resistance) under conditions of intended application. One can thus envision a continuum of effects going from for example, Couette flow, to capillary, slit, fracture and porous medium flow situations. Our aim is to analyse how the first flow measurement (a standard for testing formulations) can effectively be used for real rock flow performance. In Section 2 we consider the limitations of the standard Couette assessment and review how these are currently applied to predicting flow in capillaries and permeable media. Section 3 reviews the permeability concept for 1 and 2 dimensional fully developed flow as well as the problem of developing flow. Fully developed flow is found in artificial fractures such as plate flow and capillaries. Continually developing flow concepts are applicable to permeable flow because of the continual change in the effective aperture–the result is an increase in the effective pressure drop. A consideration of flow in non-parallel conduits introduces extensional and viscoelastic effects which we consider in Section 4. Section 5 demonstrates the effects experimentally using non Newtonian materials with shear induced structures. The experimental work has been divided in three parts: First a standard approach using a couette cell rheometer is applied. Secondly fluid flow through simple smooth parallel conduits are considered and thirdly it is shown that the viscoelastic material used in this study gives a much higher fluid flow resistance in a converging/diverging section (as in pore throats) due to extensional and viscoelastic effects. This provides the framework for understanding the behaviour of non-Newtonian fluids being assessed for application in oil recovery.

2. Microscopic behaviour

When testing different additive formulations for enhanced oil recovery (EOR) purposes, rheology data is derived from static viscometry data. This is typically a Couette cell where a constant shear rate can be applied across the whole fluid (Delshad et al., 2008; Lake, 1989). As described above, the resulting data is in the form of (shear) viscosity (μ) as a function of the applied shear rate ($\dot{\gamma}$). This can give some indications of the desirability of a particular formulation for application in oil recovery processes. For example, shear thinning behaviour would be of interest as it means that there will be good injectivity. A region of shear thickening in a generally shear thinning medium (such as is observed in some hydrolysed polyacrylamide (HPAM) materials) (Delshad et al., 2008) has potential as a high injectivity material which nonetheless will be slowed down in regions of high permeability. This would lead to better conformance control and prevention of water breakthrough by channelling. Another example is the class of non-polymeric viscoelastic materials which display shear induced structures (Cressely and Hartmann, 1998).

In a Couette cell there is a single well defined shear determined by the velocity of a moving cylinder wall while the inner cylinder wall is not moving (Fig. 1(a)). The shear rate is defined by the velocity of the moving plate (u_{max}) divided by the separation width (w), in this case in the y direction, of the 2 plates

$$\dot{\gamma} = \frac{\partial u}{\partial y} = \frac{u_{max}}{w} \tag{3}$$

In a porous medium by contrast, there is no unique value of shear. Even for a highly simplified model medium represented by a capillary or hydraulic radius model there is no unique shear associated with a particular pressure drop and flow rate. Rather in conduit (pipe, capillary or fracture) flow of a Newtonian fluid, the shear rate is proportional to the width or radial displacement from the centre line. For a rectangular conduit of infinite height (Fig. 1 (b)) this becomes

$$\dot{\gamma} = \frac{\partial u}{\partial y} = -\frac{1}{2\mu}\frac{\Delta p}{\Delta x}(w - 2y) \tag{4}$$

The shear rate varies across the opening. Any deviation from the Newtonian case therefore experiences widely varying shear rates even within an idealised conduit. However, the macroscopic bulk observed resistance factor will always be different from the microscopic Couette value except for the idealised Newtonian case.

Nonetheless, reservoir engineers use the Couette viscosity definition (Eq. 3) transplanted onto a porous medium to assess fluid flow in a reservoir (Lake, 1989). Bulk term equivalents are used on