FLOW OF SHEAR THINNING POLYMER SOLUTIONS IN HETEROGENEOUS POROUS MEDIA: TRACER DISPERSION MEASUREMENTS

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INTRODUCTION

In many natural rocks, a large polydispersity of pore size is frequently encountered which leads to large fluctuations of the velocity and to increased dispersion of passive tracers [1]. If the fluid flowing inside the porous medium has shear thinning properties, the velocity fluctuations are enhanced: in the zones of large permeability where the shear rates are large, the effective viscosity is low, and the velocity is higher than for Newtonian fluids. On the contrary, in the zones of low permeability where the shear rates are low and thus the viscosity high, the velocity is smaller. In the present paper we investigated the case of shear thinning polymer solutions in a model of heterogeneous media made of a packing of porous grains [2] and [3]. The rheological properties of polymer solutions have been characterised by the exponent α of the power law relating the shear viscosity to the shear rate. Tracer dispersion has been measured in a broad range of flow-rates for α varying between 0.4 to 0.77 (note that the polymer concentration remains constant during all the tracer dispersion measurements).

1 MATERIALS AND METHODS

The polymer used is a rigid polysaccharide: scleroglucan [4]. We chose it because of its non-ionic character which leads to rheological properties in solution quite independent of the salt content. The solutions have been carefully prepared by slow dissolution, controlled stirring and filtration through millipore membranes. The shear thinning behaviour

has been characterised by the exponent of the power law which relates the decrease of the shear viscosity to the shear rate ($\eta \cong \dot{\gamma}^{-\alpha}$) in a large range of shear rates (typically between 10^{-1} and 10^2 s^{-1}).

The double porosity material is prepared by grinding a block of sintered glass beads. Prior to sintering, the glass beads are carefully cleaned and sieved in order to have a diameter as uniform as possible: $d_b \cong 110\ \mu m$. The block obtained at the end of the sintering operation is grinded and the material sieved to obtain constant size grains. In our sample, the grains are almost spherical and their mean diameter is $500\ \mu m$.

The present study has been done with a sintered block of high porosity $\cong 30\%$ which is expected to represent the internal porosity Φ_{int} of the final grain. In such materials, the minimum diameter of the flow channels inside the grains will be the order of $20\ \mu m$: this is larger than the contour length of a polymer molecule, so that the solution can be considered as a continuous fluid. The porous grains are packed into a vertical cylinder (24 mm in internal diameter and 86 mm in length). The porosity associated with the flow paths outside the grains Φ_{ext} is of the order of 37% as for non-consolidated samples. The ratio of the permeabilities of the flow paths inside and outside the grains for Newtonian fluids is about:

$$\varepsilon = \frac{k_{int}}{k_{ext}} = \left(\frac{\Phi_{int}}{\Phi_{ext}}\right)^3 \frac{d_b^2}{d_g^2} \cong \frac{1}{39} \qquad (1)$$

We use NaNO$_3$ with a variable concentration (between 1 g/l and 2 g/l) as a tracer in the scleroglucan solutions. The concentration of NaNO$_3$ is determined from conductivity measurements; great care was taken to ensure an abrupt variation of the tracer concentration at the inlet. The dispersion coefficient K was determined fitting the concentration

variation at the outlet with the solution of "Gaussian" convection diffusion equation [1]. The molecular diffusion of the tracer D_m is independent of the polymer concentration and is taken equal to 1.15×10^{-9} m²/s [5].

2 RESULTS AND DISCUSSION

The inset in Figure 1 displays the dependence of the normalised dispersivity $K/Ud_g = l_d/d_g$ on the Péclet number $Pe = Ud_g/D_m$ for Newtonian fluids (water and water-glycerol mixture). Depending on the Péclet number, three distinct behaviours are expected. For low Péclet numbers, $Pe < Pe^*$, tracer dispersion is controlled by molecular diffusion, K is constant and the normalised dispersivity decreases as Pe^{-1}. For intermediate values of the Péclet number, $Pe^* < Pe < Pe^{**}$; inside the grains, the displacement of the tracer is still controlled by diffusion, although outside the grains, convection is dominant. If the geometrical dispersion along the backbone is neglected, the dispersivity can be predicted from a simplified statistical model involving two paths in parallel, a slow one (the inside of a grain) and a fast one (the outside of a grain) [3]. Finally, for large Péclet numbers,

$Pe > Pe^{**}$, convective displacement is dominant inside and outside the grains. Neglecting the Taylor dispersion, the normalised dispersivity is then expected to be constant. Since the velocity in the backbone V is much larger than the velocity inside the grains, $V \cong U$, thus, $Pe^* \cong 1$ and $Pe^{**} \cong 1/\varepsilon \cong 1/39$ for the sample investigated here. This analysis leads to a good description of the whole variation observed experimentally (see insert in Figure 1).

Let us now consider the case of non Newtonian shear-thinning fluids. For all the values of the exponent α characterising the viscosity, the velocity inside the grains v is very low compared to the velocity outside the grains V; thus, $V \cong U$ and Pe^* remains of the order of 1 as for Newtonian fluids. On the contrary, the value of Pe^{**} which corresponds to the cross-over from diffusive to convective displacements inside the grains, increases rapidly with α. Indeed, since the shear rate inside the grains ($\cong v/d_b$) is smaller than the shear rate outside the grains ($\cong V/d_g$), the apparent viscosity is larger inside the grains than in the backbone. This leads to an increase of the velocity contrast and, thus, to an increase of Pe^{**}. In the frame of the model of two paths in parallel [2]:

$$Pe_\alpha^{**} \cong 1/\varepsilon_\alpha \cong 1/\varepsilon^{(2-\alpha)/(2-2\alpha)} \qquad (2)$$
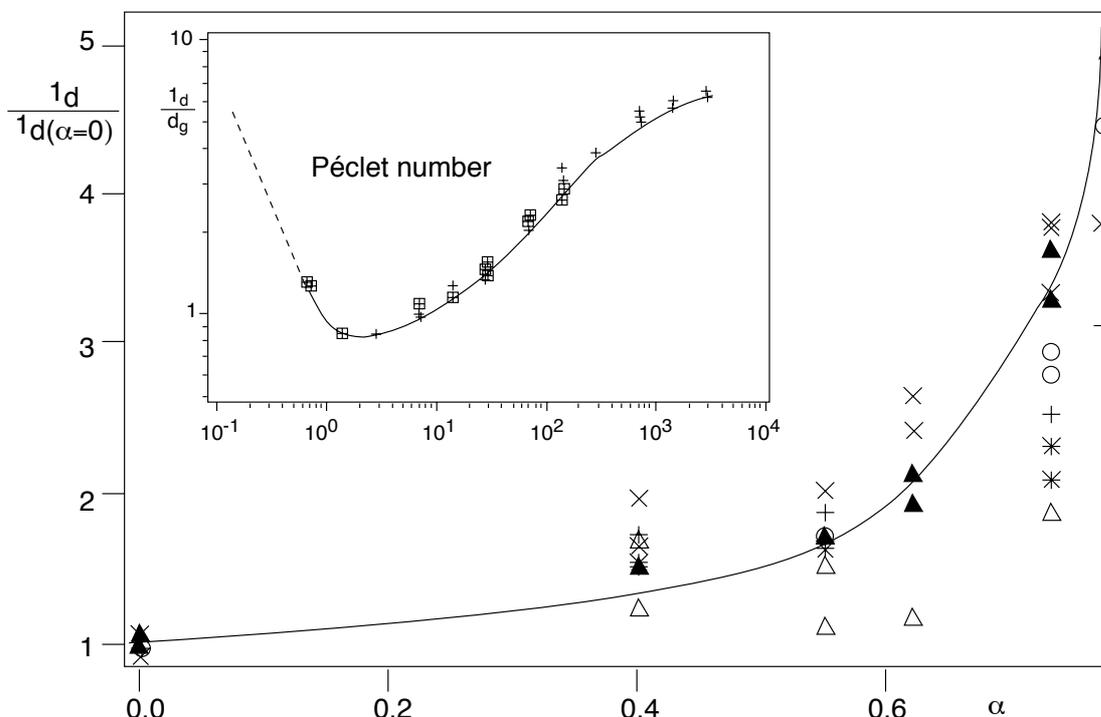

Figure 1

Variation of the dispersivity divided by the dispersivity measured with for Newtonian fluids $l_d/l_{d(\alpha = 0)}$ as a function of the characteristic exponent α for various Péclet number $Pe = Ud_g/D_m$.

(Δ): Pe = 0.7, (O): Pe = 2.8, (▲): Pe = 7, (×): Pe = 28, (+): Pe = 70, (✻): Pe = 280.

Inset: Variation of the normalised dispersivity $K/Ud_g = l_d/d_g$ as a function of the Péclet number for Newtonian fluids.

(⊞): pure water, (+): glycol-water mixture, (–) theoretical predictions.

Practically, under our experimental conditions, when α became larger than 0.5, Pe** is larger than the highest Pe accessible experimentally.

Figure 1 displays the variation of the normalised dispersivity divided by its value for $\alpha = 0$, $l_d/l_{d(\alpha = 0)}$, as a function of α. For the lowest Pe number (Pe = 0.7), Pe is smaller than Pe*, and $l_d/l_{d(\alpha = 0)}$ is almost constant. This is in agreement with the value expected in the limit Pe < Pe* since tracer dispersion is then everywhere controlled by diffusion, the dispersivity is independent of the flow field. For intermediate Péclet numbers (2.8 < Pe < 28), a large increase of $l_d/l_{d(\alpha = 0)}$ is observed. Péclet numbers range then between Pe* and Pe_α** for all the values of α; the tracer displacement is diffusive inside the grains and convective outside. The simplified model of two paths in parallel does not predict the increase observed which, thus, has to be related to geometrical dispersion along the backbone or to large heterogeneities in the sample. Experiments using echo measurement of the dispersivity are under progress and will help to clarify this point. Finally, for the largest Pe numbers (Pe $\geq$ 70), $l_d/l_{d(\alpha = 0)}$ first increases as for the intermediate values of the Péclet number and levels off at higher values of α. The variation observed is more difficult to interpret since then, depending on α, Pe is larger or smaller than Pe_α**.

CONCLUSION

In the present work, we have demonstrate that tracer dispersion measurement, in which the polymer content is kept constant, is a powerful method to investigate the structure flow in porous media. The large increase of the dispersivity observed as α increases, shows the high sensitivity of the results to the degree of the shear viscosity non linearity which can be tuned simply changing the polymer concentration. Macromolecular or colloidal systems having different type of rheological properties (for instance, having large normal stress difference or large elongational viscosity) will also be interesting to investigate provided their adsorption properties and their compatibility with the porous medium are controlled.

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