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Miscible transfer of solute in different model fractures: From random to multiscale wall roughness

Transport miscible de solutés dans différentes fractures modèles : influence de la rugosité aléatoire ou multiéchelles

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ABSTRACT

Miscible tracer dispersion measurements in transparent model fractures with different types of wall roughness are reported. The nature (Fickian or not) of dispersion is determined by studying variations of the mixing front as a function of the distance travelled but also as a function of the lateral scale over which the tracer concentration is averaged. The dominant hydrodynamic dispersion mechanisms (velocity profile in the gap, velocity variations in the fracture plane) are established by comparing measurements using Newtonian and shear thinning fluids. For small monodisperse rugosities, front spreading is diffusive with a dominant geometrical dispersion (dispersion coefficient $D \propto Pe$ or constant dispersivity $l_d = D/U$) at low Péclet numbers Pe; at higher Pe values, one has either $l_d \propto Pe$ (i.e. Taylor dispersion) for obstacles of height smaller than the gap, or $l_d \propto Pe^{0.35}$ for obstacles bridging the gap. For a self-affine multiscale roughness like in actual rocks and a relative shear displacement $\vec{\delta}$ of complementary walls, the aperture field is channelized in the direction perpendicular to $\vec{\delta}$. For a mean velocity $\vec{U}$ parallel to the channels, the global front geometry reflects the velocity contrast between them and is predicted from the aperture field. For $\vec{U}$ perpendicular to the channels, global front spreading is much reduced. Local spreading of the front thickness remains mostly controlled by Taylor dispersion except in the case of a very strong channelization parallel to $\vec{U}$.

Mots clés :
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RÉSUMÉ

Nous présentons des mesures de dispersion de traceurs dans des modèles transparents de fractures présentant différents types de rugosités de parois. La nature de la dispersion (fickienne ou non) est déterminée à partir de l'évolution du front de mélange en fonction de la distance parcourue, mais aussi en faisant varier la distance transverse sur laquelle la concentration de traceur est moyennée. Les mécanismes de dispersion hydrodynamique dominants (profil de vitesse dans l'ouverture, variations de vitesse dans le plan de la fracture) sont identifiés en comparant des mesures utilisant des fluides newtoniens et

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rhéofluidifiants. Pour des parois avec des rugosités monodisperses de petite taille, l'étalement du front est diffusif et dominé par la dispersion géométrique aux faibles nombres de Péclet *Pe* (coefficient de dispersion $D \propto Pe$ d'où une dispersivité $l_d = D/U$ constante); aux valeurs de *Pe* plus élevées, on a soit $l_d \propto Pe$ (i.e. dispersion de Taylor), pour des obstacles de hauteur plus faible que l'ouverture ou $l_d \propto Pe^{0.35}$, lorsque la hauteur des obstacles est identique à l'intervalle entre les parois. Pour une rugosité autoaffine multiéchelle semblable à celle des roches naturelles et dans le cas de parois de géométries complémentaires, avec un déplacement relatif latéral $\vec{\delta}$, le champ d'ouverture est chenalisé dans la direction perpendiculaire à $\vec{\delta}$. Pour une vitesse moyenne $\vec{U}$ parallèle aux chenaux, la géométrie globale du front reflète les contrastes de vitesses entre ceux-ci et peut être prédite à partir du champ d'ouverture. Lorsque $\vec{U}$ est perpendiculaire aux chenaux, l'étalement global du front est fortement réduit. Quelle que soit la direction du décalage, l'étalement local du front reste contrôlé par la dispersion de Taylor; cependant, lorsque le décalage est trop fort et l'écoulement trop chenalisé, le transfert entre chenaux modifie ce comportement.

1. Introduction

The geothermal reservoir of Soultz-sous-Forêts, like most geological systems, contains structures of various sizes along which flow occurs; three main types of structures were identified: individual fractures, fracture clusters and major faults (Genter et al., 1997). In order to understand these flow systems and help with managerial decisions, large scale numerical models incorporating such heterogeneities have been developed. Yet, when the transport of solutes is involved, the choice of a dispersion law (possibly scale dependent) valid at the scale of an individual fracture remains an open issue (NAS Committee, 1996).

At this scale, tracer dispersion results from the combined action of the complex velocity field (varying both in the gap of the fracture and in its plane) and of mixing by molecular diffusion. The latter allows the tracers to move from one streamline to another and homogenizes the spatial distribution of the tracers. In the classical approach, tracer particles are assumed to perform a random walk superimposed over a drift velocity. The latter is the average of the fluid velocity over an appropriate volume (the representative elementary volume or REV) while smaller scale variations induce tracer spreading. At the REV scale, the average $\bar{C}(x,t)$ of the tracer concentration over a section of the medium normal to the mean displacement satisfies the convection-diffusion equation (Auradou et al., 2005):

$$\frac{\partial \bar{C}(x,t)}{\partial t} = U\frac{\partial \bar{C}(x,t)}{\partial x} + D\frac{\partial^2 \bar{C}(x,t)}{\partial x^2} \tag{1}$$

where D is the longitudinal dispersion coefficient and U the mean velocity of the fluid (parallel to x). The value of D (or equivalently of the dispersivity $l_d = D/U$) is independent of both time and the distance travelled: it is determined by the combined contributions of molecular diffusion and advection. The relative order of magnitude of these two effects is characterized by the Péclet number: $Pe = Ua/D_m$ (D_m is the molecular diffusion coefficient; a is a characteristic length of the medium: here the mean fracture aperture).

Several experimental studies of breakthrough curves of solutes in natural fractures reported in the literature (Keller et al., 1999; Lee et al., 2003; Neretnieks et al., 1982; Park et al., 1997) measured dispersion coefficients increasing linearly with the mean flow U (or with *Pe*). Moreover, the value of the dispersivity $l_d = D/U$ observed agreed with the predictions of a perturbation analysis (Gelhar, 1986). These results suggested that dispersion is controlled (as in 3D porous media (Bear, 1972)) by spreading due to velocity variations associated to the geometry of the void structure. This determines the correlation length of the velocity field, leading to the so-called geometrical dispersion regime. However, flow in fractures is known to be frequently concentrated in long channels of high hydraulic conductance (Brown et al., 1998; NAS Committee, 1996; Tsang and Tsang, 1989). The velocity remains then correlated over distances which may be too large for establishing a Fickian dispersion regime. These previous experiments were all performed for a fixed path length: however, in order to test the validity of the Fickian description, one must measure the variation of the width of the mixing front with time t and check whether it increases, as expected, as $t^{1/2}$.

Another key factor is dispersion resulting from the flow profile in the gap of the fracture: the variation of the velocity between the walls (where it cancels out) and the middle of the gap (where it has a maximal value) stretches the solute front. This creates a concentration gradient across the gap which is balanced by transverse molecular diffusion. The decorrelation of the velocity of the solute is then determined by the characteristic time for the diffusion of solute particles across the gap. This differs from the geometrical regime in which the decorrelation is determined by the geometrical structure of the fracture. Then, the longitudinal dispersivity scales like $l_d \propto Pe$ in this so-called Taylor dispersion (instead of $l_d \sim cst$ for geometrical dispersion).

In fractures, both dispersion regimes are expected to coexist (Detwiler et al., 2000; Ippolito et al., 1993; Roux et al., 1998): at low Péclet numbers (but large enough to neglect pure molecular diffusion), dispersion is controlled by the disordered geometry, while, at higher ones, Taylor dispersion becomes the leading dispersion mechanism.