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Journal Title: Journal de physique. Lettres

Volume: 45
Issue: L
Month/Year: 1984
Pages: 767-until end od article

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Article Title: Article title not provided

Not Wanted Date: 09/04/2004

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J. Physique Lett. **45** (1984) L-767 - L-774 1er AOÛT **1984**, PAGE L-767

Classification
Physics Abstracts
62.90 – 47.55K

Study of miscible fluid flows in a porous medium by an acoustical method

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(*Reçu le 17 mai 1984, accepté le 13 juin 1984*)

Résumé. — Nous présentons des mesures de vitesse du son dans un empilement de billes de verre saturé en un mélange eau-éthanol dont on fait varier la concentration. Le facteur de formation du milieu poreux est ainsi déterminé. Les mesures de vitesse du son nous fournissent alors un moyen de suivre la dépendance en temps de la concentration pendant le déplacement d'un fluide par un autre fluide miscible. La variation du coefficient de dispersion longitudinale avec la vitesse d'écoulement du fluide injecté est alors comparée à la théorie de la dispersion dans les milieux poreux. Les mesures à faibles vitesses d'écoulement conduisent à une valeur du facteur de formation identique à celle déterminée par acoustique.

Abstract. — We present sound velocity measurements in a pack of glass beads saturated with water-ethanol mixtures of various concentrations. We thus determine the formation factor of the porous medium. Then the velocity measurements provide a means of following the time dependence of concentration during the displacement of a fluid by another miscible fluid. The variation of the longitudinal dispersion coefficient for different flow rates is compared to the theory of dispersion in porous media. From measurements at low flow rates, we derive the same value of the formation factor as the one obtained in the preliminary acoustical experiment.

1. Introduction.

Dispersion in porous media (i.e. the mixing which goes along with the flow of miscible fluids) has been the subject of many studies [1, 2]. But most experiments were carried out by using an effluent analysis technique. Here, we present a new acoustical local probe technique, performed in a porous medium consisting of glass beads packing a column, saturated with a water-ethanol mixture. We displace the saturating fluid by a water-ethanol mixture of a different concentration. Concentration profiles (i.e. the concentration time-dependence as the front moves past) in a given cross-section of the column are derived as follows : we set transmitter-receiver pairs of transducers transversely in different cross-sections of the column in which we measure the propagation time of a sound wave. Of course, we need know the relationship between the sound velocity and the concentration of the mixture saturating the porous medium : in a preliminary experiment,

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we measure the sound velocity in a porous medium saturated with different mixtures of various concentrations; this enables us to vary the density and bulk modulus of the fluid, the other parameters such as permeability, porosity, bulk modulus of the porous frame remaining constant. The acoustic propagation in porous media has been thoroughly described by Biot in 1956 [3]: comparing the experimental points with theory gives out a geometrical coefficient (α) which describes the inertial drag exerted by the fluid on the solid.

From these profiles, obtained for different flow rates, we draw the effective diffusion coefficient K_L. For low flow rates, K_L is related to the geometrical factor α determined in the preliminary experiment.

2. Determination of the geometrical factor α.

2.1 A THEORETICAL SURVEY. — In porous, fluid-filled, macroscopically homogeneous and isotropic media, one can define the fluid and solid movements by the displacement vectors $\mathbf{U}(\mathbf{r}, t)$ (fluid) and $\mathbf{u}(\mathbf{r}, t)$ (solid), averaged over volumes large compared to the pore size but small compared to the wavelength.

The complete set of motion equations [3], including viscous damping is :

$$\rho_{11}\,\ddot{u} + \rho_{12}\,\ddot{U} = P\,\nabla(\nabla . u) + Q\,\nabla(\nabla . U) - N\,\nabla \times \nabla \times u + bF(\omega)\,(\dot{U} - \dot{u}) \tag{1}$$

$$\rho_{12}\,\ddot{u} + \rho_{22}\,\ddot{U} = R\,\nabla(\nabla . U) + Q\,\nabla(\nabla . u) - bF(\omega)\,(\dot{U} - \dot{u}) \tag{2}$$

where P, Q, R are elastic coefficients, related to the fluid bulk modulus K_F, the solid bulk modulus K_S, the bulk modulus K_B of the dry porous frame (under suitable assumptions, see [4]) and the shear modulus of the aggregate N by [5] :

$$P = \frac{4}{3}N + \left\{ (1-\varphi)\left(1 - \varphi - \frac{K_B}{K_S}\right)K_S + \varphi\frac{K_S}{K_F}K_B \right\} \Big/ D \tag{3}$$

$$Q = \left(1 - \varphi - \frac{K_B}{K_S}\right)K_S/D \tag{4}$$

$$R = \varphi^2\,K_S/D \tag{5}$$

where φ stands as the porosity (fluid volume fraction) and $D = 1 - \varphi - \dfrac{K_B}{K_S} + \varphi\dfrac{K_S}{K_F}$. The density coefficients can be related to the densities of solid and fluid (ρ_S and ρ_F) by :

$$\rho_{11} + \rho_{12} = (1-\varphi)\,\rho_S \quad \text{and} \quad \rho_{22} + \rho_{12} = \varphi\rho_F$$

where ρ_{12} describes the inertial drag that the fluid exerts on the solid when one of them is accelerated relatively to the other (this term has nothing to do with viscous drag [6]).

$$\rho_{12} = -(\alpha - 1)\,\varphi\rho_F$$

where $\alpha > 1$ is a purely geometrical quantity, independent of fluid or solid densities, which is equal to $\dfrac{1}{2}\left(1 + \dfrac{1}{\varphi}\right)$ in the case of isolated spheres in the fluid [7]. In this experiment, we measure α and check that it remains constant when ρ_F varies.

The term $bF(\omega)$ governs attenuation : $b = \eta\varphi^2/k$, η is the fluid viscosity, k the permeability of the porous medium, and $F(\omega)$ a function which accounts for the decrease in friction between fluid and solid as soon as the viscous skin depth $\delta = \sqrt{2\,\eta/\rho_F\,\omega}$ becomes smaller than the pore size a (this relation defines the inferior limit of the high frequency regime $\omega \geqslant \omega_c = 2\,\eta/\rho_F\,a^2$). In a previous paper [8], we presented attenuation measurements in the high frequency regime

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($\omega \gg \omega_c$ corresponding to $\delta \ll a$
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1

with

$$A = \rho_{11}\,\rho_{22} - \rho_{12}^2,$$

These two modes were observed i
V_+ was observed [8]. This velocity
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possible, with the other parameter
determine α.

2.2 EXPERIMENTAL PROCEDURE. -
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ments are carried out at a frequen
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the acoustic waves are quasi-sphe
expression of sound velocity whe:

A preliminary experiment, usi
(without glass beads), allowed us
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here can be derived from the conv
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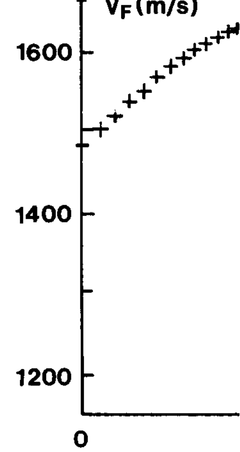

Fig. 1. — Sound velocity in a water-e
for c = 25 %.

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damping is :

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$+ \varphi \frac{K_S}{K_F} K_B \Big\}\Big/ D$ (3)

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$D = 1 - \varphi - \frac{K_B}{K_S} + \varphi \frac{K_S}{K_F}$. The
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$\rho_{12} = \varphi \rho_F$

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ents in the high frequency regime

($\omega \gg \omega_c$ corresponding to $\delta \ll a$ and $F(\omega) \propto \sqrt{\omega}$). In this regime, the velocities of the two longitudinal modes are :

$$V_{\pm}^2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{6}$$

with

$$A = \rho_{11}\,\rho_{22} - \rho_{12}^2\,, \quad B = P\rho_{22} + R\rho_{11} - 2\,Q\rho_{12}\,, \quad C = PR - Q^2\,.$$

These two modes were observed in fused glass beads [9], whereas in a pack of glass beads, only V_+ was observed [8]. This velocity V_+ depends on the fluid bulk modulus, through P, Q and R, and on the fluid density ρ_F through ρ_{12}. We vary K_F and ρ_F continuously in as wide a range as possible, with the other parameters φ, K_B, N, ρ_S, kept constant. Thus we test (3), (4) and (5), and determine α.

2.2 EXPERIMENTAL PROCEDURE. — The diameter of glass beads is between 200 and 250 μm. The glass density is $\rho_S = 2.6 \times 10^3$ kg/m^3 and its bulk modulus $K_S = 6.5 \times 10^{10}$ Pa. The beads are packed in an impervious column 20 cm high and 4 × 4 cm^2 broad. The porous medium has a measured porosity of 0.40 ± 0.02. Flows are driven in the vertical direction. Velocity measurements are carried out at a frequency of 400 kHz with a precision better than 0.5 ‰, and a spatial resolution of 3 mm (if the size of the transducer is D, the associated ratio $\lambda/D \sim 1$ shows that the acoustic waves are quasi-spherical, and not plane waves ; but Biot's theory leads to the same expression of sound velocity when considering spherical waves).

A preliminary experiment, using only water-ethanol mixtures of various concentrations (without glass beads), allowed us to determine the sound velocity variation v_F with the volume concentration c (Fig. 1). Knowing $\rho_F(c)$, we determine the variation of the fluid bulk modulus K_F along with c ($K_F(c) = \rho_F(c)\,v_F^2(c)$). In figure 2, curve $V_+(c)$ is shown. The maximum exhibited here can be derived from the convex shape of $v_F(c)$ (maximum close to 25 %). To compare these results with theory, we need calculate $V_+(c)$ for any concentration : the values of such parameters

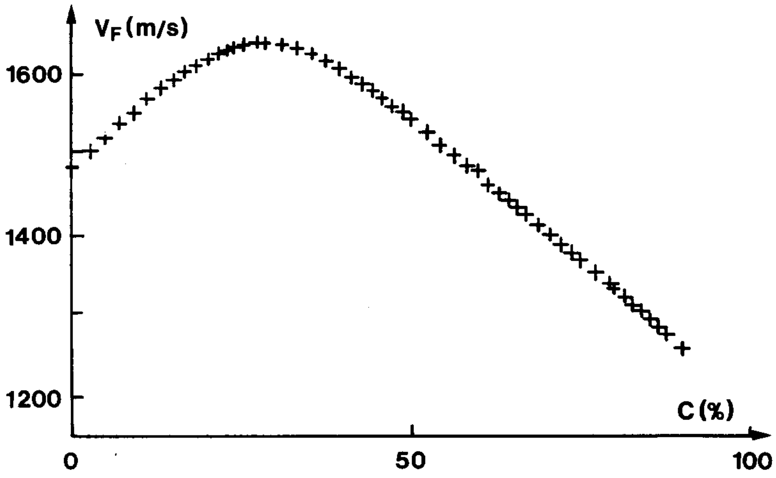

Fig. 1. — Sound velocity in a water-ethanol mixture *versus* the volume concentration. Note the maximum for c = 25 %.

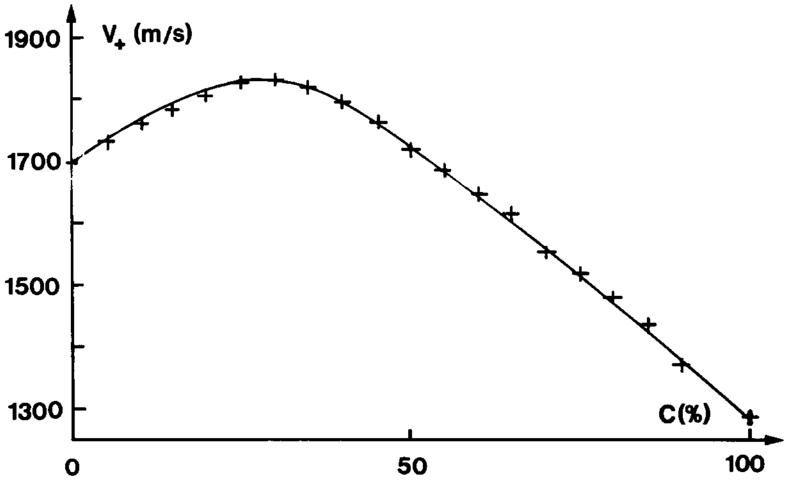

Fig. 2. — Sound velocity (fast mode) in a pack of glass beads saturated with a water-ethanol mixture of concentration c. The solid line is theoretical ($V_+(c)$-formula (6)) with a geometrical factor $\alpha = 1.66$.

as K_S, ρ_S, φ, $K_F(c)$, $\rho_F(c)$ are well known. Those of K_B, N, are estimated :

$$K_B \simeq 2.8 \times 10^8 \text{ Pa } (v_B \simeq 400 \text{ m/s } [5]) \quad \text{and} \quad N \simeq 12 \times 10^8 \text{ Pa}$$

(this choice is not critical [10]). The only parameter we have to insert in the theoretical formula (6) giving V_+, to fit the experimental curve, is α. The curve drawn in figure 1 corresponds to $\alpha = 1.66$. The fit is reasonably good for the whole curve, which allows us to say that α is indeed a purely geometrical factor, which does not depend on the fluid. This value is approximately the one expected for isolated spheres for which $\alpha = \frac{1}{2}\left(1 + \frac{1}{\varphi}\right) = 1.75$. This should mean that the packing of beads has little influence on the inertial drag, compared with isolated spheres. Knowing the relationship between the sound velocity V_+ and the concentration c will enable us to determine the time dependence of concentration in a given cross-section of the column as the mixing zone moves past the transducer.

3. Miscible fluid flows.

3.1 THEORETICAL SURVEY. — One can refer to [1] and [2] for a systematic review of miscible flows through porous media. In the particular case of incompressible fluids, with the same viscosities and densities, flowing at a constant velocity u in the Ox direction, the space and time-dependent concentration $c(x, t)$ obeys a diffusion equation :

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + K_L \frac{\partial^2 c}{\partial x^2} \tag{7}$$

where K_L stands as the effective longitudinal diffusion coefficient. For a constant coefficient K_L (i.e. not depending on concentration), simple initial conditions (at $t = 0$, $c = 1$ for $x < 0$ and $c = 0$ for $x > 0$) and an infinite sample the solution of (7) is :

$$c(x, t) = \frac{1}{2}\left(1 - \operatorname{erf}\left(\frac{x - ut}{2\sqrt{K_L t}}\right)\right) \tag{8}$$

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where $\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2} \, dy$ is
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$\Big(M = \frac{3}{2} Pe \, \mu$ and $N = 1 + \frac{3}{16}\Big($
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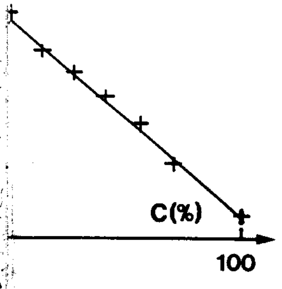

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where $\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2}\, dy$ is the well known error function. Basically, the most interesting point in miscible flows through porous media is to find out the flow velocity dependence of the effective longitudinal diffusion coefficient K_L. This coefficient accounts for the mixing of liquids through molecular diffusion and convection (i.e. the stirring of the fluid making its way through the complex geometry of the pores). Transverse diffusion [2] (not accounted for in Eq. (7)) also acts on convection in the longitudinal direction by decreasing its dispersive effects. Taylor [11] studied both theoretically and experimentally the dispersion of miscible fluids in a cylindrical tube of radius a; the dispersion is essentially due to the velocity profile of Poiseuille flow through the tube (convection). The ratio of the longitudinal diffusion coefficient K_L to the molecular diffusion coefficient D is a simple function of the dimensionless Péclet number $Pe = uL/D$ (where L stands as a characteristic pore dimension, u the mean value of the velocity in the tube). In this case, $L = a$:

$$\frac{K_L}{D} = 1 + Pe^2 .$$

In fact, a bundle of straight tubes is not a good representation of a porous medium. Saffman [12] proposed a more sophisticated model, consisting of a random network of capillaries with equal diameters, which leads to

$$\frac{K_L}{D} = \frac{1}{F\varphi} + \frac{3}{80}\left(\frac{a}{l}\right)^2 Pe^2 + \frac{Pe^2}{4}\int_0^1 (3\,\mu^2 - 1)\,\frac{M \coth(M - 1)}{NM^2}\,d\mu \qquad (9)$$

$\left(M = \frac{3}{2} Pe\,\mu \text{ and } N = 1 + \frac{3}{16}\left(\frac{a}{l}\right)^2 Pe\,\mu^2\right)$ where l is the length of the capillaries, a their radius of a pore, and $Pe = ul/D$. When $U = 0$, $K_L/D = 1/F\varphi$. F is the formation factor of the porous medium (i.e. the ratio of the conductivity of the fluid to the conductivity of the fluid-saturated porous medium). This relation derives from the formal analogy between equations governing diffusion and those governing the passage of electric current in a conducting fluid saturating the pores. Besides, it has been recently pointed out [13] that $F\varphi$ equals α, which is precisely the geometrical factor involved in acoustic equations, we determined in the previous section.

3.2 Dispersion coefficient measurements. — In preparation for a run, the column, packed with glass beads (see the acoustic experimental set-up), is saturated with the fluid to be displaced (1) by a vacuum impregnation technique. The displacing fluid (2) is injected through a valve connected to a perfusing syringe, which supplies a constant flow rate varying from 2.5×10^{-5} cm/s to 5×10^{-2} cm/s. These flow rates always correspond to laminar flows in our porous medium (Reynolds number smaller than 0.1). To avoid any fingering, we displace the lower viscosity fluid by the other one. The molecular diffusion coefficient of a water-ethanol mixture is strongly concentration-dependent [14] (10^{-5} cm²/s for 0 %, 0.38×10^{-5} cm²/s for 30 % and 1.2×10^{-5} cm²/s for 100 % in ethanol concentration). Hence K_L and the Péclet number also depend on concentration. To avoid any complication due to this dependence, we inject a displacing fluid with a concentration close to the one of the displaced fluid. We can thus define an average diffusion coefficient D which does not depend on concentration. Moreover, the viscosity and density ratios of the two fluids are close to 1 and thus, we minimize effects such as gravity segregation and fingering [2]. In the solution of equation (8) we just have to replace $c(x, t)$ by $\frac{c(x, t) - c_1}{c_2 - c_1}$, where c_1 and c_2 are the volume concentrations in ethanol of fluid mixtures 1 and 2. We worked with two pairs of water-ethanol mixtures : for the first one, $c_1 = 40$ %, $c_2 = 60$ % ($D = 4 \times 10^{-6}$ cm²/s and a sound velocity variation of 150 m/s), for the second one, $c_1 = 90$ %, $c_2 = 100$ %

($D' = 1.05 \times 10^{-5}$ cm^2/s and a sound velocity variation of 100 m/s). Through our velocity measurements in a given cross-section of the column, at a distance x_0 from the entrance end of the column, we obtain the time variation of c at x_0 with a spatial resolution of 3 mm (size of a transducer). The experimental data for different runs corresponding to various flow rates are plotted in figure 3 $\left(\dfrac{c - c_1}{c_1 - c_2}\ \textit{versus}\ \dfrac{t - t_0}{\sqrt{t}}\,(t_0 = x_0/u)\right)$. The effective diffusion coefficient is derived by matching the theoretical expression (8) of $c(x_0, t)$ to the data. In figure 4, we plotted K_L/D *versus* the Péclet number $Pe = ul/D$ (l being here the diameter of the beads, $l = 200$ µm), which covers

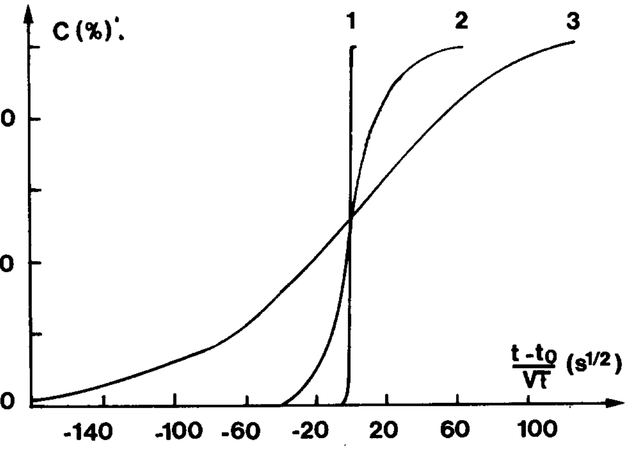

Fig. 3. — Concentration profiles $c(x_0, t)$ *versus* $(t - t_0)/\sqrt{t}$ in a given cross-section of the column for different flow rates : (1) $u_1 = 2 \times 10^{-4}$ m/s, $x_0 = 4.6$ cm ; (2) $u_2 = 10.4 \times 10^{-6}$ m/s, $x_0 = 9.68$ cm ; (3) $u_3 = 4.2 \times 10^{-7}$ m/s, $x_0 = 4.6$ cm.

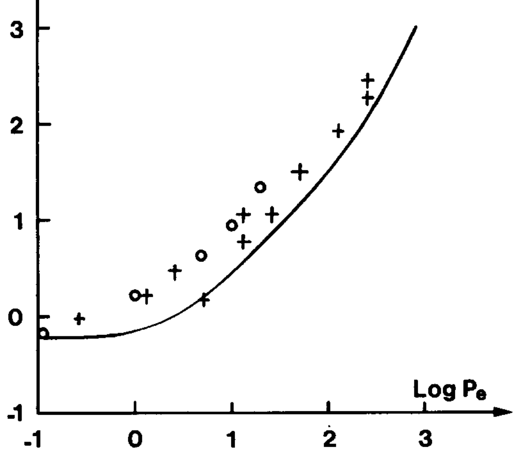

Fig. 4. — Ratio of the longitudinal dispersion coefficient K_L to the molecular diffusion coefficient D *versus* Péclet number (varying from 10^{-1} to 10^3) (log-log plot). ○ $c_1 = 90\,\%$, $c_2 = 100\,\%$; + : $c_1 = 40\,\%$, $c_2 = 60\,\%$.

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4. Conclusion.

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References

[1] Dullien, F. A. L., *Porous medic*
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[2] Marle, C., *Multiphase flow in p*
[3] Biot, M. Z., *J. Acoust. Soc. Am.*
[4] Wyllie, M. R. J., Garner, G.
[5] Stoll, R. D., in *Physics of sounc*
pp. 19-39.
[6] Landau, L. and Lifchitz, E.,
[7] Berryman, J. G., *Appl. Phys. L*
[8] Salin, D. and Schön, W., *J. Pl*

a range of 3 and a half decades. For small Péclet values, K_L/D falls off to a constant close to 0.6, which is in agreement with the value of α obtained from acoustic measurements ($1/F\varphi = 1/\alpha = 0.57$).

We see that the ratio K_L/D increases from $Pe = 10$ onwards. The solid line represents Saffman's model solution with a ratio $l/a = 5$ (expression (9)). It systematically lies below the experimental points, while still displaying the same characteristics. In fact, Saffman's theory corresponds to a specific random network of tubes with of mean length l much larger than a. For a pack of glass beads, we rather have $l \simeq a$, in which case, Saffman's model is not strictly valid (for the flow through the pores is no longer a Poiseuille flow). Recall that the Péclet number was defined with the largest characteristic pore size possible (bead diameter). Moreover, the effect of pore size dispersion is not accounted for in this model, which still remains the most thorough analysis of dispersion in porous media, although some refinements were attempted [15]. This behaviour — experimental points above the position of Saffman's curve — has already been observed by Pfannkuch [16], who compiled the results of experiments on different unconsolidated porous media, which were performed either in the lower Péclet range ($10^{-2} - 1$) or in the higher one (from 10 onwards), or in the intermediate range. No previous experiment continuously explored as wide a range from 10^{-1} to 10^3 Péclet using the same sample. (Here we vary the flow rate and the molecular diffusion coefficient but we have a well defined grain shape and dispersion in pore size, thus always defining the same Péclet number, which will not be the case for the different samples used by the other experimenters).

4. Conclusion.

The good accordance of Biot's theory with our sound velocity measurements in a pack of glass beads saturated with water-ethanol mixtures of various concentrations allowed us to determine the formation factor of this porous medium. Velocity measurements were then used to describe the time dependence of the concentration when one fluid is displaced by another miscible fluid. Contrary to previous experiments, we present here a local probe technique which provides an *in situ* investigation in a given cross-section of the porous sample. The experimental values of the longitudinal dispersion coefficient at low flow rates are in agreement with the acoustic determination of the formation factor. At higher flow rates, the values are in reasonably good agreement with the theory of mixing of miscible fluids in a porous medium, thus showing that the acoustic technique turns out to be a suitable tool for the study of concentration profiles. This should be exploited in the future, when tackling the case of non miscible fluids.

References

[1] DULLIEN, F. A. L., *Porous media. Fluid transport and pore structure* (Academic Press) 1979, pp. 329-390.

[2] MARLE, C., *Multiphase flow in porous media* (Editions Technip, Paris) 1981.

[3] BIOT, M. Z., *J. Acoust. Soc. Am.* **28** (1956) 168.

[4] WYLLIE, M. R. J., GARNER, G. H. F. and GREGORY, A. R., *Geophysics* **27** (1962) 569.

[5] STOLL, R. D., in *Physics of sound in marine sediments*, ed. by L. Hampton (Plenum, New York) 1974, pp. 19-39.

[6] LANDAU, L. and LIFCHITZ, E., *Fluid Mechanics* (Pergamon Press), Chap. I.

[7] BERRYMAN, J. G., *Appl. Phys. Lett.* **37** (1980) 382.

[8] SALIN, D. and SCHÖN, W., *J. Physique Lett.* **42** (1981) L-477.

[9] PLONA, T. J., *Appl. Phys. Lett.* **36** (1980) 259.
[10] JOHNSON, D. L., in *Excitations in disordered systems*, ed. by M. F. Thorpe (Plenum, New York) 1982.
[11] TAYLOR, G., *Proc. R. Soc. London, Ser. A* **219** (1953) 186.
[12] SAFFMAN, P. G., *J. Fluid Mech.* **6** (1959) 321-349.
[13] BROWN, R. J. S., *Geophysics* **45** (1980) 1269.
[14] *Handbook of Chemistry and Physics*, ed. by R. C. Weast (The Chemical Rubber Co, Cleveland, U.S.A.).
[15] SIMON, R. and KELSEY, F. J., *Soc. Pet. Eng. J.* **11** (1971) 99.
[16] PFANNKUCH, H. O., *Rev. Inst. Fr. Pet.* **XVIII** nº 2 (1912) pp. 1-54 (215-269).

Imprimé