DYNAMICS OF CAPILLARY FLOW AND TRANSPORT PROPERTIES IN CARBONATE SEDIMENTARY FORMATION BY TIME-CONTROLLED POROSIMETRY

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This paper was prepared for presentation at the International Symposium of the Society of Core Analyst held in Abu Dhabi, UAE, 5-9 October, 2004

ABSTRACT

The dynamics of capillary flow in porous media at the pore-scale and the absolute permeability are calculated from time-controlled porosimetry data. The study of the flow regime in Hg-air displacements obtained in mercury porosimetry show that the main flow regime is a capillary regime. An extended Washburn equation proposed by Sorbie et al. has already been used to analyse the dynamics of capillary flow, the pore filling time and the relative filling order of large and small pores. This method was applied to different calcareous porous materials characterized by different textures.

INTRODUCTION

Capillary fluid flow through porous media has been the focus of many studies during this last decade because of its importance as a process in nature and in different porous materials such as oil filled and water wet reservoirs, soils and fractured rocks [1-4]. We determine capillary flow dynamics in porous media at the pore-scale and aim to propose a method for calculating the permeability from time dependence of different physical properties. For that, we used the mercury porosimetry. Washburn (1921) linked to Laplace's equation by using a capillary model where the porous medium is simulated by a bundle of conical or cylindrical capillary tubes:

$$Pc=\frac{2\gamma|\cos\theta|}{\overline{R}c} \qquad (1)$$

where Pc is the capillary pressure; $\overline{R}_c$ is the average pore-throat size; γ is the interfacial tension; θ is the angle between mercury meniscus. Here, we have used a dynamical analysis procedure of Hg-injection curve, the so-called time-controlled mercury invasion. It allows us to determine the pore-scale complexity from time-controlled porosimetry data and to analyse the new parameters which characterize the curves of capillary pressure and volume against time. Four main rock-types are used in study (Figure 1): *Texture I* (mudstone-wackestone with mud-supported texture), *Texture II* (packstone with grain-supported texture), *Texture III* (packstone-grainstone with grain-supported texture), *Texture IV* (grainstone).

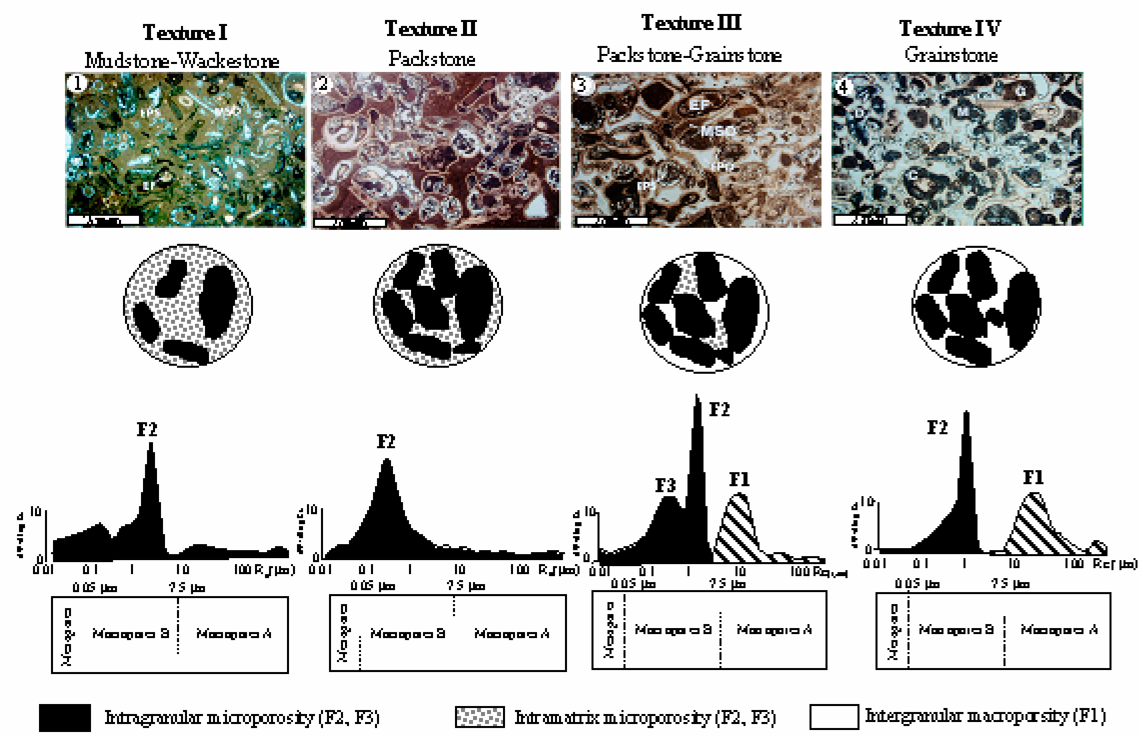

Figure 1. Definition of the four rock-textures used in this study.

EXPERIMENTAL PROCEDURE

The experimental device consists a Carlo-Erba Series 200 porosimeter, a data acquisition unit, and a microcomputer PC connected to a printer. To give a physical interpretation of the phenomena, data are analysed following two curves: V(t) and $P_c(t)$ (Figure 2).

• ***Mercury volume versus time: V(t)***. During the mercury intrusion in porous media, the volume rate versus time shows two capillary flow dynamics (Figure 2). *A rapid rate of mercury invasion* AB (between 0 and B, where a significant change of the slope is observed, corresponding to the transition between rapid to slow injection rate). The rapid rate of mercury injection versus time can be represented by a straight-line : $V = Q_1 t + \beta_1$ where $Q_1 = dV_1/dt$ is the slope of the curve, β_1 is a constant and t is time. *A slow rate of mercury invasion* BC between t_o and t_f (total saturation of sample) defined by $V = Q_2 t + \beta_2$ where $Q_2 = dV_2/dt$ is the slope of the curve, β_2 is a constant and t is time.

• ***Capillary pressure versus time: $P_c(t)$.*** During the mercury intrusion, the capillary pressure evolves following Haines jump (Figure 2). Some authors noted the same phenomena in slow drainage.

The capillary number Ca and the viscosity ratio *M* characterize the Hg-air flow regime. Three major flow regimes are defined [5]: viscous fingering, stable displacement and capillary fingering. In our case and by taking into account the experimental conditions (for mercury : $\mu_2 = 1.55 \cdot 10^{-3}$ Pa·s, $\gamma = 0.480$ N/m, $\theta = 140°$; for air : $\mu_1 = 0.018 \cdot 10^{-3}$ Pa·s), Ca varies with time as follows:

$$Ca = \frac{\alpha}{A} \cdot \begin{cases} Q_1(t) \ \ [0, t_0] \\ Q_2(t) \ \ [t_0, t_f] \end{cases} \qquad (2)$$

where $\alpha = \frac{\mu}{\gamma \cdot |\cos\theta|}$ is a constant (for the Hg-air system is $\alpha = 0.004215$); $Q_1(t)$ and $Q_2(t)$ are injection rates for rapid and slow kinetics with $Q_1(t) >> Q_2(t)$; A is the sample area. The different values of logM-logCa obtained in Hg-air porosimetry show that the main flow regime of the invading fluids is the capillary fingering. The experimental values of logM are constant 1.935 while the experimental values of logCa range from -6.66 to –8.33.

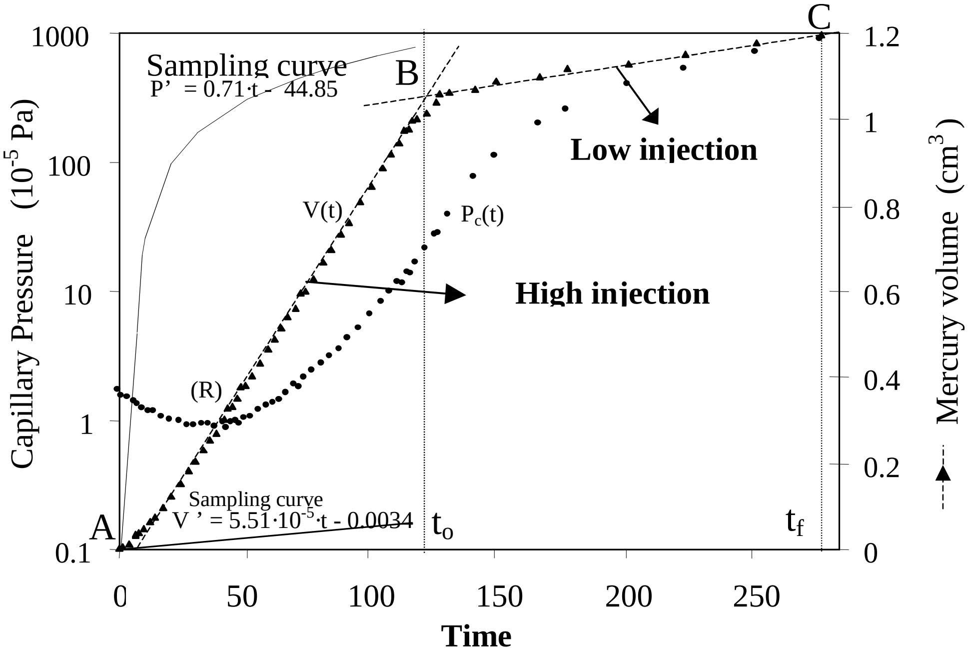

Figure 2. Temporal evolution of capillary pressure curves $P_c(t)$ and injected mercury volume V(t). Definition of different parameters of pore network complexity. P'(t) and V'(t) are sampling curves of pressure and volume versus time; t_o is the time of change from rapid rate to slow rate; t_f is the time of total core saturation; R is capillary pressure fluctuations.

DYNAMICS OF HG-AIR CAPILLARY FLOW

The simplest equation to calculate the dynamics of Hg-air capillary flow at the pore-scale is attributed to Washburn. By combining with the Hagen-Poiseuille equation, the capillary velocity (u) is given by the following equation:

$$u \equiv \frac{dh}{dt} = \frac{\Delta P}{8\mu h} \cdot R_c^2 = \frac{1}{8\mu h} \cdot \left[\frac{2\gamma|\cos\theta|}{R_c} - \rho g h \right] \cdot R_c^2 \qquad (3)$$

where h is the length of fluid penetration ; $\Delta P = Pc - \rho gh$ is the pressure drop between the meniscus and the bulk liquid ; R_c is the tube radius ; ρ is the density ; μ is the fluid viscosity ; θ is the contact angle and γ is the interfacial tension. Sorbie et al. [4] have re-examined the basis of the Washburn equation and have extended his equation. According to these authors, certain additional inertial terms may be of importance when considering the range of pore sizes and the aspect ratios commonly encountered within porous media. For steady-state flow, Sorbie et al. [4] give a slightly different form of equation (3) :

$$u \equiv \frac{dh}{dt} = \frac{\Delta P}{8\mu h} \cdot \frac{\left(R_c^4 + 4\varepsilon R_c^3\right)}{R_c^2} \quad (4)$$

where ε is a factor in the Washburn equation relating to the wall slip condition (not analysed here). For a single capillary and only under viscous forces the pore filling time t_f, is found by integrating the equation (4) (ε=0) :

$$t_f = \frac{4H^2\mu}{R_c^2 \Delta P} \quad \text{or} \quad H = \frac{Rc}{2}\sqrt{\frac{t_f \Delta P}{2\mu}} \quad (5)$$

where H is the total length of fluid penetration (or total tube length).When the flow is entirely capillary dominated, Sorbie et al. give the pore filling time t_f by the following formula :

$$t_f = \frac{2H^2\mu}{R_c \gamma |\cos\theta|} \quad \text{or} \quad H = \sqrt{\frac{t_f R_c \gamma |\cos\theta|}{2\mu}} \quad (6)$$

The Washburn equation predicts that wider tubes will fill up more quickly than narrow ones. So, for viscous dominated systems, the final time t_f is proportional to $1/R_c^2$ while for capillary dominated systems the final time t_f is proportional to $1/R_c$. We calculated the length of Hg-air front displacement h and the capillary velocity flow dh/dt from relationship (6) for different carbonate textures. Results show that in all cases the capillary velocity dh/dt decreases as the capillary flow time increases (Figures 3, 4). It is due to the fact that mercury injection investigates pores the pore-throat size of which decreases. The samples with two-three modes structures, large well-connected pores show a high capillary velocity flow (Figures 3, 4).

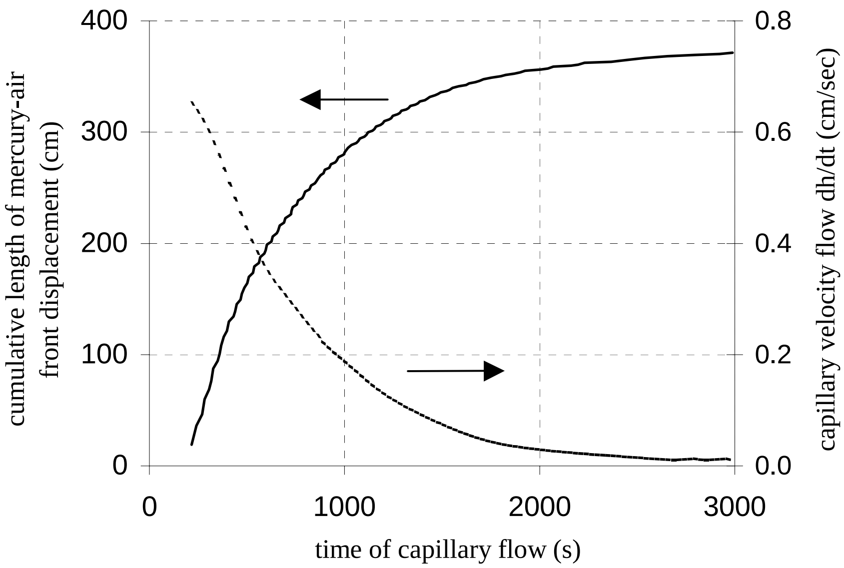

Figure 3. Length of mercury-air front diplacement and capillary velocity flow versus time in texture II. Φ = 16.79 %, k = 363.86 mD.

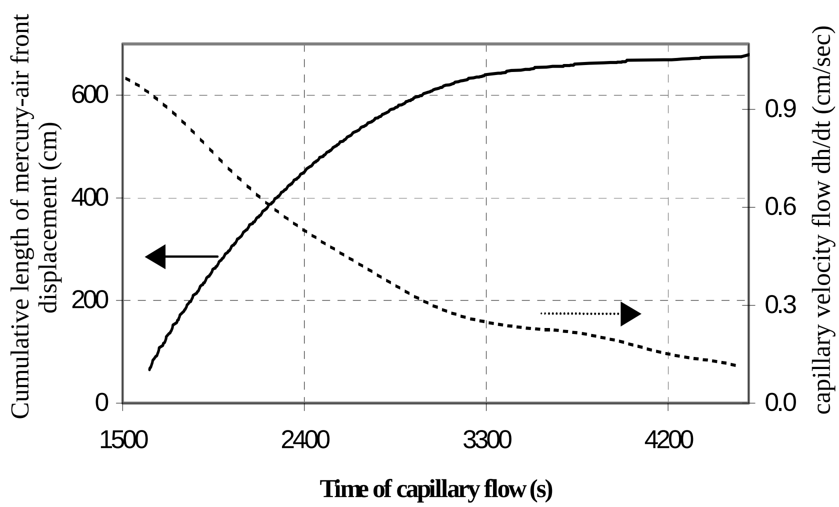

Figure 4. Length of mercury-air diplacement front and capillary velocity flow versus time in texture IV: Φ=38.71 % ; k=1187.42 mD.

TRANSPORT PROPERTIES FROM HG-CAPILLARY FLOW

Many attempts have been made to calculate permeability k from primary capillaric parameters such as diameters, lengths and positions of the pores and throats. Chatzis [1]