Influence of the capillary and the viscous forces during the drainage process in a porous media

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Abstract: - In this paper, we simulate an ascending air phase flow in a vertical porous channel initially saturated with a liquid phase. The numerical study is performed for large range of injected air mass flow rate from the bottom to the top. The different forces intervening in the drainage process is analyzed according to several permeabilities. The results show that for a weak gas mass flow rate, the capillary effect is dominant. In this case, the gas saturation in a porous channel is proportional to the permeability. For more important gas mass flow rate, the saturation behavior becomes inversely proportional to the permeability of the porous channel.

Key-Words: - two phase flow, capillary pressure, viscosity forces, relative permeability, saturation behavior

1 Introduction

Two phase flows in porous media are phenomena currently met in various industrial fields. Examples include oil reservoir engineering, post accident analysis of nuclear reactors, drying processes and geothermal systems. In the oil industry, the primary petroleum recuperation covers only 30 to 40 percents of oil from oil fields. However, when oil production declines, a gas phase (CO2 …) is injected into the reservoir to mobilize the oil and increase the production. A large number of factors can affect this phenomenon, including capillary, viscous and gravity forces.

Many experiments were elaborated in order to understand dynamics and invasion process [1], [2], [3]. On the other hand, many analytical and numerical studies were given in order to simulate different cases of capillary and gravity effects [4], [5]. In the literature, drainage experiments in porous media initially saturated with a wetting phase, when a non wetting phase is injected, has been largely devoted by using various type of fluids and different angle values. The porous medium will be subjected to pressure gradients due to the effects of gravity [6] and viscous forces [7], [8]

In this study, Hassler's experiments [9] are analyzed in order to compare different forces effects intervening in a drainage process. These experiments consist of injecting a non-wet phase (gas) from the bottom to the top of a porous channel. The top extremity is maintained wet. The porous matrix is saturated with the wet phase (water). A large range of a gas mass flow rate is applied for different permeabilities of porous channel.

2 Problem Formulation

The Darcy's law which describes the fluid flow in porous media was generalized for two-phase flow, including the macroscopic inertial terms for a steady state as follows:For (for i =l,g)

$$\frac{\rho_i}{\varepsilon . S_i} \cdot \left(\vec{v}_i . \nabla \vec{v}_i \right) = -\vec{\nabla} P^i + \rho_i \cdot \vec{g} - \frac{\mu_i}{K_i} \cdot \vec{v}_i \qquad (1)$$

K and ε are respectively is the permeability and the porosity of the porous medium, K_{rl} and K_{rg} are the relative permeabilities for each phase.

2.1 The relative permeability model

Several studies were conducted to establish the relationship between the relative permeability for each phase and the saturation. The most commonly used relationships, are the power law functions as mentioned by [10]:

$$K_{rl} = S_e^4 \qquad (2)$$

$$K_{rg} = (1 - S_e)^2 (1 - S_e^2) \tag{3}$$

In these relations, S_e is the effective liquid phase saturation defined by:

$$S_e = \frac{S_l - S_r}{1 - S_r} \tag{4}$$

2.2 The Capillary pressure model

Levrett as given by [11] developed a correlation for capillary pressures in packed beds of unconsolidated materials:

$$P_c = \sigma \sqrt{\frac{\varepsilon}{K}} J(S_l) \tag{5}$$

$J(S_l)$ is the Levrett function which depends only on the liquid saturation S_l. σ is the surface tension between phases, ε is the porosity of the porous environment and K is the medium permeability. In order to take into account the variability of the capillary pressure according to permeability, the model of Scheidegger as mentioned by [11] is introduced. This model shows the relation between the capillary pressure and the saturation by the equation 9.

$$P_c = \frac{\sigma}{(k/\varepsilon)^{1/2}} \cdot \left[0.364\left(1 - e^{-40(s_g)}\right) + 0.221 \cdot s_g + \frac{0.005}{0.96 - s_g} \right] \tag{6}$$

2.3 Boundary Conditions

2.3.1 Conditions on velocities

Let's consider $\vec{v}$ (u, v) in a Cartesian reference. U_{ie} is the velocity imposed at the entry Figure (1). For ($i = l, g$)

$$\begin{cases} u_i\,(x, y=0) = 0 & , \quad v_i(x, y = 0) = 0 \\ u_i\,(x, y = d) = 0 & , \quad v_i\,(x, y = d) = 0 \\ u_i\,(x = 0, y) = U_{ie} & , \quad v_i\,(x = 0, y) = 0 \\ \left.\dfrac{\partial u_i}{\partial x}\right|_{x=L} = 0 & , \quad v_i(x = L, y) = 0 \end{cases} \tag{7}$$

2.3.2 Conditions on gas saturation

In order to have some known conditions reigning at the exit side (at the top) of the porous massif, we consider that this area remains wet all the time. This assumption permits to consider a critical gas saturation $S_{gc} = 0.2$ as given by Houpert [4].

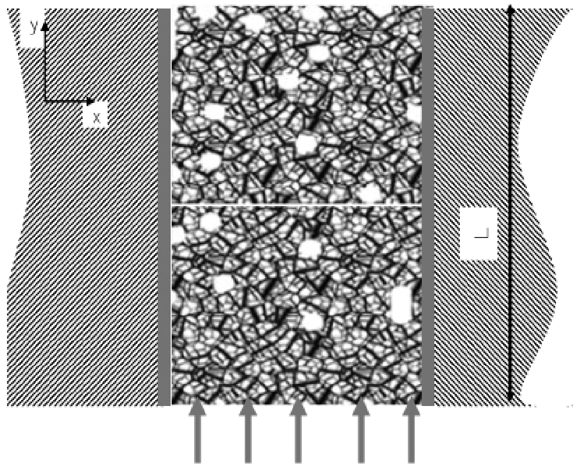

Fig. 1 Problem setting

3 Method of resolution

The problem is solved using the numerical finite volume method with a structured mesh and a finer grid at the exit side. The SIMPLE algorithm developed by Patankar [12] is used for the calculation of the pressure fields. The saturation S is known by identifying the pressure difference $P^g - P^l$ with the capillary pressure $P_c(S)$ represented by equation (6).

4 Results analysis

In order to understand the behavior of the capillary pressure model, and to be able to interpret the two-phase flow thereafter, the figure 2 shows the capillary evolution according to different porous channel permeability, while keeping a fixed porosity ε =0.2. The graph shows that the capillary pressure behaves in an inverse way to the permeability. Indeed, we can note that for a same value of the S_g saturation, the capillary pressure decreases globally when the permeability increases. Therefore, for a same value of the capillary pressure, the saturation in gas becomes more important when the permeability increases. As a conclusion it would seem that a porous environment with an increasing permeability, submitted to the only capillary forces (slow flow), expand the saturation of the gas phase.

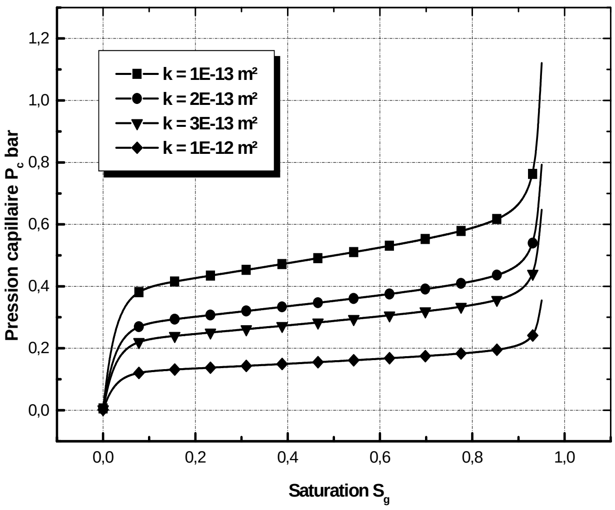

Fig. 2 The Behavior of Scheidegger capillary pressure model according to k, (ε =0.2)

In order to verify this hypothesis, we will proceed to simulations of gas flows in an initially saturated matrix with water. Two air mass flow rate will be examined, corresponding to a very slow flow (u_g = 0,01 cm/s) and the other 100 times more important (u_g = 1 cm/s). The analysis of the two simulations permits to evaluate the influence of capillarity forces on the saturation in the different cases of permeability of the channel.

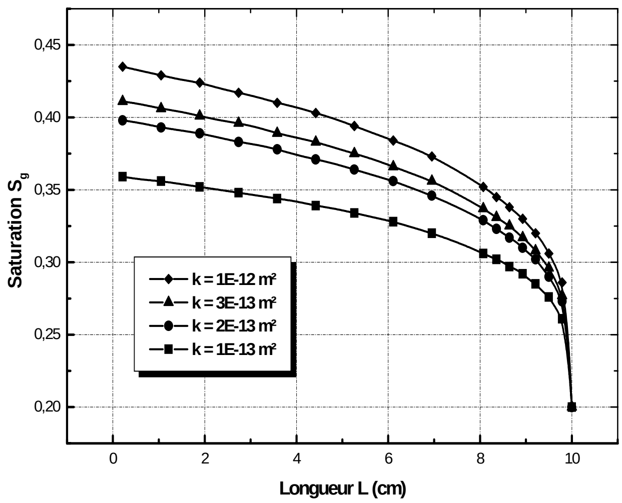

Fig. 3 The gas saturation behavior according to different k (u_g=10^{-4} m/s)

Figures 2 and 3 describe respectively the gas phase and the capillary pressure behaviors within the porous massif for u_g = 10^{-4} m/s (very slow flow). From the bottom to the top, the gas saturation decreases as well as the capillary pressure. At the exit side, the saturation corresponds to the boundary condition s_g =0.2.

Following what has been announced previously, the saturation in a gas phase grows with the permeability k of the solid environment. This result needs, in order to be explained, an important number of analyses.

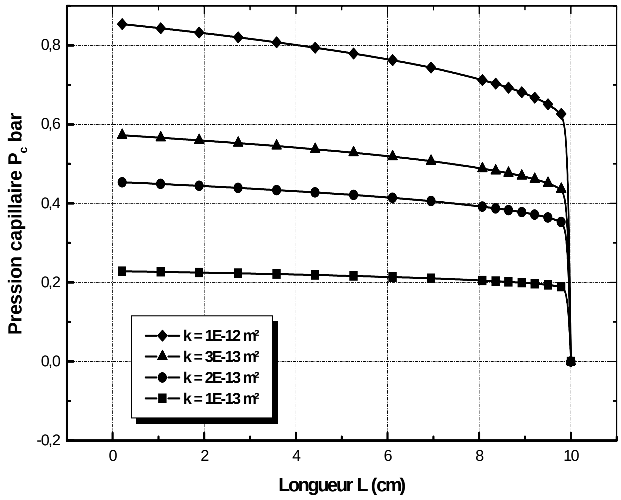

Fig. 4 The capillary pressure behavior according to different k (u_g=10^{-4} m/s)

For more important velocities (u_g =10^{-2} m/s), we can conclude from figures 5 and 6 that the saturation in gas phase decreases for the increasing values of the permeability. This result announces an inverse behavior compared to the slow flows.

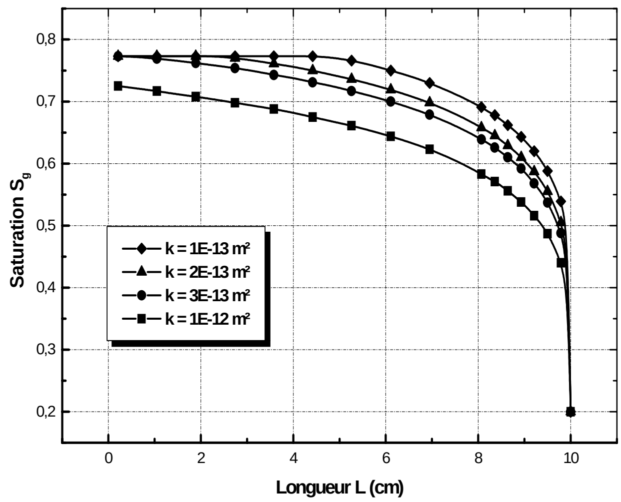

Fig. 5 The gas saturation behavior according to different k (u_g=10^{-2} m/s)

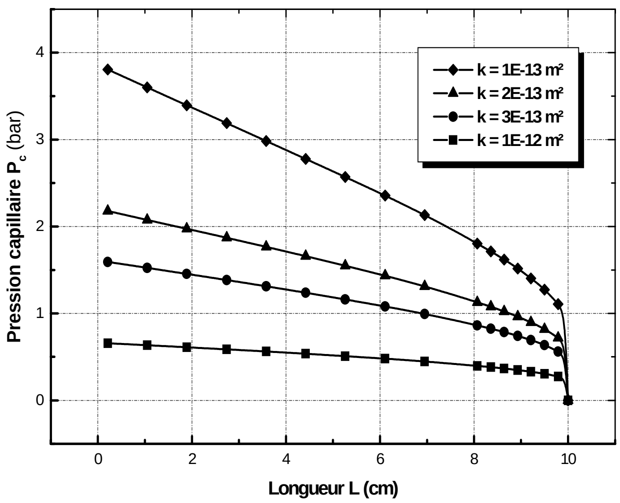

Fig. 6 The capillary pressure behavior according to different k (u_g=10^{-2} m/s)

5 Conclusion

In this study, we analysed the behavior of the injected gas saturation in initially saturated porous channel. The distribution of the gas phase is intimately related to the pressure drop.

In general, we conclude that the saturation of the gas phase in the drainage process is influenced by the gas mass flow rate and the porous environment. This requires a sufficient pressure. However, a more meticulous analysis demonstrates that the distribution of gas phase behaves of two distinct manners in front of the permeability. In the case of the very slow flows the saturation in gas phase is proportional to the permeability of the porous environment. The truly motor of the flow in this case is capillarity. In the case of faster flows the saturation becomes inversely proportional to the permeability. The viscous forces become predominant and take more importance for weaker permeabilities.

The transition from the flow owed to the capillary forces to the flow owed to the viscous forces will be evaluated in further studies.

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