Numerical Study of Viscous Fingering in Heterogeneous Porous Media

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ABSTRACT

The displacement of a fluid by a second immiscible fluid is a fundamental process which is relevant for many technological applications, particularly in the petroleum industry. Water is the fluid widely used to push oil to production wells. During this immiscible displacement, a viscous fingering instability appears at the water-oil interface. This undesirable phenomenon leads to a low oil sweeping efficiency. To prevent this situation, techniques called EOR (Enhance Oil Recovery) are used. These methods have technical, economic and environmental disadvantages. Therefore, the objective of this work is to seek a rational use of EOR techniques by determining the right place and the appropriate time to operate them. In many previous studies, the effects of viscosity ratio, interfacial tension and flow rate are investigated. In this study, we numerically investigate the effect of the heterogeneity of the medium and the presence of the fracture on this phenomenon. Three different configurations are studied. The obtained results allowed to locate the regions where the behaviour of the instability varies during displacement in the porous medium, regions where instability is increasing and others where it remains constant. a qualitative comparison between the different cases is also made.

1. INTRODUCTION

Oil recovery is occurring in three modes: primary recovery, secondary recovery and tertiary recovery also called Enhanced Oil recovery (EOR) [1]. Primary recovery uses reservoir pressure as a natural drive mechanism [2] since it does not use any energy input [3]. In most cases, this natural mechanism is inefficient as it recovers only 10% of the OOIP (original Oil in place) [4] [5]. Therefore, we use training modes by introducing additional energy to displace the oil and maintain the reservoir pressure [6]. The most basic and common method is the injection of water (waterflooding) [7]. The injected fluid sweeps the oil left after the primary phase into the porous medium pushing it towards the production well [7]. Previous research has shown the limits and inefficiency of this method, particularly in heavy oil systems where large quantities of oil remain trapped in the oil fields at the end of the operation [8]. The phenomenon responsible for this poor sweeping is called viscous fingering. This phenomenon was introduced, for the first time, by Engelberts and Klinkeberg in the early fifties but it still a current for researchers [9].

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It is an instability that has occurred by the formation of viscous fingers at the interface of two immiscible fluids when the displacing fluid is less viscous than the displaced fluid [5], [10], [11], [12], [13]. In order to improve oil production, solutions, called EOR (Enhanced Oil Recovery), are provided. These solutions tend to reduce the effect of this phenomenon which is considered inevitable [14]. Among these solutions, we have Steam-based thermal method [14], the injection of polymers which is considered to be the most developed technique [15] and the injection of surfactants which eliminate considerable amount of oil trapped after initial waterflooding [16]. These techniques are effective because they increase the sweeping efficiency. However, they have limitations in certain types of reservoirs. Benyamin Yadali Jamaloei et al studied low tension polymer flooding (LTPF) for heavy oil reservoirs. They propose this technique because thermal methods are inefficient and present many problems, especially in thin formations [15], [17]. P. Druetta and F. Picchioni cited the problem of polymer degradation due to a high adsorption rate which makes this technique economically unfeasible [15]. Currently, the technology of surfactant injection is attractive. Therefore, several varieties of surfactants are applied. However, the prices of these surfactants are excessive and their impact on the environment is harmful [9].

Under technical difficulties, economic concerns and environmental challenges, it is better to explore the technique of water injection in oil recovery. This exploration will allow better control of EOR techniques by acting in the right place and at the right time.

2 PHYSICAL MODEL

In order to model the immiscible displacement in porous medium in unsteady regime, we are interested in a water-oil displacement in a horizontal domain in 2D ($\Omega \in R^2$). Fluids are incompressible and the medium is non-deformable. We consider in this study the Five-spot configuration. In this configuration, one injection well is in the center and four production wells at the corners of the square (Fig. 1) [18]. This is a standard configuration frequently used in oil recovery. For reasons of symmetry, we are interested in a quarter of this domain. So, the computational domain is a square of $2m \times 2m$ dimensions (Fig. 2). At $t = 0s$ the medium is fully saturated with oil ($S_0 = 1$). Water ($\rho_w = 998.2\, kg.m^{-3}$, $\mu_w = 0.00103\, kg.m^{-1}.s^{-1}$) is injected through an injection well maintained at a pressure $P_{inj} = 1.79\, Mpa$ to push oil ($\rho_o = 826\, kg.m^{-3}, \mu_o = 0.00762076\, kg.m^{-1}.s^{-1}$) to a production well at $P_{prod} = 1.31\, Mpa$ [19].

The different cases studied in this work are represented in (Fig.3). In the first case, the porous medium is homogeneous (Fig. 3.a). In the second case, the porous medium is split into two zones (Fig. 3.b). Zone1, located near the injection well, is very permeable compared to zone2. The permeability ratio of the two zones is equal to 5. Finally, in the third case, we are interested in a fractured medium (Fig. 3.c). The model considered for the fracture is the double model (DM). The fracture is a porous medium of the same porosity as the solid matrix but of very high permeability. This large difference in the permeability causes serious problems in oil recovery [20]. E. Holzbecher studied the effect of the permeability ratio on the global behaviour of a displacement of two fluids [21]. The permeability ratio of the fracture and matrix is equal to 10^4. The length and the aperture of the fracture are respectively equal to 1m and 1cm (Fig. 3.c). For simulating this flow Ansys Fluent as CFD software is used. For all the cases, a square mesh is used with special treatment and refinement near the wells. A fine mesh is also used near and inside the fracture. The number of cells in the two first cases is 166 538 cells. In the third case 339 457 cells.

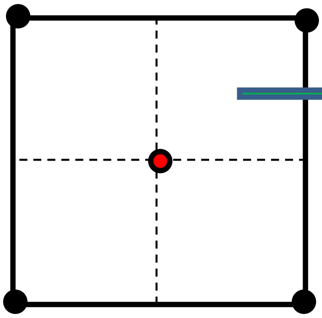


Fig. 1: Five-spot model

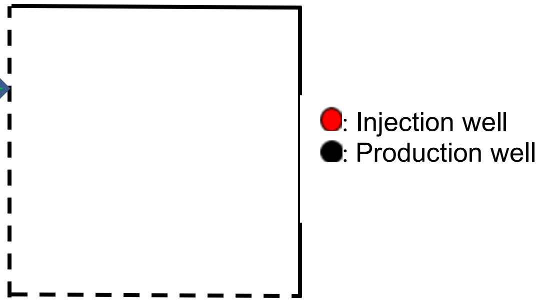


Fig. 2: Computational domain

(a) homogenous (b) layered (c) fractured

Fig. 3: porous medium

3. MATHEMATICAL MODEL

When the process is isothermal, the multiphase flows in an undeformable porous medium are governed by the following equations [22], [19]:

Mass conservation equation: The mass balance equation for each of the phases are:

$$\frac{\partial(\phi.\rho_i.S_i)}{\partial t} + (\rho_i u_i) = 0. \quad i = oil,\ water \tag{1}$$

Momentum: The momentum equations represented by Darcy's generalized law for each phase are written as follows:

$$u_i = -\frac{K.K_{ri}}{\mu_i} \nabla P_i \tag{2}$$

The combination of the two equations gives:

$$\frac{\partial(\phi.\rho_i.S_i)}{\partial t} - \left(\rho_i \frac{K.K_{ri}}{\mu_i} \nabla P_i\right) = 0 \tag{3}$$

where ϕ, K are respectively the porosity and the permeability of the porous medium. K_{ri}, S_i, $\rho_i$et $\mu_i$are respectively the relative permeability, saturation, density and viscosity of the phase i.

The porous medium is fully saturated by the two fluid phases, therefore:

$$\sum S_i = S_o + S_w = 1 \tag{4}$$

These equations are completed by the relative permeability and capillary pressure relationships [18,23]:

The relative permeability is given by Brooks-Corey relationship:

$$K_{ri} = K_{rw}(S_w,\ S_{rw}) \tag{5}$$

where S_{rw} is residual water saturation.

The relation between the pressures of the two phases is given by the capillary pressure:

$$P_C(S_w) = P_o - P_w$$

The finite volume method is used to solve these equations.

4 RESULTS AND DISCUSSION

The representation of the saturation fields as a function of time allows to make a qualitative comparison between the different cases studied. The Fig. 4, Fig. 7 and Fig. 8 show the distribution of the oil in the porous media.

As shown in Fig.4, the fingers appear and progress along the diagonal path connecting the injection well to the production well. From t=5.58s, the finger which advances along the central diagonal accelerates to reach the production well at t=11.58s. We also observe that the fingers converge towards the production well from t=08.58s. As the diagonal is the most sensitive direction, pressure and velocity profiles are plotted along this direction.

Fig.5 shows that the pressure gradient is significant in the region near the production well, the reason why the fingers converge towards this point.

Fig.6 shows velocities tending to zero except near the two wells and in the viscous fingers. This explains the penetration of water into the oil.

We observe in Fig.6 a distribution of the oil through the porous medium different from that of the homogeneous medium. The viscous fingers tend to flow in the higher permeability zone which is located near the production well. The lower permeability zone tends to slow down the progression of viscous fingers formed in zone1. When these fingers arrive at this zone, they change the direction to head towards the production well. Water breakthrough occurs at t=9.60s.

Fig.8 also shows the phenomenon of viscous fingering that occurs in the presence of a fracture. The fingers quickly converge towards the fracture which is considered to be a very permeable medium. This fracture generates a preferential flow which delays the breakthrough of water until t=24.20s.

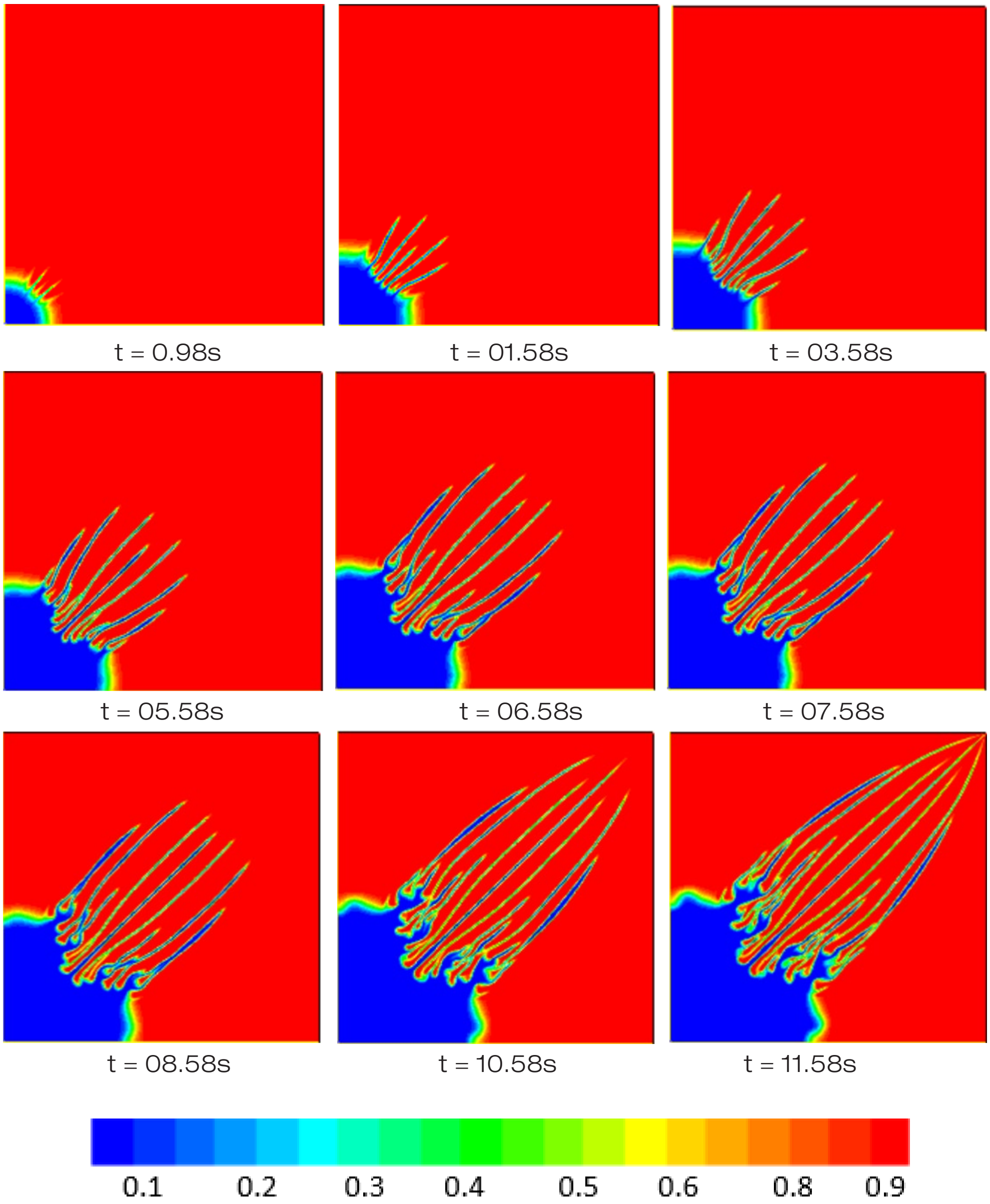

t = 0.98s
t = 01.58s
t = 03.58s
t = 05.58s
t = 06.58s
t = 07.58s
t = 08.58s
t = 10.58s
t = 11.58s

Fig. 4: Oil saturation field versus time in a homogeneous porous medium

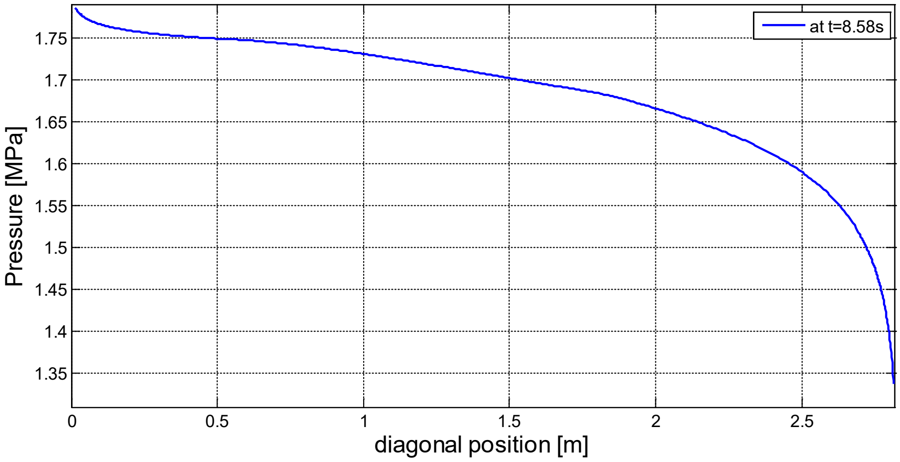


Fig. 5: pressure profile along the diagonal at t=8.58s.

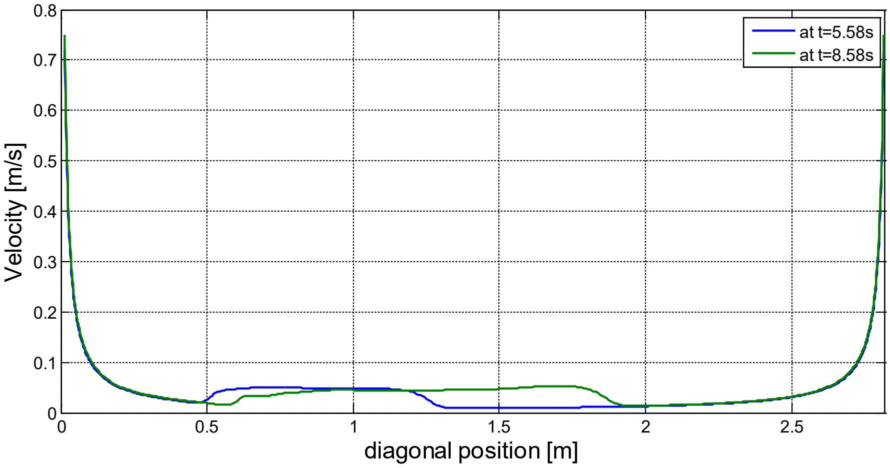
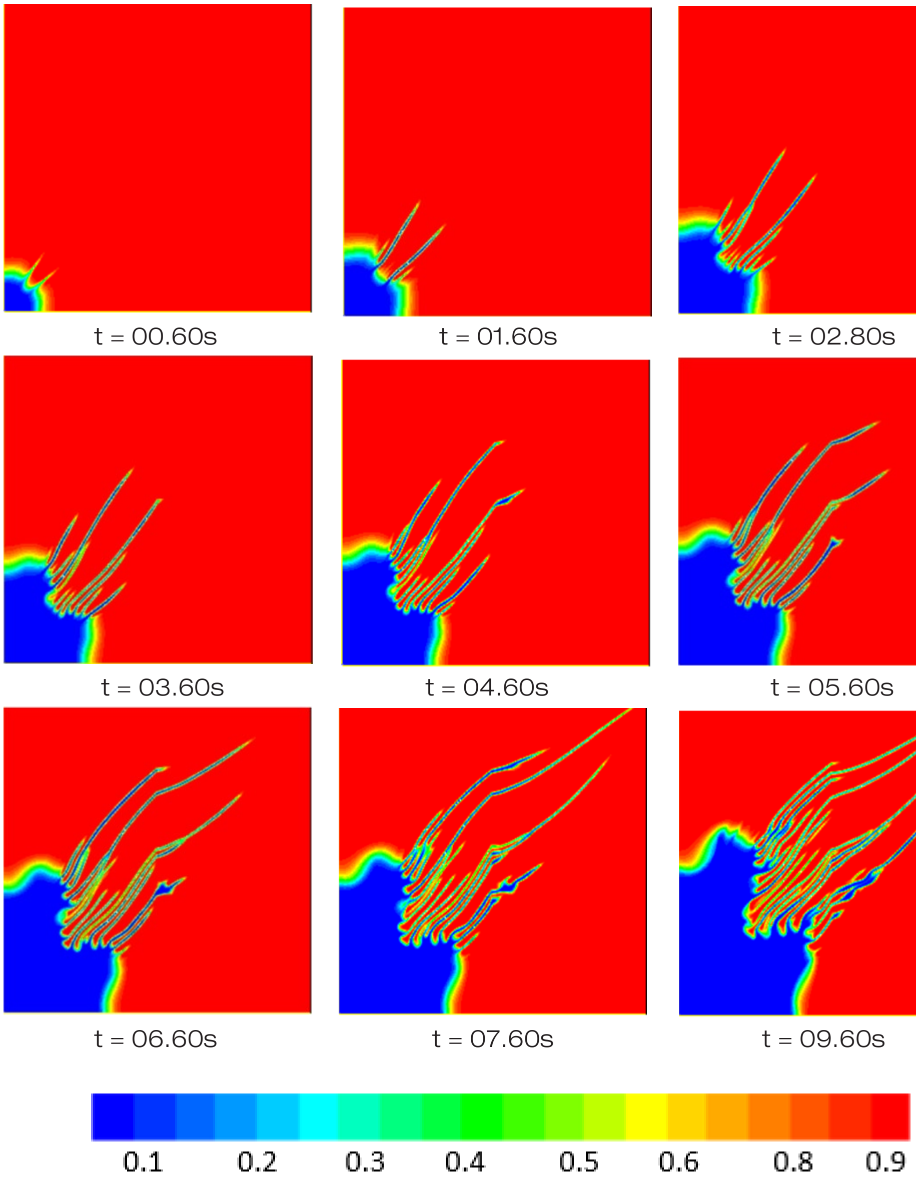


Fig. 6: velocity profile along the diagonal at t=5.58s and t=8.58s.

In order to give a quantitative character to the phenomenon of instability, we represent the number of fingers as a function of time. A dimensionless time, defined by Benyamin Yadali Jamaloei et al, is used for this representation. The dimensionless time is the time of the displacement divided by the breakthrough time [14], [24]. This representation is given for the three studied cases.



t = 00.60s

t = 01.60s

t = 02.80s

t = 03.60s

t = 04.60s

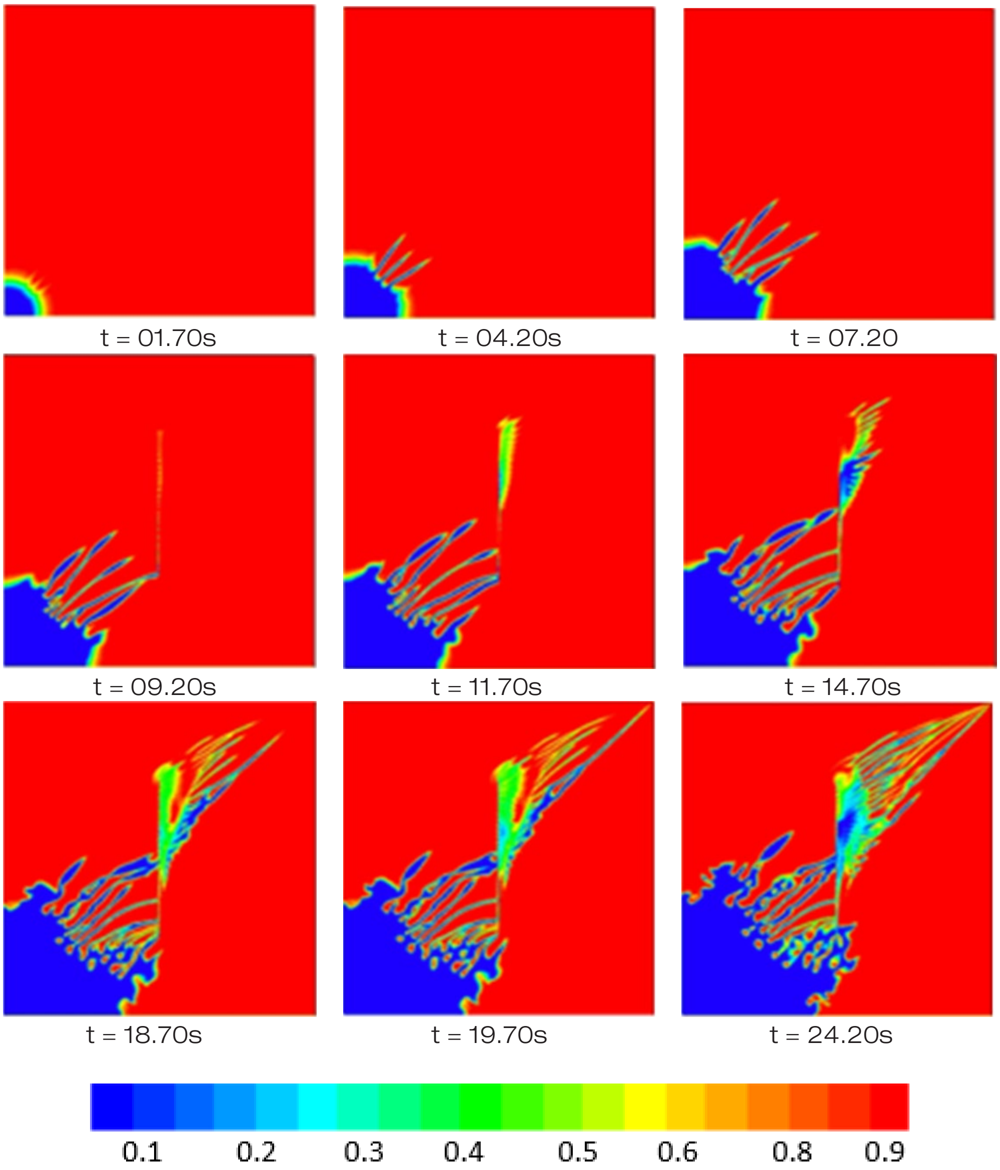
t = 05.60s

t = 06.60s

t = 07.60s

t = 09.60s

Fig. 7: Oil saturation field versus time in a layered porous medium



t = 01.70s t = 04.20s t = 07.20

t = 09.20s t = 11.70s t = 14.70s

t = 18.70s t = 19.70s t = 24.20s

Fig. 8: Oil saturation field versus time in fractured porous medium

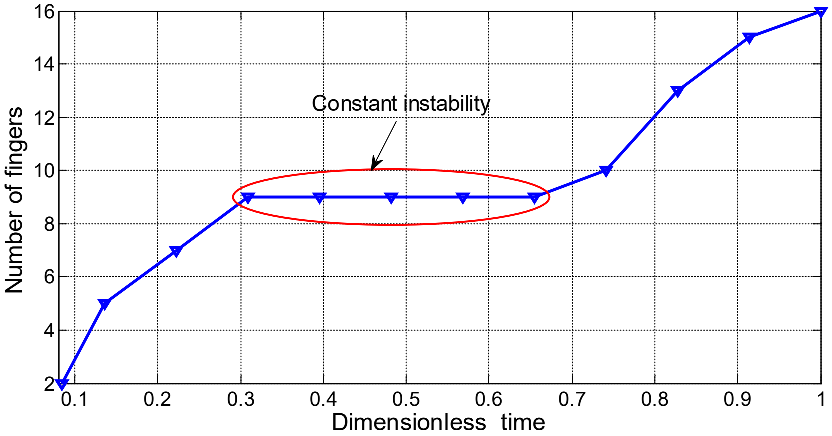


Fig. 9: Number of fingers versus dimensionless time in homogeneous porous medium

According to Fig. 9, the evolution of the instability goes through three stages:

Stage 1: near the injector well, an increase in the number of fingers is quasi-linear.

Stage 2: the instability is constant. The viscous fingers progress in the porous medium but their number remains constant.

Stage 3: near the production well, the instability increases. A quasi-linear increase is also recorded in this region.

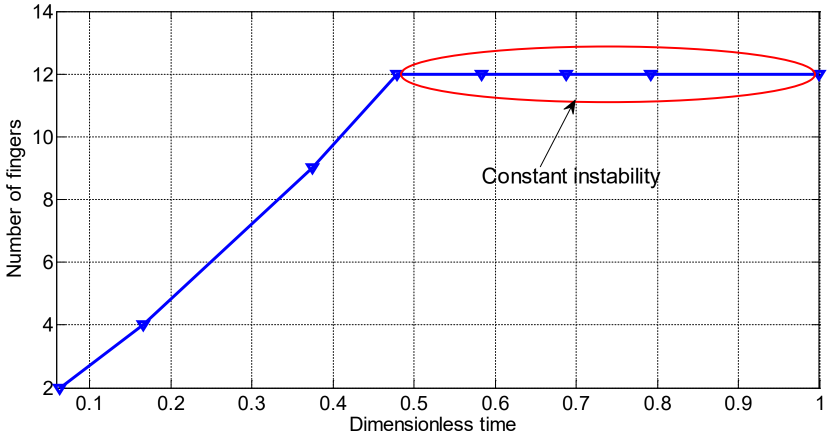


Fig. 10: Number of fingers versus dimensionless time in layered porous medium

Stage 1: In the higher permeability zone, the increase in the number of fingers is quasi-linear.

Stage 2: In the lower permeability zone, the instability is constant.

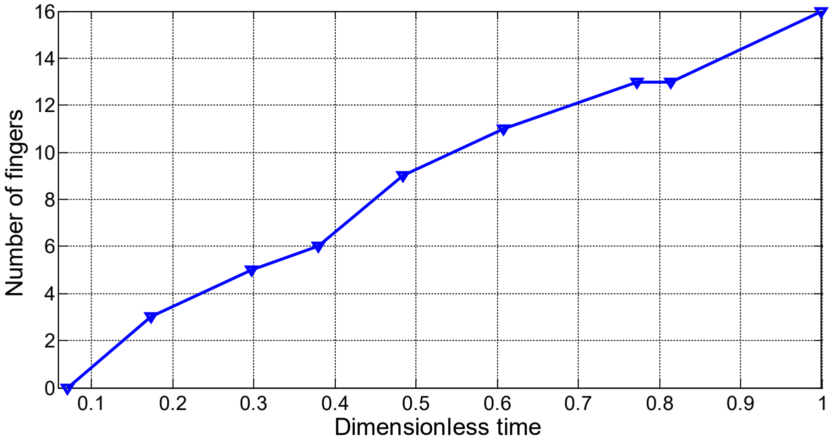


Fig. 11: Number of fingers versus dimensionless time in fractured porous medium

In the presence of the fracture, the instability is very important. The number of viscous fingers increases almost linearly between the injection well and the production well.

CONCLUSION

This paper presents a numerical study of the phenomenon of viscous fingering during water-oil displacement in porous media. The effect of heterogeneity, due to the presence of regions of different permeability and the presence of a fracture, on this phenomenon was examined. The results obtained in this study give good insight into the dynamics of water-oil instability. This dynamic which is directly related to the final oil recovery rate, will lead to a rational use of EOR techniques. This rational use will reduce the problems in relation to costs and environment.

We have observed, in the case of a homogeneous porous medium, that the instability, which is expressed by the number of developed fingers, remains constant in a region located between the injection and the production wells. In the case of a layered porous medium with different permeabilities, the instability is constant in the lower permeability region. However, in the presence of a fracture, the instability always increases.

Consequently, it is in the regions where the instability increases that it is necessary to intervene to apply EOR techniques, not in the regions where the instability is constant.

Finally, it would be more interesting to extend this study for other configurations to determine the behaviour of the instability. A preliminary numerical study for each case is necessary before the use of EOR techniques.

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