Analysis of a drainage efficiency in stratified porous media

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Abstract: The oil recovery from reservoirs formed of more subsurface rock formations can be hindered by the variability of the rocks permeability. This element can strongly influence the oil recovery and the efficiency of the drainage process. In order to understand this phenomenon and to propose a technical solution thereafter, the simulation of an ascending air phase flow in a saturated vertical porous channel, composed of two layers with different permeabilities is done. The numerical study is performed in order to evaluate the effect of injected air mass flow rate, the effect of the porous column width and their permeability variations. The results show that some regions in the channel are not correctly drained due to high pressure losses in those regions.

Key-Words: inertial two-phase flow, pressure drop, recovery process, stratified porous matrix, saturation behavior.

1 Introduction

The injection of gases into liquid saturated porous media is of theoretical and practical interest, notably to mobilize oil from their natural reservoir and to increase the production. A large number of factors can affect this phenomenon, including physical aspect such as the capillarity, viscous and gravity forces [1, 2, 3] or characteristics of geological formations. Currently, full field sophisticated models such as dual porosity and permeability models are commonly used in reservoir simulation. Furthermore, gridding techniques have received great attention in the petroleum literature lately to accurately represent detailed geological features [2].

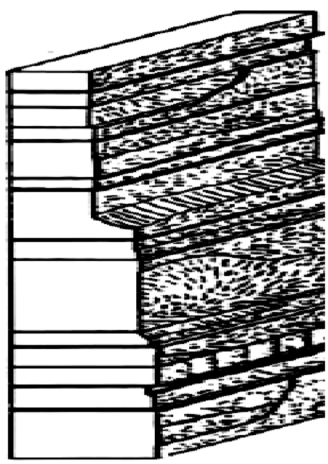

fig.1 example of stratified geological formation

There are several alternatives for modelling multi-phase flow in a heterogeneous porous medium. Current reservoir characterization tools can provide high-resolution reservoir models involving a very large number of gridblocks. Hence, performing accurate flow simulations raise practical problems in terms of computational costs. Upscaling is then used to decrease the number of gridblocks in the flow simulation model, in order to obtain faster runs. This problem is particularly challenging when dealing with two-phase flows, and has been widely investigated for several decades [3]. Another approach consists in searching for a homogenized description for flow at large-scale, in order to find the upscaled form of flow equations [4]. This allows the derivation of intrinsic parameters for the flow at the desired scale and is independent of the size of gridblocks.
For more than 60 years, a large number of models have been developed to characterize the waterflood behaviour of a stratified medium [5]. A great difficulty consists in accounting for the effects of gravity, capillary and viscous forces, that allow fluids to flow from one stratum to another. Viscous forces are particularly difficult to take into account. They are induced by the viscous coupling between the saturation field and the pressure field, via the saturation-dependant mobility term in the pressure equation. It depends on relative permeability curves and on the viscosities of considered fluids. During the waterflood, the saturation field's evolutions make the pressure and velocity fields evolve. This,

in turn, influences the evolution of the saturation field. Such a non-linearity makes it impossible to derive analytical solutions without relying on several assumptions.

Early results have been obtained under capillary or gravity equilibrium assumptions [6], for which viscous forces are negligible compared to other forces. Under this assumption, the local saturation field can be obtained independently of the pressure field. Average properties can then be derived in the vertical direction and this assumption was used to reduce the dimension of the considered system. Another way to overcome the problem of viscous coupling consists in working under the steady-state or quasi-static flows assumptions [7, 8] for which the velocity field is fixed during the flood. For more general cases, however, viscous forces are not negligible and dynamic flows have to be considered. Two main approaches allow to take into account viscous forces. The first approach [9, 10] assumes that layers are non-communicative. As no crossflow can occur from one stratum to another, the effect of viscous forces is to change the injection velocity in each layer, as a function of the injected fluid's position and mobility. At early times, the velocity in each layer is directly proportional to the layer's absolute permeability, and the injected fluid flows faster in more permeable layers. If this fluid is less mobile than the fluid in place, the mobility in a layer will decrease as the front advances, and the injection rate will decrease in more permeable layers. This mechanism tends to reduce the difference in velocity between less permeable and more permeable layers, although it cannot completely stabilize the process. If the injected fluid is more mobile than the fluid in place, on the contrary, the mobility in layers will decrease while flooding, and more permeable strata will always be favored.

The second Approach [11, 12, 13] assumes a perfect communication between all layers. Under this assumption, the crossflow occurs instantaneously between all layers, to rearrange the pressure distribution, such that there is no pressure gradient in the vertical direction. This is a special case of vertical equilibrium, due to viscous forces [14].

The subject of this study is to evaluate the constraints related to the drainage process in a stratified vertical porous media. The matrix initially saturated with a liquid phase is submitted to an ascending air flow with a given mass flow rate (fig.1). We assume that all layers communicate between them. In this approach, the viscous forces are taken into account. The influences of the matrix configuration, the mass flow rate and the permeabilities of strata are analyzed.

2 Problem Formulation

The volume averaging of the momentum and continuity equations for two phase flow liquid and gas phases flowing simultaneously in porous media has been examined by many authors: Slattery [15], Bear and Bensabat [16] and Whitaker [17]. Grosser [18] include in a semi-heuristic momentum equation many effects including, in addition to the microscopic inertial and macroscopic inertial terms, the microscopic interfacial shear stress and microscopic interfacial surface tension gradient force.

The current problem will be described using individual properties of each phase. The Darcy's law which governs the fluid flow in porous media is generalized for two-phase flow, by including the microscopic and macroscopic inertial terms [19], for a steady state as follows: (for i =liquid, gas)

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

The microscopic inertial term (quadratic term) is justified by the fact that for relatively large velocities, an entire excess pressure drop is noticed. In this formulation, the Brinkman term is not considered. Actually, it has a significant influence only when the permeability is relatively important.

In the equation (1), K_i and ε are respectively the effective permeability and the porosity of the porous medium, where:

$$CF_i = \frac{K^{1/2}}{C_E} CF_{ri} \quad (2)$$

K is the permeability of the porous medium, C_E is the Eurgun constant and CF_{ri} is the relative inertial coefficient. Saez and Carbonnell [20] proposed the following correlation to describe CF_{ri}

$$\begin{cases} CF_{rl} = K_{rl} \\ CF_{rg} = K_{rg} \end{cases} \quad (3)$$

The effective permeability for each layer is given as follows:

$$K_{1i} = K_1 . K_{ri} \quad (4)$$

$$K_{2i} = K_2 . K_{ri} \quad (5)$$

and K_{ri} are the relative permeabilities for each phase.

In order to complete the description of the mathematical model the mass balance is considered in a steady state as follows:

$$\nabla(\rho_i \cdot \vec{v}_i) = 0 \qquad (6)$$

2.1 The relative permeability model

The relative permeability concept is introduced to describe the multiphase flows in porous media. Many authors [19] use the Corey model (i.e.) power law functions to describe the relative permeabilities as follows:

$$K_{rl} = S_e^4 \qquad (7)$$

$$K_{rg} = (1-S_e)^2(1-S_e^2) \qquad (8)$$

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

$$S_e = \frac{S_l - S_r}{1-S_r} \qquad (9)$$

2.2 The Capillary pressure models

Since, a general theoretical prediction of the capillary pressure is not obtainable, correlations are obtained from experiments. Several correlations used in the study of isothermal and iso-concentration two-phase flow in porous media are given by Kaviany [19]. The correlations are made either to the imbibition or the drainage experimental data. In order to take into account the variability of the capillary pressure according to permeability, the model of Scheidegger is used [19, 21]. This model presented in the equation (10), shows the relation between the capillary pressure and the saturation

$$\langle P_c \rangle = \frac{\sigma}{(k/\varepsilon)^{1/2}} \cdot \left[0.364\left(1-e^{-40(1-s)}\right) + 0.221(1-s) + \frac{0.005}{s-0.08} \right] \qquad (10)$$

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 (see fig.2). For ($i = l, g$)

$$\begin{cases} u_i\,(x = 0, y) = U_{ie} \quad , \quad v_i\,(x = 0, y) = 0 \\ \left.\dfrac{\partial u_i}{\partial x}\right|_{x=L} = 0 \quad , \quad v_i(x = L, y) = 0 \end{cases} \qquad (21)$$

2.3.2 Conditions on Pressure

Concerning the pressure field, it requires only one condition (gradient). We consider that in the exit side, the fluid is submitted to the atmospheric pressure. On the other hand, the pressure - velocity coupling is solved using the SIMPLE algorithm (Semi Implicit Method for Pressure Liking Equations) [24]. It will permit us to calculate the pressure field, in particular the pressure of injection (in the entry side).

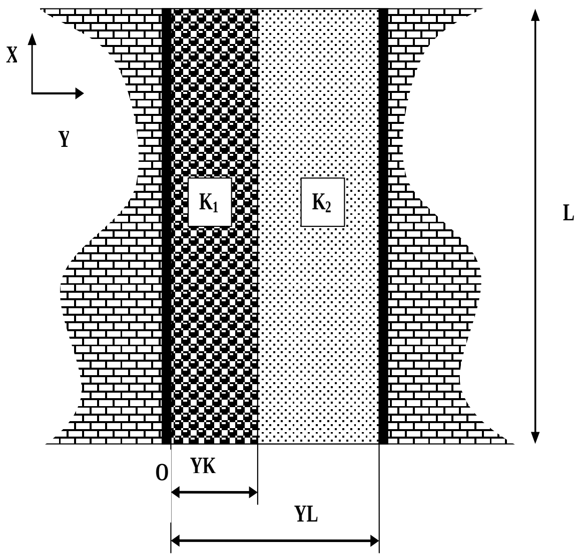

fig. 2 Problem setting

2.3.3 Conditions on gas saturation

We consider that the area at the outlet of the porous massif to be wet at all time. This assumption permits to consider a critical gas saturation $S_{gc} = 0.2$ [1, 18, 19].

2.4 Closure equations

The mathematical model is now completed, considering equations (22) and (23) as follows:

$$P^g - P^l = P_c(s) \qquad (22)$$

$$S_g + S_l = 1 \qquad (23)$$

3 Method of resolution

The governing system is solved using the numerical finite volume. A particular attention is made in the gridding process in order to assure the continuity of the system in the interface between the two layers. The calculated pressures in each phase permit to evaluate the saturation behavior by the slant of the capillary pressure model $P_c(S)$ represented by equation (10).

4 Results analysis

4.1 Test case – Homogeneous porous matrix

In order to compare the results with some previous ones given for one direction, the simulation is made first for a homogenous porous channel [1, 22]. As shown in fig.3 and fig.4, the saturation as well as the capillary pressure behaviors reflect a one dimension (*x direction*) variation of those parameters. Actually, due to the x direction of the injection gas, the homogeneity of the porous matrix and finally due to the weakness of the wall effect compared with the matrix resistance, the saturation remain constant in the horizontal direction. In the previous Work [1], the same results are shown in one direction.

We can conclude from this result that for an increasing gas mass flow rates, we can note an increasing capillary pressure. It permits to deduce that it is necessary to exert an increasing gas injection pressure in order to obtain an increasing flow rate. In this case, gas saturation S_g increases.

4.2 Stratified porous matrix

4.2.1 Influence of the injected gas mass flow rate

The fig.5 shows that the gas saturation in the least permeable region is more important. Actually, we can note from the previous results that the necessary forces applied to maintain a given mass flow rate increase in order to compensate the matrix resistance. Let's add to it an increasing gas mass flow rate which needs increasing forces. This state of fact, lead to a more important capillary pressure difference between the two regions close to the entry side fig.6 and which is responsible of a more gas saturation. As a conclusion, we can certify that for a given imposed pressure in the entry side, the pressure losses in the least permeable region will be more important. As a result, the gas saturation in this region will be weaker.

4.2.2 Influence of the permeability variation

Fig.7 and fig.8 describe respectively the gas phase and the capillary pressure behaviors within the porous massif for a given gas mass flow rate according to permeability in the least permeable region (we maintain K_1 =1.E-10 m²). 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. We can note this time again that the gas saturation in least permeable region is inversely proportional to the permeability. The same explanation provided for the previous case can be used to interpret this result. Indeed, the pressure of injection in the least permeability region is more important than the second region. As a result, the gas saturation becomes more important. Finally we can conclude from this section that two stratified regions with more important difference of permeabilities can generate innacessibleses regions by the injected fluid.

4-2-3 Influence of the porous column width

We can note from fig.9 and fig.10 that the influence of the permeability variation for a given gas mass flow rate between the two layers is localized in the weaker permeability region just at the entry side for *YK/YL* =O.705. This influence becomes more important when *YK/YL* decrease. We can see from fig.9 that the gradient of the capillary pressure between the two regions is very important in the case of *YK/YL* =O.26. It means that for a stratified porous matrix with very different geometrical characteristics, the drainage process can be inefficient in the lowest permeability region.

5 Conclusion

The goal of the current study is to evaluate the influence of some physical and geometrical aspects of a stratified porous channel on the drainage process. The comprehension of those effects can lead for a more efficient fluids recovery (oil …), especially for non-homogenous reservoirs or for highly fractured reservoirs.

As a conclusion of this study, we can certify that for a given imposed pressure in the entry side, the pressure losses in the least permeable region will be more important. As a result, the gas saturation in this region will be weaker. On the other hand, we can conclude from the permeability variation analysis section that two stratified regions with more important difference of permeabilities can generate innacessibleses regions by the injected fluid. Finally, the analysis of the geometrical aspect show that the drainage process can be inefficient in the lowest permeability region and the injected fluid follows the least resistant path. These last results explain some failures in the oil recovery from reservoirs fractured artificially, like “Rhourd El Baguel” oil field, the second more important field in Algeria. The perspective of this study is to provide some solutions using some geometrical modifications of the reservoir in order to produce adjustments in the pressure distribution.

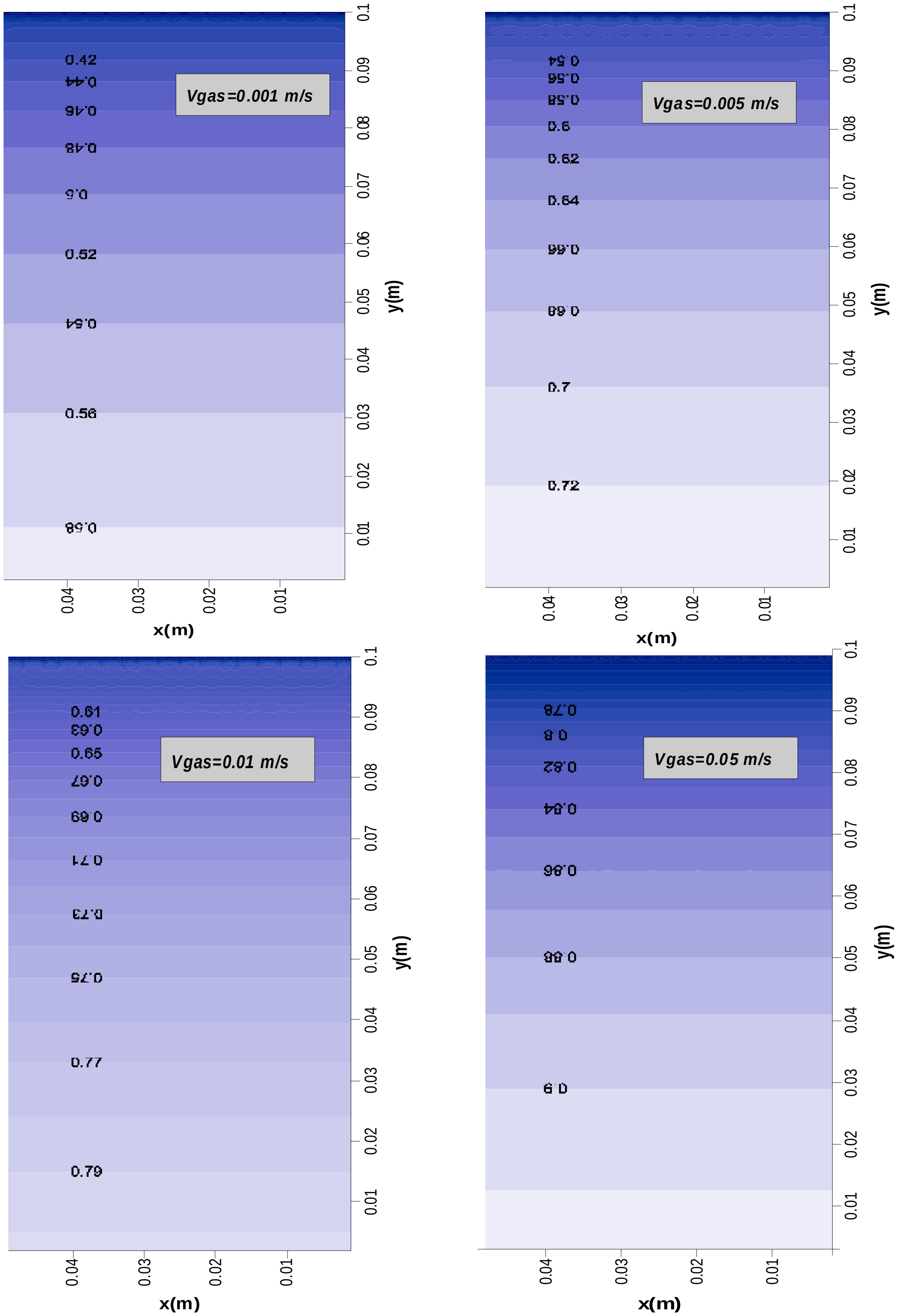

fig.3 Influence of the gas mass flow rate on the saturation behaviour in the case of homogenous porous channel $K=2.E\text{-}13\ m^2$

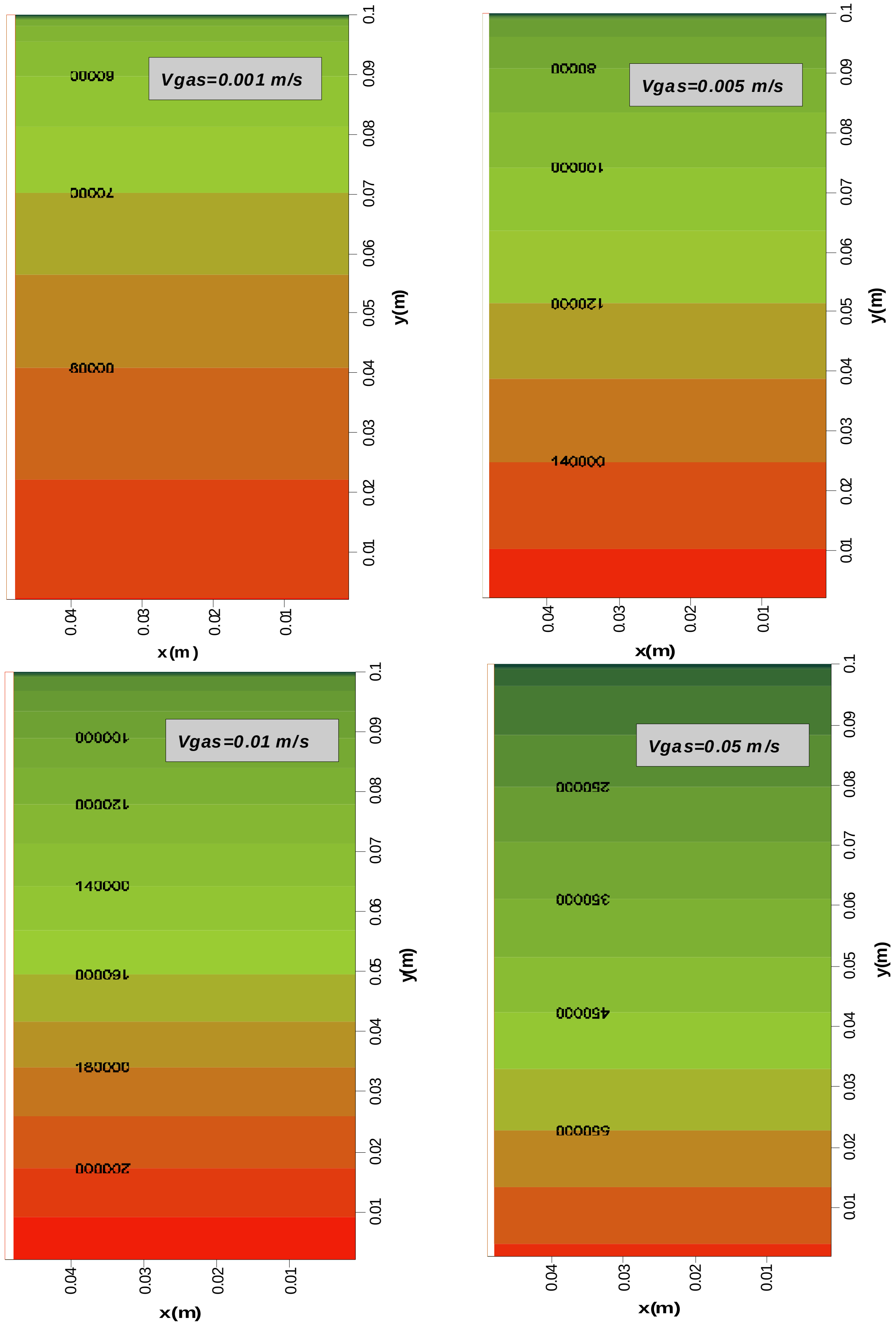

fig.4 Influence of the gas mass flow rate on the capillary pressure behaviour (Pa) in the case of homogenous porous channel $K=2.E\text{-}13\ m^2$

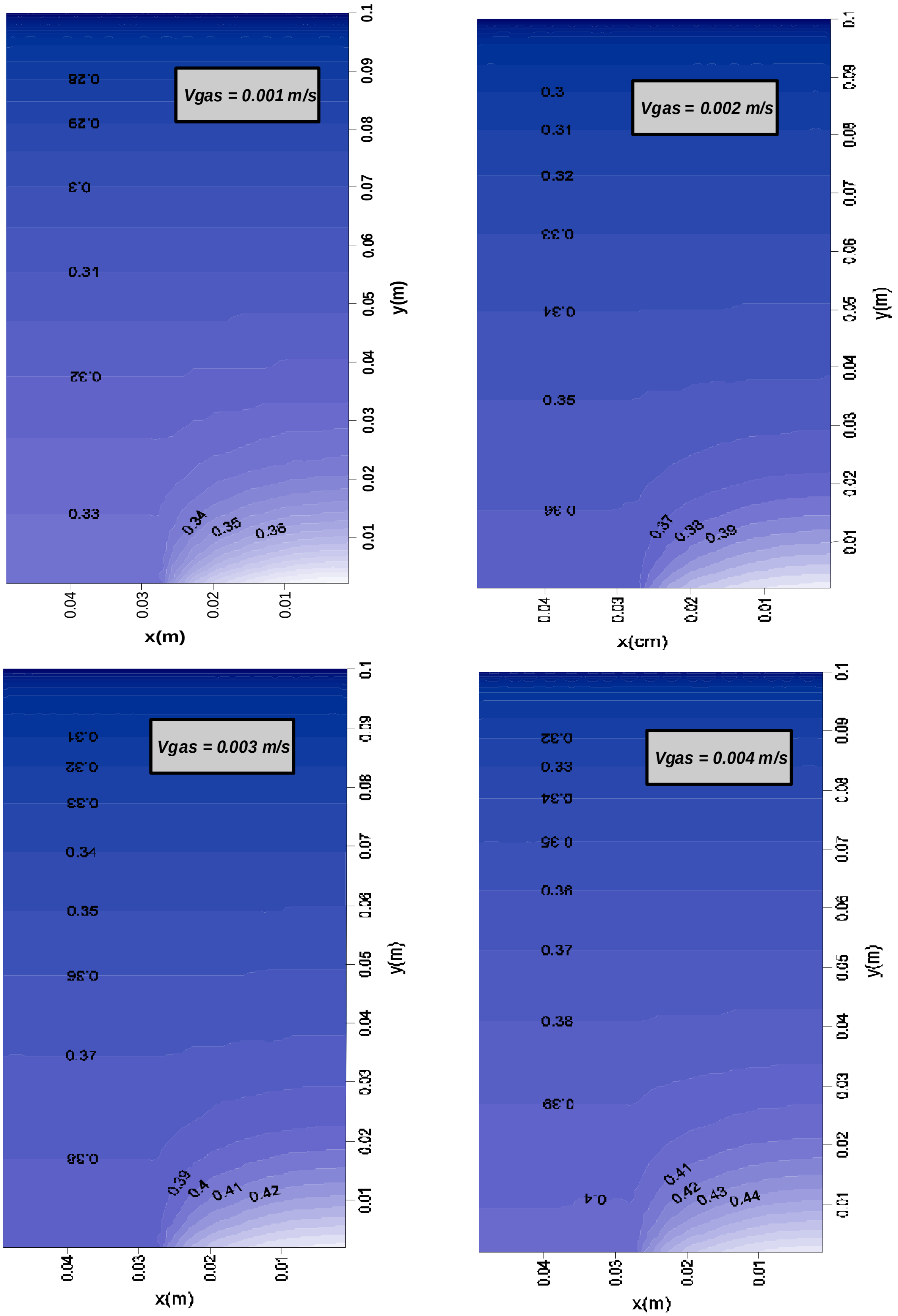

fig.5 Influence of gas mass flow rate on saturation behaviour in the case of the stratified porous channel (*YK/YL=0.5*), $K_1=1.E\text{-}10\ m^2$, $K_2=2.E\text{-}13\ m^2$

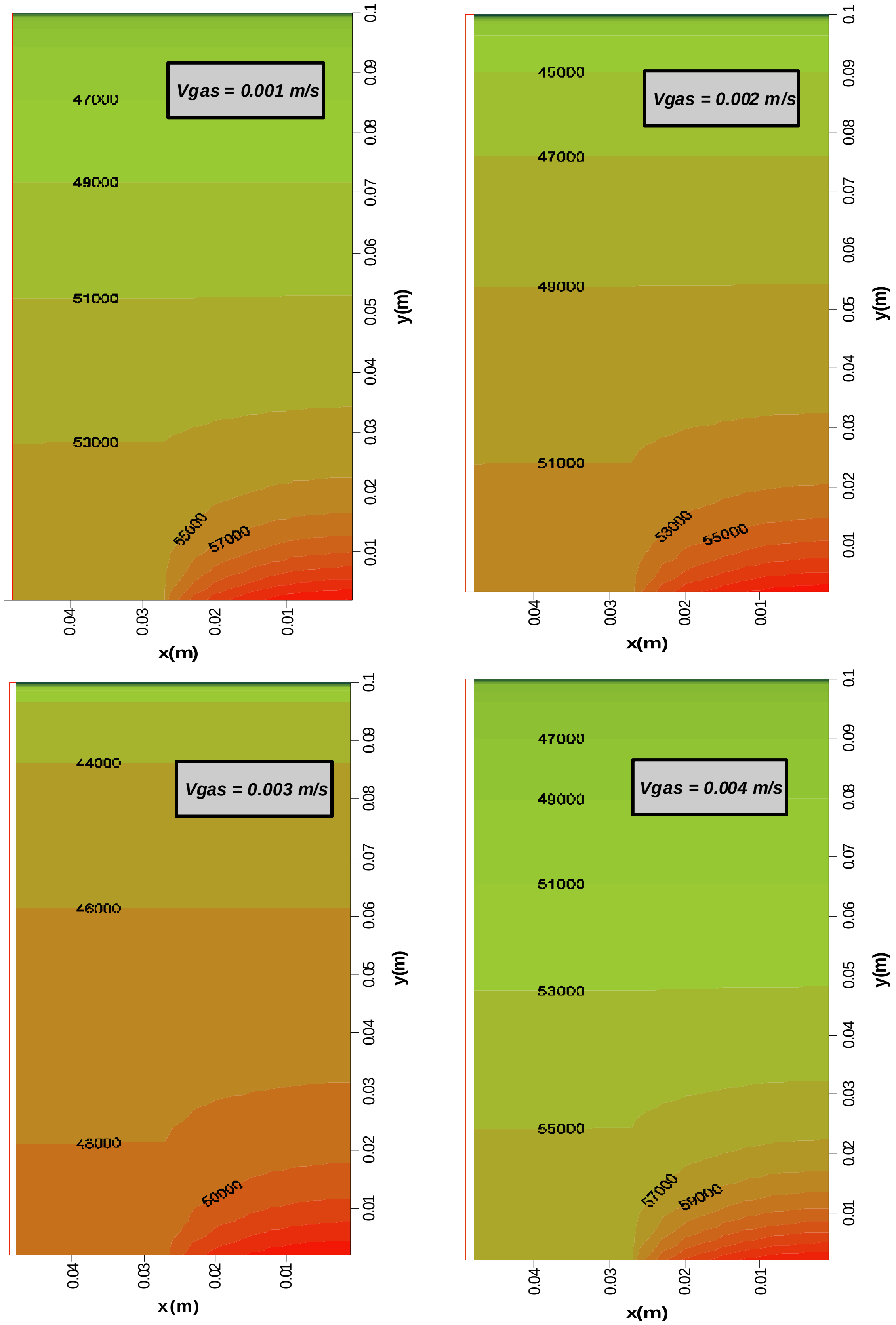

fig.6 Influence of gas mass flow rate on capillary pressure behaviour (Pa) in the case of the stratified porous channel (*YK/YL=0.5*), $K_1=1.E\text{-}10\ m^2$, $K_2=2.E\text{-}13\ m^2$

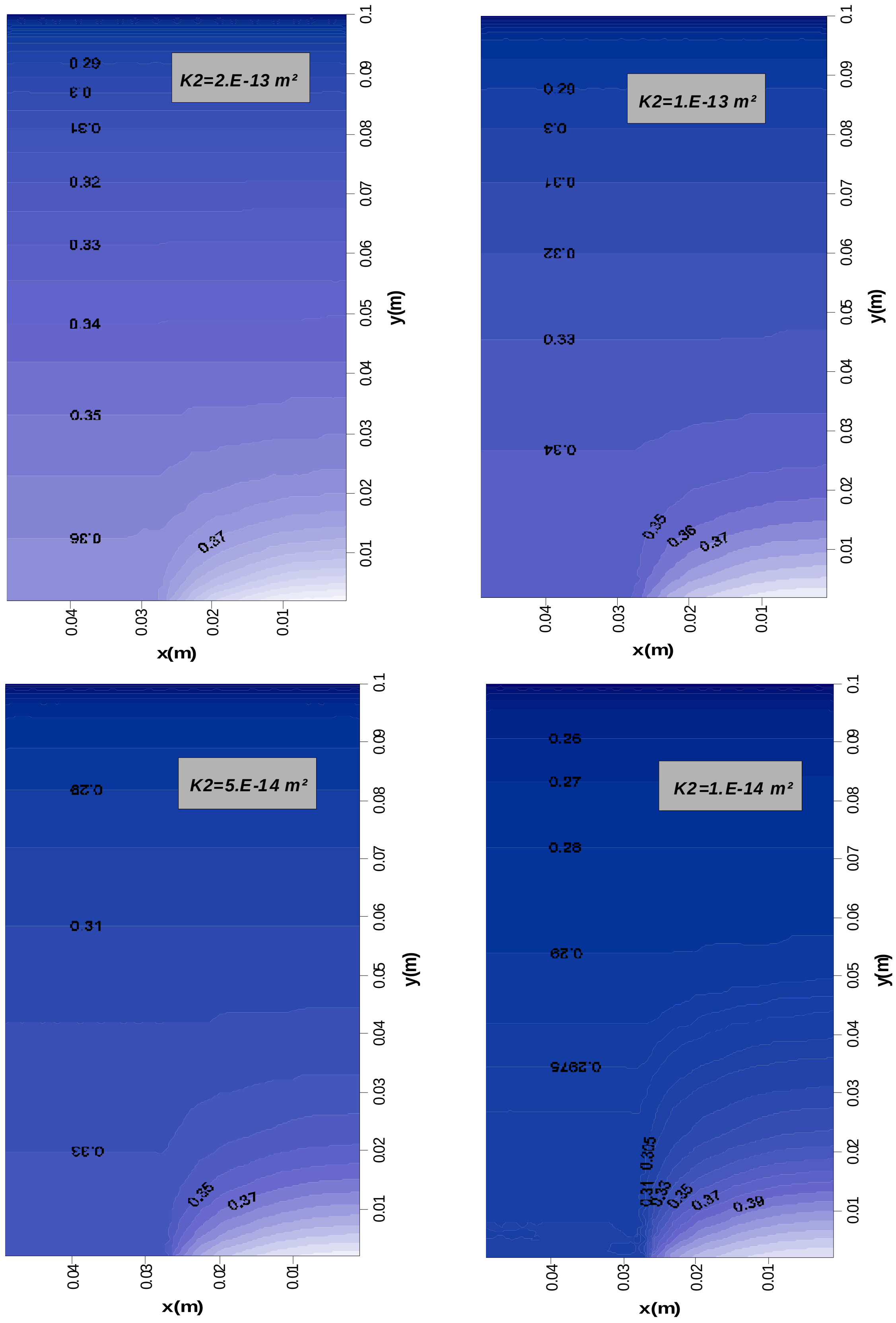

fig.7 Influence of the permeability's variation on the saturation behaviour in the case of the stratified porous channel (*YK/YL=0.5*), $K_1=1.E\text{-}10\ m^2$, $v_{gas}=0.001\ m/s$

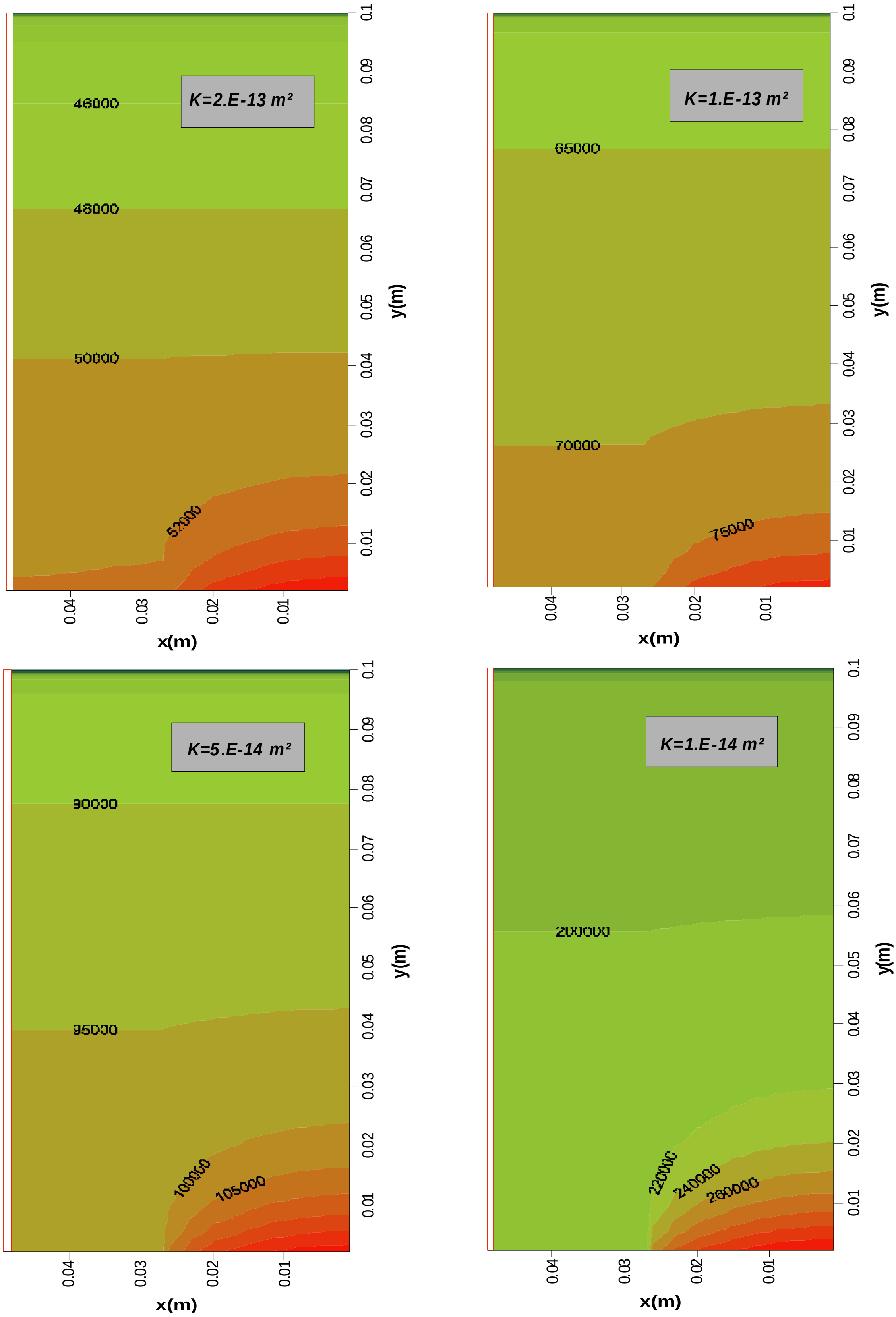

fig.8 Influence of the permeability's variation on the capillary pressure behaviour (Pa) in the case of the stratified porous channel (*YK/YL=0.5*), K_1*=1.E-10 m²*, v_{gas} *=0.001 m/s*

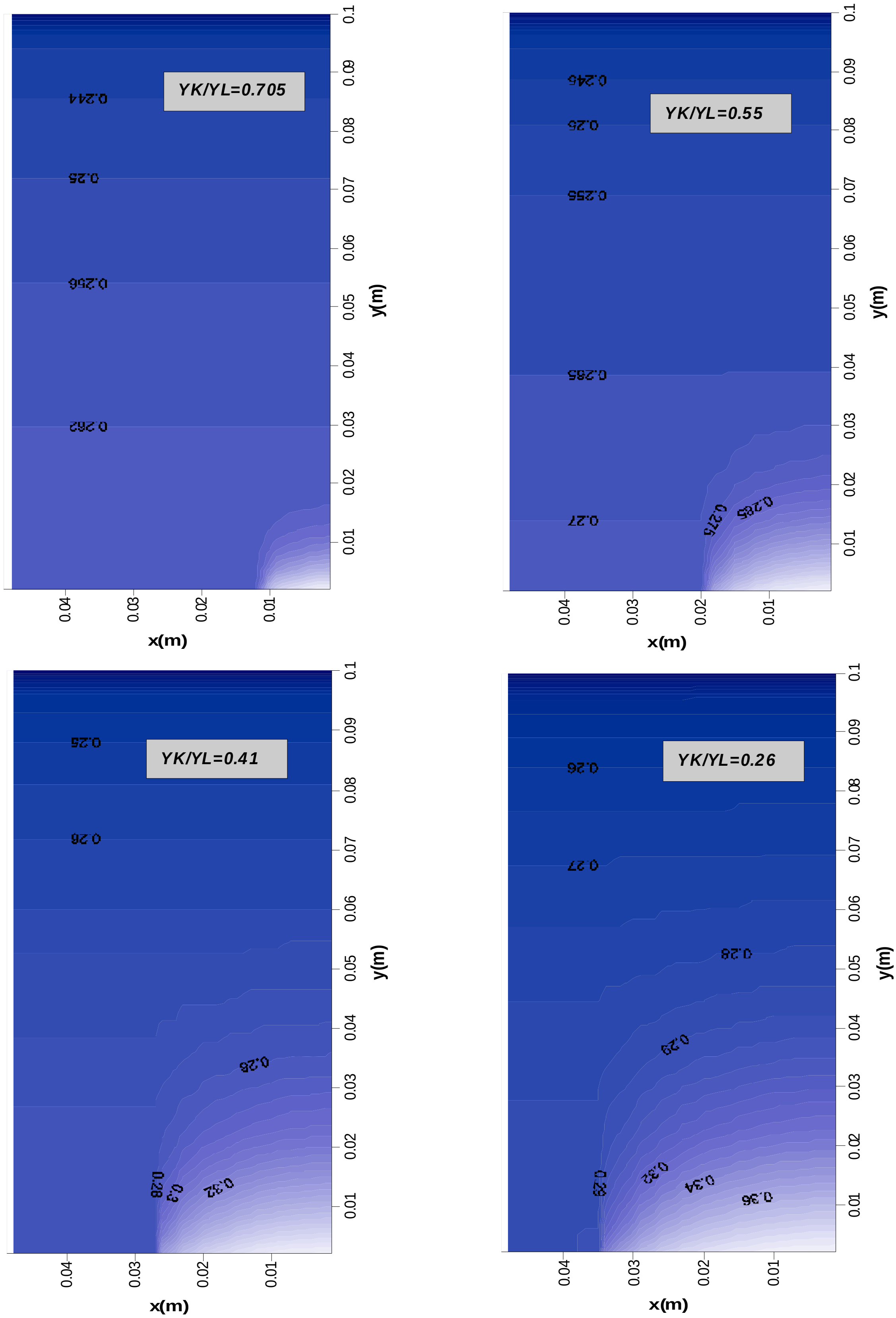

fig.9 Influence of the column width on the saturation behaviour in the case of the stratified porous channel K_1=1.E-10 m², K_2=2.E-13 m², v_{gas} =0.001 m/s

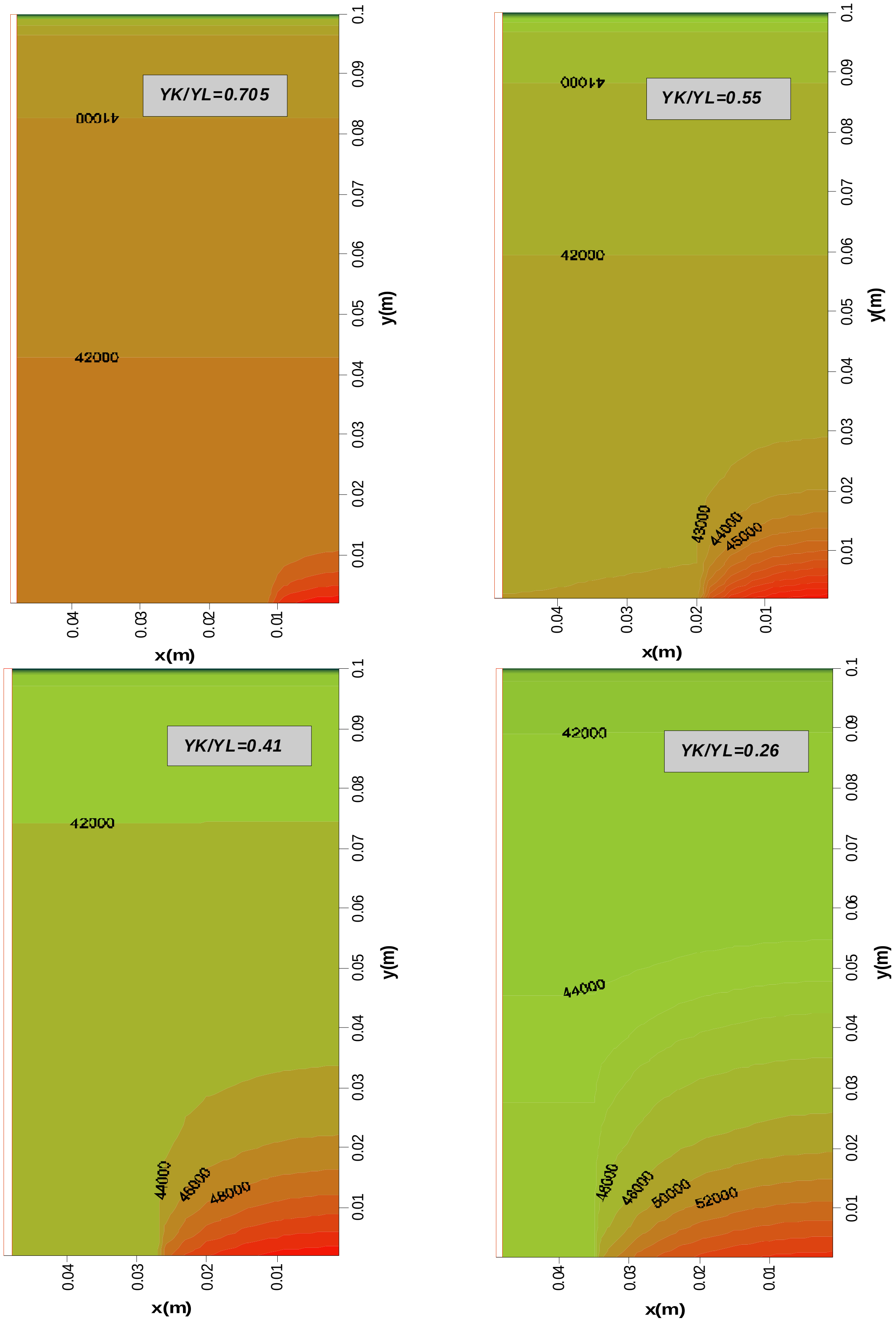

fig.10 Influence of the column width on the capillary pressure behaviour (Pa) in the case of the stratified porous channel K_1=1.E-10 m², K_2=2.E-13 m², v_{gas} =0.001 m/s

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