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International Journal of Multiphase Flow 28 (2002) 1965–1981

International Journal of Multiphase Flow

www.elsevier.com/locate/ijmulflow

Experimental study of two-phase flow in three sandstones. II. Capillary pressure curve measurement and relative permeability pore space capillary models

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Received 29 March 2001; received in revised form 12 August 2002

Abstract

By means of the porous plate method and mercury porosimetry intrusion tests, capillary pressure curves of three different sandstones were measured. The testing results have been exploited jointly with three relative permeability models of the pore space capillary type (Burdine's model type), these models are widely used and in rather distinct fields. To do so, capillary pressure has been correlated to saturation degree using six of the most popular relations encountered in the literature. Model predictions were systematically compared to the experimentally measured relative permeabilities presented in the first part of this work. Comparison indicated that the studied models underestimate the water relative permeability and over-estimate that of the non-wetting phase. Moreover, this modeling proves to be unable to locate the significant points that are the limits of fields of saturation where the variation of the relative permeabilities becomes consequent. We also showed that, if pore structure is modeled as a "bundle of capillary tubes", model predications are independent of the capillary pressure curve measuring method.

Keywords: Experiments; Capillary pressure curves; Mercury porosimetry; Models; Relative permeability

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0301-9322/02/$ - see front matter

PII: S0301-9322(02)00091-5

1. Introduction

Two-phase flow in porous rocks is encountered in several important applications, including oil production, enhanced oil recovery, gas storage techniques, etc. Attempting a theoretical solution of two-phase flow would require a great deal of information, which is not always available. In practice, the problem is circumvented by using macroscopic equations based on the relative permeability concept and on the capillary pressure curves (Dullien, 1992; Marle, 1981).

The term of relative permeability is usually introduced to make clear the dependence of effective phase permeability on the degree of saturation for a given phase (Kaviany, 1991; Ramakrishnan and Capiello, 1991). The capillary pressure, defined as the difference in pressures acting on both sides of menisci subsisting in pore space, is related to the saturation of a given phase through capillary pressure curves. While several modeling types are proposed for the relative permeability curves (empirical, statistical, pore scale network models) (Dullien, 1992; Bear, 1988), capillary pressure curves have to be determined by experiment (Auriault, 1987).

The present work aims at characterizing the simultaneous flow of gas and liquid phases in three different sandstones: two Vosges sandstones and a Fontainebleau one. In a previous publication (Dana and Skoczylas, submitted for publication), the authors presented the relative permeability curves of the three mentioned rocks, in parallel with the experimental procedure and set-up adopted. This article will focus on the measuring of the capillary pressure curves by two different methods: the porous plate method and by the more classic mercury porosimetry intrusion tests. Using six different correlations, experimentally obtained results will be exploited jointly with three pore space capillary type models (Burdine type models) to predict relative permeability curves. Model prediction will be systematically compared to measured relative permeabilities.

The Burdine type models studied are of special interest since they are frequently employed (Lewandowska and Laurent, 1999; Tanai et al., 1997; Mayer et al., 1992; Firoozabadi and Aziz, 1991) and usually adapted/adopted as a good approximation for use in parallel with multiphase flow simulators by environmental engineering researchers (Oostrom and Lenhard, 1998; Guarnaccia et al., 1997; Katyal et al., 1991; Lenhard and Parker, 1987; Parker et al., 1987). They also have the advantage of producing simple analytical expressions of the relative permeability.

It is worth mentioning, however, that pore level investigations are now possible and are already used to study the evolution of relative permeability as a function of saturation (e.g. Bekri et al., 2001).

2. Capillary pressure curve measurement

2.1. Experimental set-up and procedure

In the following, we present the results and the experimental methods aimed at measuring the capillary pressure curves. The first is the porous diaphragm method (the Welge method). The second is the classic mercury porosimetry method, which is generally used to determine pore size distribution and so will not be discussed in detail here.

The Welge method is based on the drainage of a sample initially saturated by the wetting phase. The studied sample remains in contact with a semi-permeable diaphragm which, at pressures lower than the breakthrough pressure, is permeable only to the wetting phase. The latter communicates through the diaphragm with the atmosphere. The non-wetting phase confining the sample is maintained at a constant pressure in order to penetrate and to expel the saturating fluid towards graduated capillaries. Balance is accomplished when the flow of the wetting phase through the diaphragm is no longer observed. Using the total volume driven out, the saturation of the sample corresponding to this capillary pressure ($P_c = P_{nw} - P_{atm}$) is determined. By increasing the pressure of the non-wetting phase in small steps, we determine the states of balance which follow. The cycle described above corresponds to drainage, lowering non-wetting phase pressure will enable us to obtain the relation $P_c = P_c(S_w)$ in imbibition. The major difficulty of this type of measurement arises from long time periods necessary to the establishment of equilibrium (Marle, 1981), and from problems related to gas dissolution.

The experiments of drainage conducted in this work were carried out using the experimental set-up represented by Fig. 1.

The testing cell (capacity of 60 MPa) is well adapted for cylindrical samples 37 mm in diameter and 70 mm high or more. In order to curtail the experiment time, 32 mm high test samples were used.

The sample (1) lies on a porous ceramic disc (2), i.e. the semi-permeable diaphragm, which is in contact with a metallic diffuser (3). The latter's role is to facilitate the arrival of the fluid expelled towards the drainage system of the cell. These three components are wrapped in a thin layer of adhesive inside the rubber sealing (4). A spring (6) was inserted between the plate of injection (7) and the sample in order to improve the contact between the various components. The gas injection (5) is ensured by the supply reservoir (11). The gas pressure is controlled by the valve (9) and directly measured using the pressure gauge (8). In order to reduce the possible variations of the pressure due to the penetration of the sample, a surge tank (10) of much greater volume than the samples pore volume was used. The graduated capillaries (12), one of which is separated and the second in contact with the sample saturating fluid, allow the measurement of volume evaporated and expelled respectively. The premises on which the testing takes place are kept at a constant temperature of 20 °C so as to avoid any influence from temperature variation on gas pressure, viscosity and surface tension of the fluids used.

The tests are carried out in two stages:

(I) The first one is reserved for determining the sample pore volume. The sample is placed for 48 h in a drying oven at 105 °C. Thereafter, it is mounted in the testing cell and is saturated by forcing the wetting fluid flow. The complete saturation of the sample is considered completed when the absence of any air bubble in the downstream piping leading to the capillaries is observed for at least 12 h. The sample is then taken out of the cell, and the comparison of the sample weights, dry and saturated, makes it possible to determine porosity and pore volume. This first phase can last, for materials tested, from 3 to 14 days according to the permeability of the unit "sample and porous plate". During saturation, the sample is assembled exactly in the same manner as that in the following phase of the experiment in order to observe the same conditions.

(II) In the second stage, the specimen is assembled and saturated, again in accordance with the first step. This constitutes a necessary stage so that the continuity of the wetting phase through the sample and the porous diaphragm is ensured. Thereafter, the saturating fluid

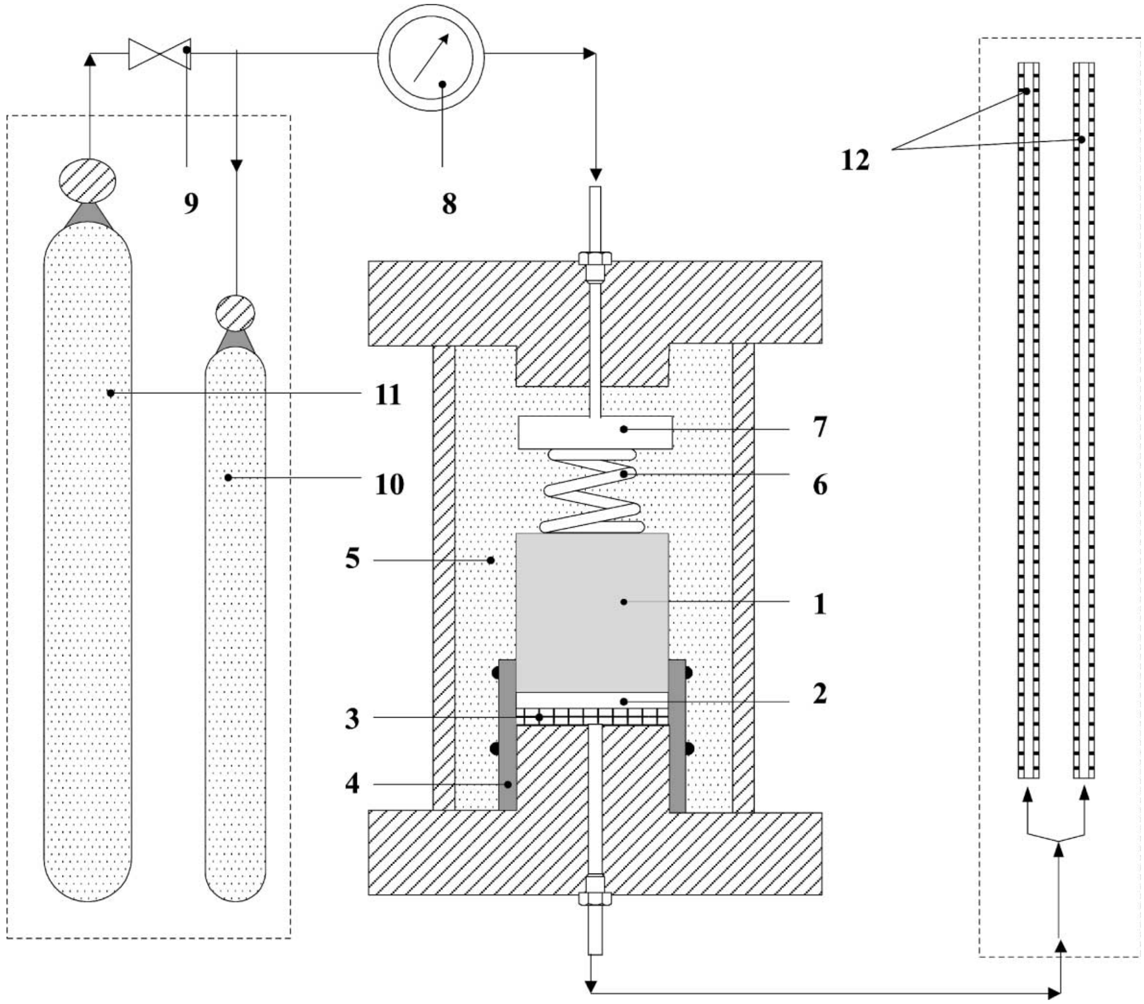

Fig. 1. Experiment of drainage: experimental set-up with: (1) sample, (2) semi-permeable diaphragm, (3) diffuser, (4) rubber sealing, (5) injection gas, (6) contact spring, (7) injection plate, (8) pressure gauge, (9) control valve, (10) surge tank, (11) feed reservoir, (12) graduated capillaries.

is drained from the sample by the application of a constant gas pressure. The expelled volume of the fluid corresponding to this pressure is deduced from the height of the water column read in the graduated capillaries. Since the saturating fluid is always in contact with the atmosphere via the capillaries, the capillary pressure is thus equal to the imposed gas pressure. The equilibrium between capillary pressure and saturation is considered to be achieved when the height in the capillaries remains constant, the criterion is to observe stabilization for 18 h at least. The increase in the capillary pressure by small steps allows the determination of the corresponding saturation degrees and the capillary pressure curve is obtained. The test is stopped when the first gas bubbles are observed in piping downstream of the sample. In this work, the average duration of this phase of drainage experiment was 2–3 months.

Remark

- It is significant to maintain good contact between the sample tested, the porous disc, diffuser, and the testing cell, not only to ensure the continuity of the pressure through these different components, but also to prevent the accumulation of the saturating liquid on the level of these interfaces. Such accumulations can lead, during increase in the gas pressure, to expelled volumes much greater than the sample pore volume.
- The residual saturation measured at the end of the test should not be interpreted as a definite value of residual saturations, the appearance of air bubbles downstream of the core sample can be the consequence of the release of gases dissolved in the saturating liquid or of an unspecified leakage. This was the case in our tests where the imposed capillary pressure never reached the breakthrough pressure of the semi-permeable disc.

2.2. Materials and results

This paragraph is reserved for the presentation of capillary pressure curves obtained either by the mercury porosimetry method or by the porous diaphragm method. Two Vosges and one Fontainebleau type of sandstone were studied using experiments presented above. The samples used were cylindrical in form, 37.0 mm in diameter and 32.0 mm high. Table 1 summarizes their principal characteristics. A liquid, water, was employed as the wetting fluid with Argon U as the gas of injection. The principal characteristics of these fluids are summarized in Table 2. The breakthrough pressure of the porous diaphragm is 300 kPa.

After the saturation of the sample, the gas is let into the testing cell at a constant pressure and in small steps. The first two steps of drainage are carried out with a gas pressure of 5 and 10 kPa, respectively. Thereafter, the pressure step is fixed at 10 kPa until the saturation of the sample becomes lower than 50%, starting from this point, the pressure increase is fixed at 20 kPa until the end of the test. When gas bubbles appear in piping leading to the capillaries, the sample is taken

Table 1
Tested rock characteristics

	ρ_B	ρ_S	ϕ_{total}	S_{BET}	K
Vosges-1	2.15	2.59	17	0.64	5.0×10^{-13}
Vosges-2	2.06	2.57	20	3.10	2.0×10^{-14}
Fontaine	2.36	2.60	9.5	0.03	2.0×10^{-13}

where ρ_B, ρ_S are, respectively, the bulk and skeletal density (g/cm^3), ϕ_{total} is the total porosity (%), S_{BET} is the specific surface (m^2/g), and K is the average intrinsic permeability (m^2) of the core sample.

Table 2
Utilized fluid characteristics at 20 °C

	Viscosity (cP)	Surface tension (mN/m)	Viscosity ratio μ_g/μ_l
Argon	0.0226	–	–
Water	1.0	72.8	0.0226

out of the cell, its saturation is checked by weighing and is compared with that determined by expelled total volume. For the tests conducted, a deviation of 2–3% was found. This variation is probably due to the volumes accumulated in the assembly used.

The tests of mercury porosimetry were carried out using commercialized equipment (Poresizer 9320 V2.03). To ensure the repetition of the results obtained, each sandstone studied was the subject of two experiments. The two tests gave similar results.

The comparison of the results obtained, either by the test of drainage or by the injection of mercury, for the three sandstones is given in Fig. 2. Fig. 3 depicts water saturation as a function of capillary pressure deduced from obtained results of porosimetry tests with mercury injection. This

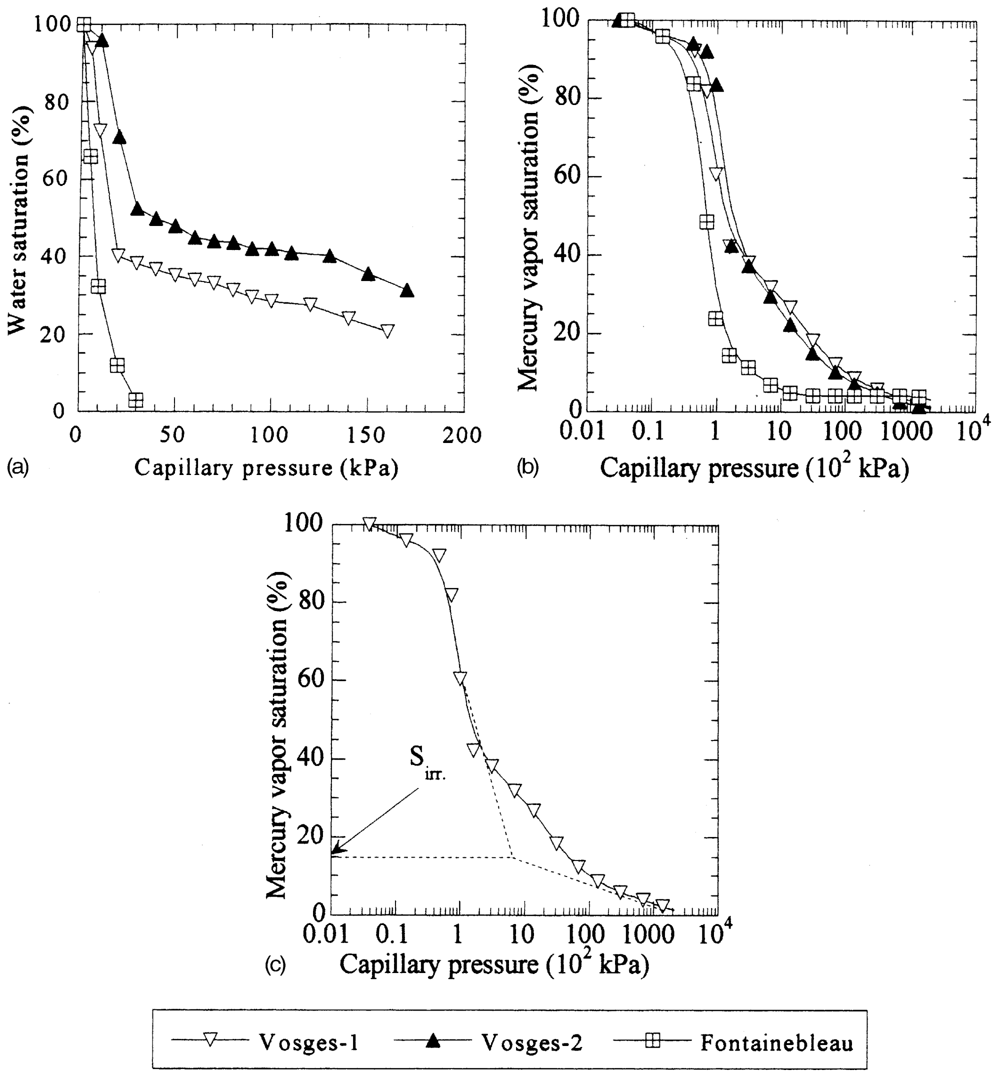

Fig. 2. Comparison of capillary pressure curves obtained by the porous plate method (a) and by the mercury porosimetry method (b); (c) determination of wetting-phase residual saturation.

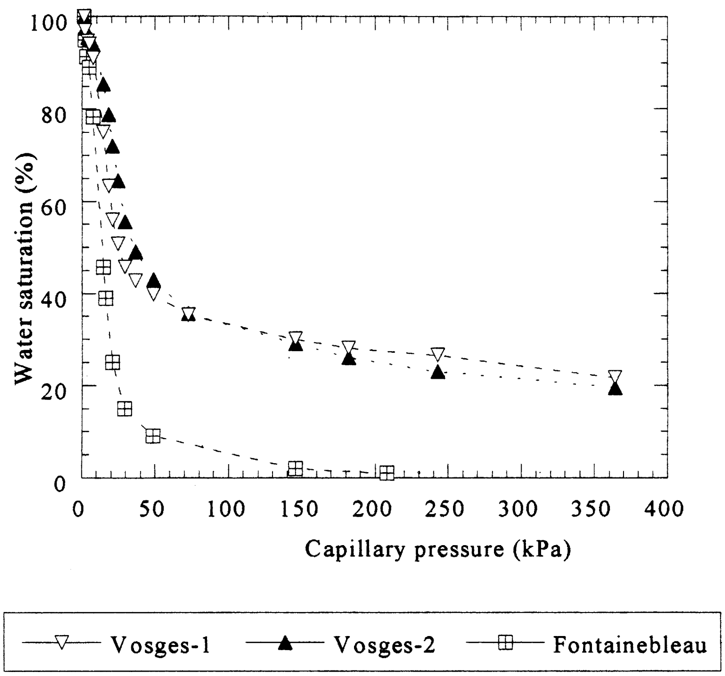

Fig. 3. Capillary pressure curve deduced from mercury porosimetry.

allows an easier comparison with Fig. 2a and shows that the differences between capillary pressure curves obtained by the two tests remain acceptable given the simplistic picture of the pore structure as considered in the "bundle of capillary tubes model". To correlate both tests, system characteristics used in plotting Fig. 3 are as follows: water–air interfacial tension is 72.8 mN/m with zero contact angle, for mercury-vapor system superficial tension is 480 mN/m, and the contact angle measured through mercury vapor is 40°.

Pore size distribution is obtained by using the "bundle of capillary tubes" model. As concluded in the last part of the present work, using this model with capillary curves emanating from the drainage or mercury intrusion experiments would lead to the same pore size distribution (see also Dana, 1999).

The curves of capillary pressure determined by the drainage or mercury porosimetry tests show the same total tendencies and this for the three studied sandstones (Fig. 2a and b). An estimate of the values of the breakthrough pressure and residual wetting-phase saturation of the three sandstones are given in Table 3. Residual wetting-phase saturation is determined as shown in Fig. 2c.

Residual saturation values, for the two Vosges sandstones, are in good agreement with those obtained by Dana and Skoczylas (submitted for publication) during two-phase steady-state experiments (30% for Vosges-1 and 38% for Vosges-2). For the Fontainebleau sandstone difference in residual saturation is, however, more important (3.5% against 15%). Authors believe that this is a result of problems related to samples tested as reported in Dana and Skoczylas (submitted for publication).

Table 3
Estimate based on drainage tests and mercury porosimetry

	Drainage test		Mercury porosimetry	
	P_c^b (kPa)	S_{irr} (%)	P_c^b (kPa)	S_{irr} (%)
The Vosges-1	7.5	30	83	15
The Vosges-2	12.5	45	97	15
Fontainebleau	<5	3.5	47	5

In the drainage tests where the surface tension is not very high, we also underline that the homogeneous (narrow) porosity of the sandstone of Fontainebleau (as reported by Dana and Skoczylas, submitted for publication) produced a convex-like curve (Fig. 2a) contrary to the conventional S-shape curves presented by the other sandstones. Some numerical results have been presented along this line by Jerauld and Salter (1990).

3. Capillary pore space models

Three models of the capillary pore space type are studied here: Burdine's equation (known also as Wyllie and Gardner's model), Childs and Collis-Georges, and Mualem's model. A detailed description of these models can be found in Dullien (1992) and Bear (1988). The objective of these models is to determine the relative permeability on the basis of the pore space characteristics as deduced from the capillary pressure curves or from mercury intrusion curves. Capillary hysteresis are not taken into account, and this type of model ascribes all pore volume to the pore entry radius (Dullien, 1992). The general methodology specific to these models is based on three principal assumptions (Mualem, 1986):

1. The porous medium is seen as a group of inter-connected cylindrical straight pores and arbitrarily distributed in the sample. The pores are defined by a characteristic length, called the "pore entry radius" (R), and statistically described by a density function $f(R)$. Surface porosity remains unchanged whatever the section considered.
2. In an elementary porous unit, the flow is regarded as a flow of the Hagen–Poiseuille type. The individual conductivity of each pore is calculated by the traditional analogy with the law of Darcy. The total conductivity of the medium is obtained by integration on all the pores saturated—the majority with these models are written for the wetting phase—participating in the flow.
3. The pore size distribution of the rock can be obtained from the capillary pressure curves (P_c–S_w). Laplace's law of capillarity relates the radius (R) to the capillary pressure (P_c) at which the pore is filled or drained.

These models are different, primarily, in the way in which the geometry of the elementary porous unit and its participation to the total permeability are interpreted (for further details see Dana, 1999).

In their final forms, Burdine's equations can be written as follows (Dullien, 1992):

$$k_{\mathrm{rw}}(S_{\mathrm{e}}) = [S_{\mathrm{e}}^2] \int_0^{S_{\mathrm{e}}} \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}^2(S_{\mathrm{e}})} \Big/ \int_0^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}^2(S_{\mathrm{e}})} \tag{1a}$$

$$k_{\mathrm{rnw}}(S_{\mathrm{e}}) = [(1 - S_{\mathrm{e}})^2] \int_{S_{\mathrm{e}}}^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}^2(S_{\mathrm{e}})} \Big/ \int_0^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}^2(S_{\mathrm{e}})} \tag{1b}$$

The model of Mualem may be written in the form (Mualem, 1976):

$$k_{\mathrm{rw}}(S_{\mathrm{e}}) = [S_{\mathrm{e}}^n] \left(\int_0^{S_{\mathrm{e}}} \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}(S_{\mathrm{e}})} \Big/ \int_0^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}(S_{\mathrm{e}})} \right)^2 \tag{2a}$$

$$k_{\mathrm{rnw}}(S_{\mathrm{e}}) = [(1 - S_{\mathrm{e}})^n] \left(\int_{S_{\mathrm{e}}}^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}(S_{\mathrm{e}})} \Big/ \int_0^1 \frac{\mathrm{d}S_{\mathrm{e}}}{p_{\mathrm{c}}(S_{\mathrm{e}})} \right)^2 \tag{2b}$$

Based on the experimental results of 45 soils in written sources, Mualem (1976) found that $n = 0.5$ yields the best results.

The model of Childs and Collis-Georges (CCG) is given as follows (Dullien, 1992):

$$k_{\mathrm{rw}}(S_{\mathrm{e}}) = [S_{\mathrm{e}}^n] \int_0^{S_{\mathrm{e}}} \frac{S_{\mathrm{e}} - x}{p_{\mathrm{c}}^2(x)} \,\mathrm{d}x \Big/ \int_0^1 \frac{1 - x}{p_{\mathrm{c}}^2(x)} \,\mathrm{d}x \tag{3a}$$

$$k_{\mathrm{rnw}}(S_{\mathrm{e}}) = [(1 - S_{\mathrm{e}})^n] \int_{S_{\mathrm{e}}}^1 \frac{1 - x}{p_{\mathrm{c}}^2(x)} \,\mathrm{d}x \Big/ \int_0^1 \frac{1 - x}{p_{\mathrm{c}}^2(x)} \,\mathrm{d}x \tag{3b}$$

This model has been used with various values of n (see references quoted in Mualem, 1986). As in the original proposed form, here n is set to 1. The last two models are usually written for the wetting phase, but simple modification allowed us to extend them to the non-wetting phase (see Dana, 1999).

In the above Eqs. (1a)–(3b), the subscripts 'w' and 'nw' stand for wetting and non-wetting phases respectively. k_{r} is the relative permeability, $P_{\mathrm{c}}(S_{\mathrm{e}})$ is the capillary pressure relation, and S_{e} ($S_{\mathrm{e}} = (S_{\mathrm{w}} - S_{\mathrm{irr}})/(100 - S_{\mathrm{irr}})$) is the wetting phase effective saturation expressing the pore space available to the flow. The terms in square brackets of the right-hand member are empirically chosen to take the pore tortuousity into consideration (Dullien, 1992; Mualem, 1986; Mualem, 1976).

4. Model predictions versus experiments

As we can note from the equations above, relative permeability curves can be predicted from the capillary pressures curves. In the various fields where porous media are involved, a great number of empirical relations were suggested in order to improve correlation of the capillary pressure to the degree of saturation. In this work, six of the relations most used will be adopted.

4.1. Capillary pressure curve correlation

The equations adjusted to our experimental results obtained by the porous diaphragm tests and the mercury porosimetry, are as follows:

1. The equation of Gardner of the form (quoted in Fredlund and Xing, 1994):

$$S_e = \frac{1}{1 + g_1 p_c^{g_2}} \tag{4}$$

g_1 [(1/Pressure dimension)^{g_2}], g_2 [dimensionless] are fitting parameters.

2. The equation of Brooks and Corey (quoted in Dullien, 1992) which is largely used by rock mechanics researchers, is written:

$$S_e = \left(\frac{p_c^b}{p_c}\right)^{\lambda} \quad (p_c \geqslant p_c^b) \tag{5}$$

p_c^b [pressure units] is the breakthrough pressure threshold of penetration, and λ [dimensionless] indicates the index of the pore size distribution. These parameters can be obtained as follows: if one traces S_e versus P_c in a logarithmic plan, the points then obtained are on a line. The slope of this line is λ and the ordinate at $S_e = 1$ is p_c^b. In fact, the optimization of these parameters will produce a better correlation, this is why they are regarded here as fitting parameters. Eq. (5) combined with discussed models presented above, can generate simple analytical forms for the relative permeability. With the equations of Burdine, for example, we have

$$k_{rw}(S_e) = (S_e)^{(2+3\lambda)/\lambda} \tag{6a}$$

$$k_{rnw}(S_e) = (1 - S_e)^2(1 - S_e^{(2+\lambda)/\lambda}) \tag{6b}$$

known as the equations of Brooks and Corey.

3. The equation of Farrell and Larson (quoted in Fredlund and Xing, 1994), already used for electric conductivity, is written:

$$S_e = \frac{1}{f_1}\ln(p_c/f_2) \tag{7}$$

f_1 [dimensionless], f_2 [pressure units] are fitting parameters.

4. van Genuchten (1980) recommended a more general form of Eq. (4):

$$S_e = \left(\frac{1}{1 + (gn_1 p_c)^{gn_2}}\right)^{gn_3} \tag{8}$$

gn_1 [1/pressure units], gn_2, gn_3 [dimensionless] being fitting parameters. van Genuchten (1980), proposed a methodology to estimate the parameters of his equation, but for restricted cases. By combining Eq. (8) with the model of Mualem, he also derived the following expression for the wetting phase relative permeability:

$$k_{rw}(S_e) = S_e^{1/2}[1 - (1 - S_e^{1/gn_3})^{gn_3}]^2 \quad \text{if } gn_3 = 1 - 1/gn_2 \ (0 < gn_3 < 1) \tag{9}$$

Written sources refer to Eq. (9) as the Mualem–van Genuchten's model.

Table 4
Average values of R^2 obtained

Equation	(R^2)
Brooks and Corey	0.96
McKee and Bumb	0.94
Gardner	0.97
Van Genuchten	0.99
Fredlund and Xing	0.99
Farrell and Larson	0.88

5. The equation of McKee and Bumb (also called distribution of Boltzmann, quoted in Fredlund and Xing, 1994) which proposes an exponential function of the form:

$$S_e = \exp(-(p_c - m_1)/m_2) \tag{10}$$

m_1 and m_2 are fitting parameters with pressure dimensions.

6. Fredlund and Xing (1994), aiming at a better description of the capillary pressure curves suggested the following form:

$$S_e = \left[\frac{1}{\ln(2.71828 + (p_c/fr_1)^{fr_2})}\right]^{fr_3} \tag{11}$$

fr_1 [pressure dimensions], fr_2, and fr_3 are fitting parameters.

In certain cases, the coupling of one of the three models of paragraph (III) with the relations of capillary pressure, can generate simple analytical forms for the relative permeability. Dana (1999) gave several possible solutions.

Generally these equations give a coefficient of correlation (R) which is more than acceptable. The average values of (R^2) are given in Table 4, these average values are calculated for all the tests and the rocks tested.

For the Vosges-2 sandstone, an example of comparison between the experimental curves of the capillary pressure and the proposed relations are given in Fig. 4. The values of the identified parameters relating to each equation are presented in tabular form (Table 5). P1, P2, and P3, in Table 5 refer to the fitting parameters as the appear, in order, in the corresponding correlation and have the same units, e.g. P1 and P2 are equal to g_1 and g_2 respectively, in Gardner's equation (Eq. (4)). Fitting coefficients specification is based on [kPa] for drainage tests and on [bar] for the mercury porosimetry tests. The results concerning the two other sandstones are given in the appendix.

4.2. Relative permeability simulation

Having compared the experimental curves of capillary pressure with the relations previously suggested, the various parameters were identified. Thereafter, the results obtained are used

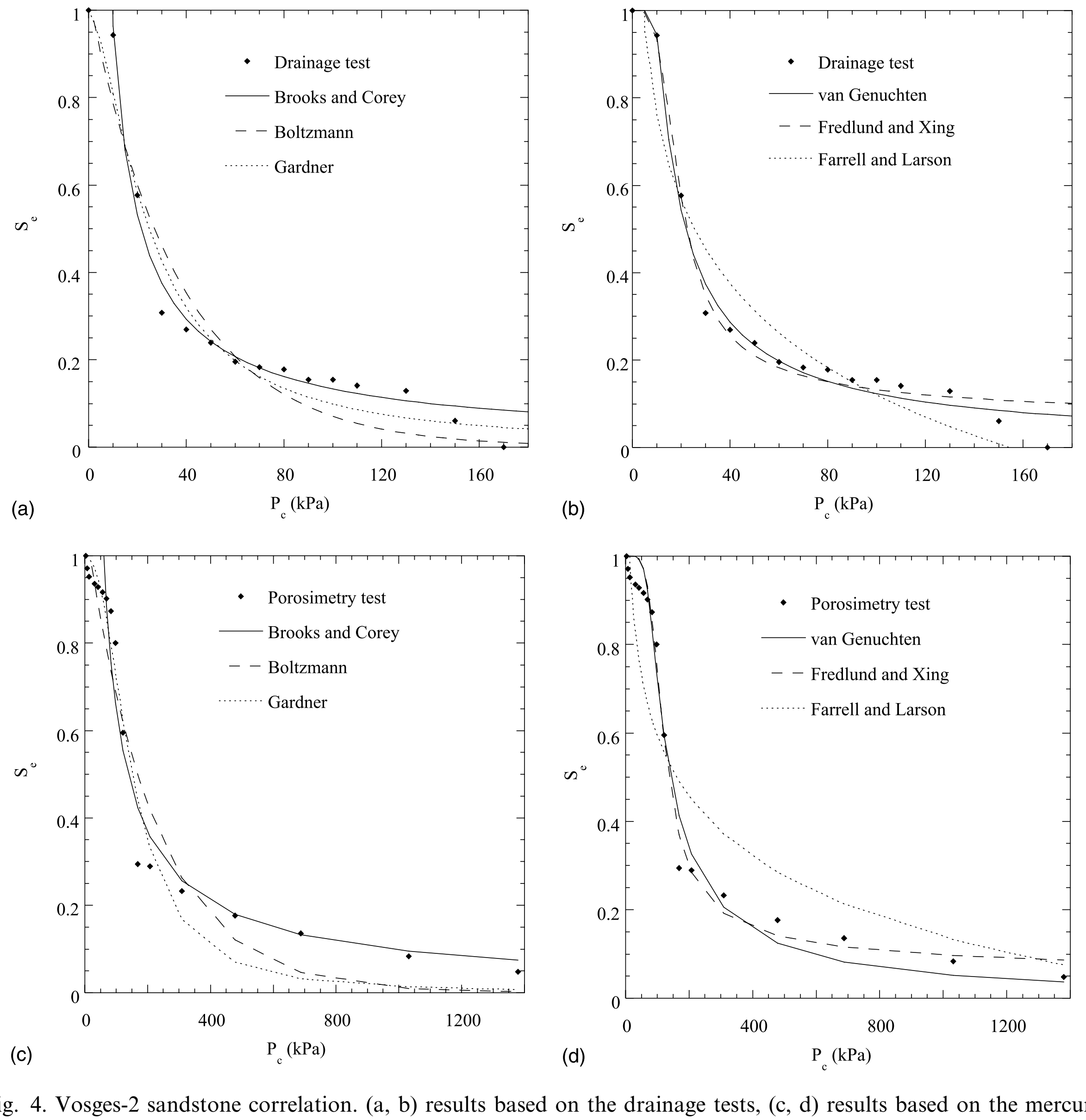

Fig. 4. Vosges-2 sandstone correlation. (a, b) results based on the drainage tests, (c, d) results based on the mercury porosimetry tests.

jointly with the studied models to examine their validity. The absence of a systematic analytical expression of the relative permeability lead us to write a Fortran code to fulfil integration numerically that was validated on simple examples (see Dana, 1999).

In order to follow one of the major assumptions of these models, in particular the possibility to obtain the pore size distribution using capillary pressure curves, we have determined the relative

Table 5
Vosges-2 sandstone, parameter values

	Tests of drainage			Tests of mercury porosimetry		
	P1	P2	P3	P1	P2	P3
Brooks and Corey	0.095	0.87	–	0.6	0.84	–
McKee and Bumb	0.01	0.375	–	0.166	2.19	–
Gardner	9.12	1.59	–	0.39	2.27	–
van Genuchten	9.7	9.0	0.1	1.26	5.58	0.21
Fredlund and Xing	0.152	3.93	1.01	0.98	4.43	1.03
Farrell and Larson	3.6	0.042	–	5.0	0.129	–

permeability on the basis of P_c–S_e relations obtained by drainage experiments or by the mercury porosimetry tests.

To systematize the comparison, we chose the following presentation; results calculated using a given P_c–S_e correlation, with the parameters determined by the two methods, are simultaneously compared to the relative permeability experimental results as measured by Dana and Skoczylas (submitted for publication).

Figs. 5–7 give a representative draft of the obtained results, more complete presentation of confrontation "model-measurement" is given in Dana (1999).

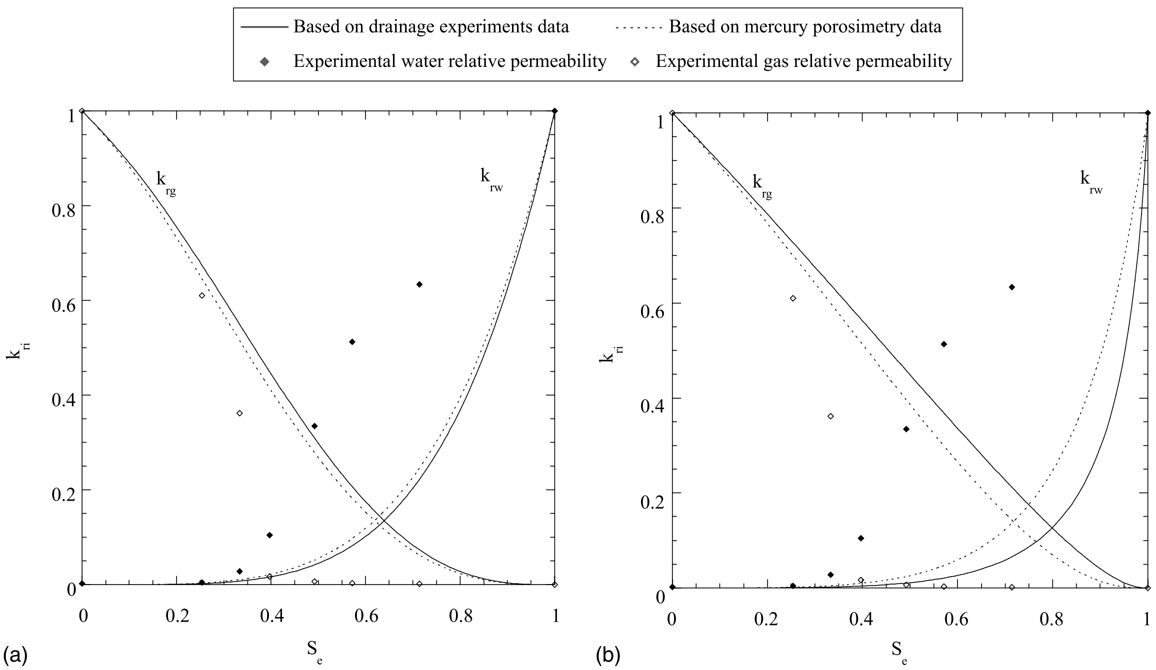

Fig. 5. Fontainebleau sandstone. Simulation by the Childs and Collis-Georges model using relations of (a) Brooks and Corey and (b) Boltzmann.

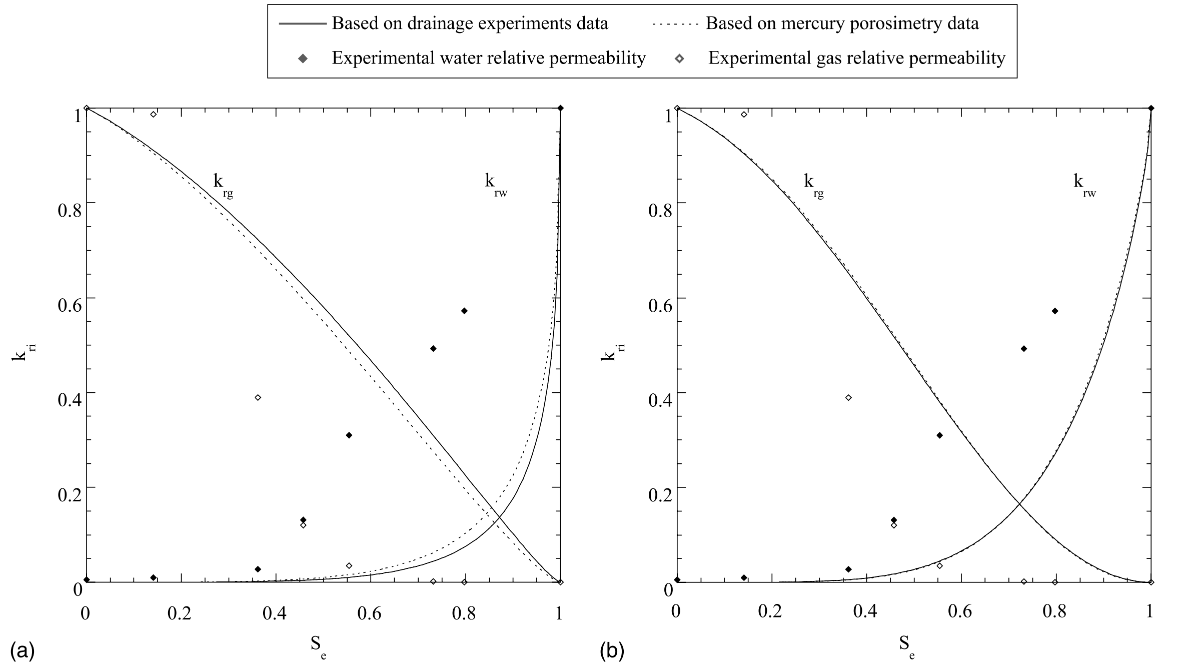

Fig. 6. Vosges-1 sandstone. Simulation by the model of Mualem using relations of (a) Gardner and (b) van Genuchten.

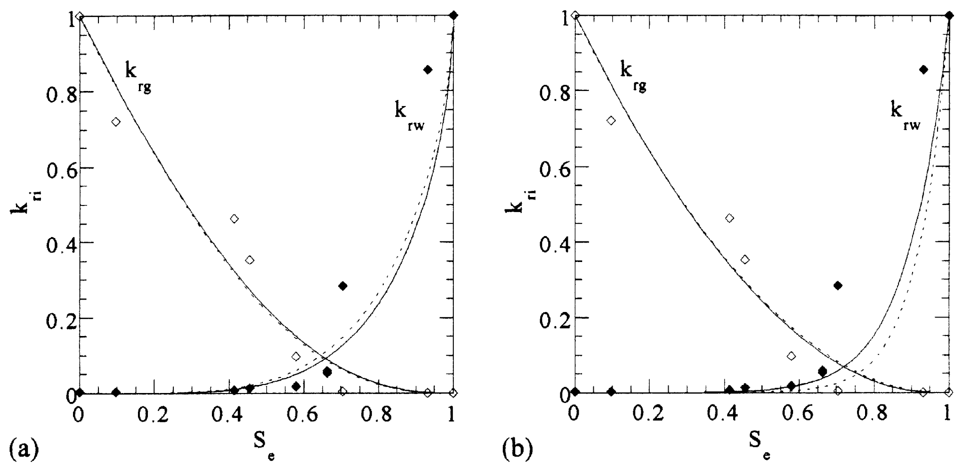

Fig. 7. Vosges-2 sandstone. Simulation by the Burdine's equations using relations of (a) Fredlund and Xing and (b) Farrell and Larson.

The results obtained generally show that the studied models underestimate the water relative permeability and over-estimate that of the gas phase. This remains true whatever the correlation P_c–S_e used. With the exception of the equations of Gardner and McKee and Bumb, the response of all the models considered seems to remain independent of the method of determination of the capillary pressure curves (Figs. 5–7).

For the three rocks tested, only the Vosges-2 coefficients of relative permeability have been reproduced in a satisfactory manner, and this with the model of Childs and Collis-Georges or that of Wyllie and Gardner, except when they are used with the equation of Gardner or McKee and Bumb.

5. Conclusions

The porous plate (drainage) experiments designed to measure capillary pressure curves are a difficult task since they are time consuming and very sensitive to different error sources. However, capillary pressure curves still constitute an unavoidable step for didactic and modeling purposes in rather distinct engineering fields. Capillary pressure curves determined during this work have been used to describe two-phase flow in three different sandstones and to examine the validity of some capillary pore space models. Results revealed the following conclusions.

Using the "bundle of cylindrical capillaries" as a pore space model jointly with models presented above, the capillary pressure curves, determined by the drainage or the mercury porosimetry tests, lead mainly to the same curves of relative permeabilities. This fact mean that pore size distribution obtainable by drainage or mercury porosimetry would be the same, once again, if the pore space is seen as a "bundle of cylindrical capillaries".

Generally, the results obtained for the studied sandstones show that the models of the statistical type underestimate the water relative permeability and over-estimate that of the non-wetting phase. Moreover, this modeling proves to be unable to locate the significant points that are the limits of fields of saturation where the variation of the relative permeabilities becomes consequent. For the three rocks tested, only the Vosges-2 coefficients of relative permeability were reproduced in a satisfactory way, and this with the model of Childs and Collis-Georges or that of Wyllie and Gardner.

According to the models considered, the relative permeability to a given phase is mainly governed by hydraulic conductivities specific to the pores of various sizes. When the connectivity and the spatial distribution of these pores were not taken into consideration in a realistic way, flow mechanisms aside, significant differences between models and measurements were observed. In previous articles the authors (Dana and Skoczylas, 1999, submitted for publication) have shown that relative permeabilities seem to be mainly governed by the way in which the saturated pore space fraction, corresponding to the steep part of the permeability curves, ensures continuous paths for the flow of a given phase.

Appendix A. P_cS_e correlation parameters

The fitting parameters appearing in the capillary pressure curve correlations (4)–(11) are given in Tables 6 and 7, for the Vosges-1 and Fontainebleau sandstones.

Table 6
Vosges-1 sandstone, parameter values

	Tests of drainage			Tests of mercury porosimetry		
	P1	P2	P3	P1	P2	P3
Brooks and Corey	0.0467	0.762	–	0.333	0.593	–
McKee and Bumb	0.00097	0.241	–	0.098	1.686	–
Gardner	14.692	1.397	–	0.734	1.5497	–
van Genuchten	17.68	5.036	0.169	2.136	5.78	0.14
Fredlund and Xing	0.083	3.283	1.083	0.664	3.67	0.94
Farrell and Larson	4.321	0.0177	–	5.46	0.09	–

Table 7
Fontainebleau sandstone, parameter values

	Tests of drainage			Tests of mercury porosimetry		
	P1	P2	P3	P1	P2	P3
Brooks and Corey	0.0367	1.36	–	0.403	1.72	–
McKee and Bumb	0.002	0.089	–	0.11	0.72	–
Gardner	399.69	2.21	–	4.81	3.7	–
van Genuchten	8.19	1.7	2.22	1.60	3.86	0.9
Fredlund and Xing	0.132	1.5	5.44	0.627	3.87	2.27
Farrell and Larson	2.78	0.0168	–	3.66	0.0852	–

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