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Spontaneous Imbibition in Small Cores

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Abstract

This paper presents experimental data for co-current spontaneous imbibition into cores having bulk volumes from 0.1 to 12 cm^3. Simple experiments of brine imbibing into air-filled cores were carried out. Homogeneous sandstone cores (Berea and Bentheim) and a carbonate core (Mt. Gambier) were used in the experiments. The experimental data were scaled using the scaling laws reported in the literature.

The results demonstrate that reliable experimental data of spontaneous imbibition can be obtained for the small cores of homogeneous porous rocks. Such data are of immense interest for validating the predictive value of network models based on micro-CT images of rock fragments with bulk volumes as small as 0.3 cm^3. The data for cores of different sizes were satisfactorily scaled using five different methods[6, 11, 14, 15, 18]. The recovery models proposed by Ma *et al.*[15] and Viksund *et al.*[20] produced an excellent match for the normalized gas recovery data. Although the Li and Horne model[11] successfully correlated the imbibed water volume as a function of time, the model failed to correlate the normalized recovery data. A comparison of the scaled data with data previously reported for water-gas systems showed excellent agreement.

1. Introduction

Accurate prediction of spontaneous imbibition is crucial in optimization of oil and gas recovery processes, e.g., assessing water injection performance in oil fields and determining residual gas saturation in gas fields. Network models based on micro-CT images promise great potential to better understand and more accurately predict the dynamics of imbibition processes[1].

Advances in extracting representative networks from micro-CT images of porous materials have improved the predictive capabilities of the network models[2, 3]. The networks extracted from the images are used in models to predict multiphase flow properties such as relative permeability, capillary pressure and spontaneous imbibition process. All these predictions need to be validated using laboratory data in order to test the predictive value of the network models. The imaged rock fragments are small compared to conventional cores having bulk volumes of the order of 0.1 cm^3.

A number of attempts have been made to compare limited laboratory measurements with network model predictions[1, 4, 5]. Although the results of these comparisons are encouraging, the networks used were derived using computer generated process-based reconstructions of the porous medium which have significantly different properties to the cores used in the actual experiments. Moreover, the experimental data used were obtained on conventional cores having bulk volumes of at least 10 cm^3, which are several orders of magnitude larger than those of the rock fragments used to produce the micro-CT images.

Scaling of spontaneous imbibition has long been used as a predictive tool for estimating the field performance of water-wet, fractured reservoirs subjected to water flood/drive. In this approach, simple imbibition tests on small reservoir cores are scaled to estimate reservoir performance. A number of scaling approaches have been proposed and tested against experimental data [6-11]. The bulk volumes of rock samples were varied in order to study the effect of plug size on the imbibition process (Table 1). The table shows that the smallest core used in these tests had a bulk volume that is several orders of magnitude larger than the core fragments typically used for micro-CT imaging.

The aim of this paper is to provide simple and well-defined experimental data for spontaneous imbibition in order to demonstrate that reliable experimental data can be produced on small core plugs which are of comparable size to rock fragments used in micro-CT imaging. This data will be used for testing and validation of image based network models. The comparisons with scaling laws for water-air systems will also be of interest to applications in geothermal and gas reservoirs.

2. Scaling of Spontaneous Imbibition

Spontaneous imbibition of water into a matrix block is a very complex process and depends on many factors such as permeability, wettability, shape, and size of the matrix, boundary conditions, and interfacial tension and viscosities of the fluid system. Detailed reviews of hydrocarbon recovery by spontaneous imbibition have been reported[11, 12].

Spontaneous imbibition of water into gas-saturated porous rocks can be considered to be a piston-like displacement with the imbibed mass given by the Handy[13] equation,

$$m_w^2 = \left(\frac{2 p_c k_w \phi A_c^2 \rho_w^2 S_w}{\mu_w} \right) t \qquad (1)$$

where m_w is the mass of the water imbibed, p_c is the capillary pressure, k_w is the water permeability, ϕ is the porosity, A_c is the cross sectional area open to flow, ρ_w is the water density, S_w is the water saturation behind the front, μ_w is the water viscosity and t is the imbibition time. Eq. 1 was shown to be in good agreement with experimental data for spontaneous water imbibition into dry outcrop sandstone samples[13].

There are two main disadvantages in using Eq. 1 for characterizing spontaneous imbibition. Firstly, gravity is not considered. Since most of the spontaneous imbibition tests for water-gas systems are made with the rock samples mounted vertically, Eq. 1 can only describe early-time data when imbibitions rates are high and viscous forces dominate. With time the imbibitions rate decreases and gravity effects become important. Secondly, it is not straightforward to calculate k_w and p_c from a spontaneous imbibition test, thus both properties must be measured separately.

Scaling of spontaneous imbibition is another approach to predict field-scale performance. Various scaling equations have been reported to quantify hydrocarbon recovery as a function of time for different rocks at the same wettability conditions[6, 11, 14, 15].

Based on the scaling law reported by Rapoport and Leas [16], Mattax and Kytes[6] presented an equation to scale the behavior of hydrocarbon recovery from strongly water-wet fractured oil reservoirs by means of spontaneous imbibition,

$$t_{D,MK} = \alpha \sqrt{\frac{k}{\phi}} \frac{\sigma}{\mu_w} \frac{1}{L^2} t \qquad (2)$$

where t_{DMK} is the dimensionless time (s), α is a units conversion factor (3.16×10^{-4}), k is the absolute permeability (md), σ is the interfacial tension (mN/m), and L is the characteristic length of the sample (cm). They set a number of conditions for Eq. 2 to hold. These include identical core shapes and boundary conditions, the same viscosity ratio and initial fluid distributions in the experiments, the same relative permeability, and proportional capillary pressure functions. They validated the scaling law with experimental data for water imbibition into oil-saturated alundum and sandstone cores. Ma *et al.*[17] have suggested that the data used contained errors and that some of the data may have been misinterpreted. Later, Kazemi *et al.*[14] modified Eq. 2 by replacing L with a new characteristic length, L_S to compensate for the effect of shapes and boundary conditions:

$$L_S = \frac{1}{\sqrt{F_S}} = \sqrt{V_b / \sum_{i=1}^{n} \frac{A_i}{s_{Ai}}} \qquad (3)$$

where F_S is the shape factor, V_b is the bulk volume of the rock sample, n is the number of surfaces open to imbibition, A_i is the area open to imbibition in the i^{th} surface and s_{Ai} is the distance from the side with A_i to the center of the sample.

Ma *et al.*[15, 17] reported that L_S could not correlate data for one-end-open system counter-current imbibition with that for all-face-open systems. They defined a new characteristic length, L_C:

$$L_C = \sqrt{\frac{V_b}{\sum_{i=1}^{n} A_i / l_{Ai}}} \qquad (4)$$

where l_{Ai} is the distance that the imbibition front moves from inlet to the outer boundary. They used the literature data[6,7,9] for water imbibing into oil-saturated sandstone, alundum, and aluminum silicate cores. They stated that Eq. 2 holds for identical viscosity ratios with increase in wetting phase viscosity from 1 to 15 cp, but does not hold if the non-wetting phase is a gas. They further modified Eq. 2 to include the effect of non-wetting phase viscosity, μ_{nw}:

$$t_D = \alpha \sqrt{\frac{k}{\phi}} \frac{\sigma}{\sqrt{\mu_w \mu_{nw}}} \frac{1}{L_C^2} t \qquad (5)$$

This empirical relationship was later verified experimentally by Zhang *et al.* [9] for oil-water systems on Berea cores.

Zhou *et al.* [18] proposed a scaling equation for counter-current imbibition with dimensionless mobilities of wetting and non-wetting phases by neglecting the effect of gravity,

$$t_D = \alpha \sqrt{\frac{k}{\phi}} \frac{\sigma}{L_C^2} \sqrt{\lambda_{rw}^* \lambda_{rnw}^*} \frac{1}{\sqrt{M^*} + \sqrt{1/M^*}} t \qquad (6)$$

$$\lambda_r^* = \frac{k_r^*}{\mu} \qquad (7)$$

$$M^* = \frac{\lambda_{rw}^*}{\lambda_{rnw}^*} \qquad (8)$$

where λ_r* is the characteristic mobility and M* is the characteristic mobility ratio. They used the end point relative permeabilities to calculate λ_r* and M*. Eq. 6 failed to satisfactorily correlate data for the same rock with different wetting phase viscosities. The data used was obtained from water-air and water-oil imbibition experiments in the low-permeability diatomite cores.

Most of the scaling theories have been developed for counter-current oil-water imbibition and tested for different boundary conditions. Less has been done for scaling co-current gas-water imbibiton processes. Li and Horne[11] proposed a scaling equation for co-current imbibition of water into gas-saturated porous media (Berea, chalk, and Graywacke cores):

$$t_D = c^2 \frac{\lambda_w p_c}{\phi} \frac{S_{wf} - S_{wi}}{L_C^2} t \qquad (9)$$

$$c = \frac{b}{a} = \frac{\Delta \rho g L}{(S_{wf} - S_{wi}) p_c} \qquad (10)$$

$$a = \frac{A \lambda_w (S_{wf} - S_{wi})}{L} p_c \qquad (11)$$

$$b = A \lambda_w \Delta \rho g \qquad (12)$$

where λ_w is the water mobility at the imbibition front, S_{wf} is the water saturation at the imbibition front, S_{wi} is the initial water saturation, p_c is the water saturation at the imbibition front, a and b are constants associated with capillary and gravity forces, respectively, $\Delta\rho$ is the density difference between water and gas and g is the gravitational constant. Eq. 9 is derived from the Darcy's equation for a piston-like displacement. It is not straightforward to determine S_{wf} and p_c from the experiments. Li and Horne suggested that c can be obtained using constants a and b, which need to be determined from a plot of imbibition rate versus the reciprocal of gas recovery:

$$Q_w = \frac{dN_{wt}}{dt} = a\frac{1}{R} - b \qquad (13)$$

where Q_w is the volumetric rate of water imbibition, N_{wt} is the cumulative volume of water imbibed, and R is the gas recovery in terms of pore volume. The authors reported that Eq. 9 scales the spontaneous imbibition of water into different porous media (Berea, chalk, and Graywacke cores) with different initial water saturations. One of the feature of Eq. 9 is that almost all the factors involved in cocurrent spontaneous imbibition including porosity, permeability, pore structure, matrix size, fluid viscosity, initial water saturation, wettability, interfacial tension, capillary pressure, relative permeability, and gravity, are considered. The shortcoming of the scaling law, as reported by the authors, is the difficulty in correlating the entire imbibition process for different rock types.

Another way to scale spontaneous imbibition is the use of the normalized hydrocarbon recovery. Aronofsky *et al.*[19] presented an empirical equation which relates the normalized oil recovery (R_N) to time by an exponential function:

$$R_N = 1 - e^{-\beta t} \qquad (14)$$

where β is a rate constant. R_N is defined by

$$R_N = \frac{R}{R_\infty} \qquad (15)$$

R is the recovery at time t, and R_∞ is the ultimate recovery.

Ma *et al.*[15] modified the Aronofsky *et al.* [19] correlation by replacing t with t_D (as defined by Eq. 5) to account for different boundary conditions and viscosity ratios:

$$R_N = 1 - e^{-\gamma t_D} \qquad (16)$$

where γ is the non-wetting phase production decline constant, which was reported to be 0.05 for oil-water systems in sandstone, alundum, and aluminum silicate cores[15].

Viksund *et al.* [20] proposed another empirical equation for oil recovery from strongly water-wet porous media with zero initial water saturation, which is given by

$$R_N = 1 - \frac{1}{(1 + 0.04\,t_D)^{1.5}} \qquad (17)$$

They showed that Eq. 17 represented all their experimental data for oil-water systems with zero initial water saturation in sandstone and chalk core samples.

Li and Horne[11] presented a different type of normalized recovery for gas–water system imbibitions,

$$R_N = cR \qquad (18)$$

where c is the ratio of gravity to capillary forces defined by Eq. 10. They report that Eqs. 9 and 18 successfully scaled their spontaneous imbibition water-air experiments in sandstone, chalk, and Graywacke rock samples.

3. Experimental Approach

Core Preparation. Core samples of approximately 2.5cm in diameter by 2.5cm in length were cut from blocks of Berea and Bentheim sandstones and Mount Gambier carbonate. These dimensions represent the conventional laboratory scale in this study. The rock types were chosen because of their known relatively homogenous nature and wettability condition (strongly water-wet). Both are extremely important for validating network model predictions. After the spontaneous imbibition experiments with the laboratory-scale cores, the cores were progressively cut down in size as shown in **Fig. 1** and the experiments repeated. **Table 2** gives the dimensions of the cut-down cores.

The sandstone samples were cut using 0.4% by weight NaCl brine and dried in an oven at 90°C for 24 hours. After drying, the sandstones were baked in a furnace at 550°C for 24 hours with the purpose to reduce the reactivity of the clay minerals in the sandstones. The cores were then slowly cooled down to the room temperature over a period of 24 hours. The porosity and permeability of the A-series cores were measured using a helium porosimeter and micropermeameter, respectively. The gas permeability was corrected for the Klinkerberg slippage effect. The Amott wettability indices for the largest cores were also measured to ensure that the cores were strongly water-wet. The porosity, permeability and wettability indices are assumed to be representative for all down-sized samples.

Fluids. Brine (2% by weight NaCl) and air were used as the wetting and the non-wetting phases, respectively. The density and viscosity of brine were measured to be 1.066 g/cm^3 and 1.0 cp while 0.00129 g/cm^3 and 0.0185 cp were used for the density and viscosity of air, respectively. The surface tension for the brine-air system was assumed to be 72 mN/m.

Apparatus. A simplified schematic of the equipment for the spontaneous imbibition measurements is shown in **Fig. 2.** The apparatus consists of an imbibition chamber, a non-water-wet core holder which is designed to keep the core vertical during the experiment, a petri dish of 14cm in diameter and 7.5 cm in height, a precision scale with an accuracy of 0.1mg and a capacity of 210g, a remotely controlled motorized lab jack with a speed range of 0.2μm/s to 1.7mm/s and a PC for data acquisition.

Co-current spontaneous imbibition experiments were performed by bringing the bottom face of the sample into contact with the brine and measuring the weight change as a function of time. The core was suspended from a hook underneath an electronic balance. The major part of the sample remains immersed in the brine-saturated air in a closed chamber. All experiments were conducted at zero initial water saturation. The maximum relative error in saturation measurements is calculated to be 0.4% for the smallest core. The cores were cleaned in the Soxhlet extraction chamber using 50% Methanol and 50% Toluene and then dried in an oven at 90°C until there was no change in weight before the next stage of the experiment. The reproducibility of the experimental procedure was tested for all the experiments by performing the same experiment twice. **Figs. 3 and 4** show examples of the reproducibility tests for the largest and smallest Bentheim cores.

Meniscus Jump Correction. At the first contact between the free brine in the container and the air-filled rock, there is always an increase in weight because of the liquid surface energy and capillary suction. This sudden jump in weight measurements is known as the meniscus contact effect and the data is corrected for this[21]. The correction was done by subtracting the first reading on the balance from the recorded weight increase data.

Apparatus Accuracy Check. The experimental apparatus was validated by measuring spontaneous imbibition of silicone-oil into glass capillaries and spontaneous imbibition of millipore water into nanoporous Vycor glass rods.

Glass Capillaries. Both height-time and weight-time experiments were simultaneously carried out. Glass capillaries of 0.5, 0.65 and 1.05 mm in radii and 50mm in length were used. The silicone oil used in the experiments (purchased from Dow Corning) had a surface tension of 21.1mN/m, density of 0.965g/cm^3 and viscosity of 0.5 cp. Before measurements, the capillaries were cleaned by full immersion in chromic acid for 20 minutes, followed by 20 minutes in a mixture of concentrated hydrochloric acid (50%) and distilled water (50%). The capillaries were then thoroughly rinsed with distilled water and dried in an oven at 100°C for 24 hours. Measurements were carried out at room temperature (22 ± 0.5 °C).

The height-time measurements were made using still video images. The results of the height were converted to those of weight using the density of the silicon oil and the cross-sectional area of the capillary tube.

The results were compared with a form of Terzaghi analytical equation as presented by Lu and Likos [22]:

$$t = \frac{\phi h \mu}{k \rho g}\left(\ln\left(\frac{h}{h - h_f}\right) - \frac{h_f}{h}\right) \qquad (19)$$

where h is the final static height and h_f is the height at the rising front. The results shown in **Fig. 5** indicate excellent agreement between the three measurements.

Vycor Glass Rod. A weight-time measurement was made using a Vycor glass rod cuboid of dimension (0.42 x 0.43 x 1.0 cm^3). A millipore water was used ($\sigma = 72.75$ mN/m, $\rho = 1.0$ g/cm^3 and $\mu = 0.95$ cp) as the imbibing fluid. Prior to the experiment, the Vycor samples were cleaned in a mixture of concentrated sulphuric acid (30%) and hydrogen peroxide solution (70%) followed by rinsing in millipore water and drying in vacuum at 70°C. The mean pore diameter as reported by the manufacturer and the porosity are 4nm and 28%, respectively. The present data is in good agreement with the previously reported measurements reported by Huber *et al.*[23] as shown in **Fig. 6.**

4. Results and Discussion

Spontaneous Imbibition Results. Figs. 7 - 9 show the experimental results of pore volume (PV) water imbibed versus square root of time for Berea, Bentheim and Mt. Gambier samples, respectively. The data is plotted for all core sizes. Water saturations were determined by converting the mass of water spontaneously imbibed to volumes using the density of water. Suzanne *et al.*[24] observed two straight line regions on the plot of PV against $\sqrt{t}$. The present data shows the same behavior. The early-time line represents the capillary-dominated period while the late-time shows the diffusion-dominated period. The transition period between two straight line regions shows the effect of gravity forces slowing down the imbibition front.

The data obtained using cores A, B, and C (with the same length and different diameters) shows that reproducible spontaneous imbibitions measurements can be obtained when the water imbibed is scaled with PV. As the length of the cores is decreased (cores D and E), the imbibitions front reaches the top of the core earlier, which is reflected in the data by an earlier start of the second straight line portion of the imbibition curve.

The experiments with the smallest cores produce only a few data because of the shorter length of the samples. At the first contact between the water and the core, some of pores are instantaneously filled with water for all experiments. The ratio of this volume to PV was negligibly small for the larger cores, but it became significant for core E – the smallest core. We argue that the higher values of water imbibed for cores E (especially for Berea and Bentheim cores) results from this effect. The experimental error for these cores is estimated to be approximately 5% PV.

It can be observed that spontaneous imbibition is faster in Bentheim and Mt. Gambier cores than in Berea cores, which may be due to the effect of absolute rock permeability on the rate of spontaneous imbibition. However, this effect is suppressed as the core length decreases (cores D and E).

The residual gas saturations were determined at the end of the imbibition tests to range between 29-35% for the Berea cores, 21–26% for the Bentheim cores, and 29-33% for the Mt. Gambier cores. The 10% difference between Berea and Bentheim might result from the difference in rock permeability. The difference between Bentheim and Mt. Gambier (although both have similar permeability) is likely due to the differences in the pore structures of sandstones and carbonates.

Scaling of Spontaneous Imbibition Data. Fig. 10 shows a comparison of scaling laws for the Berea data. For these experiments, $L_S = L/\sqrt{2}$ and $L_C = L$. **Fig. 11** shows a comparison between the correlations of Mattax and Kyte[6], Li and Horne[11], Kazemi *et al.*[14], Ma *et al.*[15], and Zhou *et al.*[18]. There is clearly a shift in dimensionless time between the different models. This shift is eliminated by multiplying the dimensionless time by different constants. For example, the Kazemi *et al.* dimensionless time is twice the Mattax and Kyte time because $L_S = L/\sqrt{2}$ and the Ma *et al.* dimensionless time is approximately 7 times higher than the Mattax and Kyte time due to the geometric mean of both viscosities used in Eq. 5. Following Zhou *et al.*, we used $k^*_{rw} = 0.14$ and $k^*_{rg} = 0.6$ in our calculations of characteristic mobilities. This model gives dimensionless times which are smaller by a factor of about 7 compared to those for the Mattax and Kyte model. The Li and Horne and Zhou *et al.* models produce similar results for the dimensionless time although the former differs from the latter in that it also includes gravity effects. We determined *a* and *b* values for each experiment using the plot of Q_w vs. $1/R$ and calculated *c* using Eq. 10. The data used to determine the parameters *a* and *b* for the Li and Horne model was for the transition period when both viscous and gravity forces are important. The early-time capillary dominated data and late-time diffusion-dominated portions were ignored. The c values determined are given in Table 2. We used water permeability instead of absolute permeability as stated by Li and Horne. S_{wf} was determined from the experiments as the saturation when the imbibition front reaches the top side of the cores and the corresponding p_c was taken from the data on a sister plug[25]. The results in Fig. 10 show that all Berea data are scaled very well.

Figs. 12-13 show the plots of PV water imbibed versus dimensionless time for Bentheim and Mt. Gambier rocks, respectively. The results are compared to the correlations of Mattax & Kyte and Li & Horne. The data for the smallest cores (cores E) for all rock types are not well aligned with those for the larger cores. This difference is likely due to the lack of sufficient early-time data. Upon the first contact most of the rock pore volume was instantaneously filled with brine (i.e. it occurred in less than two seconds). As a result, most of the data recorded for the smallest samples is for the diffusion-dominated period as can be seen in Figs. 7-9. The results suggest that representative data for spontaneous imbibition can be obtained for cores having bulk volumes of down to approximately 0.3 cm^3 (cores D in this study).

Scaling of Data for Different Rock Types. We used the data for the experiments with the largest cores (A) and the smallest cores (E) to compare the normalized recoveries defined by Ma *et al.* [15], Viksund *et al.* [20] and Li and Horne [11] for all three rocks. The results of the first two models shown in Fig. 14 indicate that both correlations scale our data perfectly. For the smallest cores, only late-time data is available due to the experimental limitations discussed previously. The late-time difference between both correlations may be due to the value used for γ (0.05 suggested for oil-water systems[15]).

The results obtained using Eq. 18 proposed by Li and Horne are shown in Fig. 15. The match obtained for the recoveries for different cores is clearly unsatisfactory. Although the reason for this is unclear, it is likely due to the determination of the parameter "*c*". This is particularly true for the smallest cores where the data of transition period is limited.

We also used the Viksund correlation to scale a number of data sets reported for gas-water systems with zero initial water saturation[11, 26, 27, 28, 29]. A comparison between our data and literature data is shown in Fig. 16. The rock types and rock properties are summarized in Table 3. The agreement between the different data sets is excellent.

All the previously discussed correlations with the exception of the Li and Horne model were based on oil-water systems and successfully correlated our air-brine data. Curiously, the correlation of Li and Horne which was specifically developed for a gas-water system was not as successful. Although the model successfully correlated the imbibed water volume as a function of time (see Fig. 10) it failed to correlate normalized recovery data (see Fig. 15).

5. Conclusions

Co-current spontaneous imbibiton experiments were performed on two outcrop sandstones and one outcrop carbonate samples. The following conclusions are made;

- High-accuracy, simple brine displacing air spontaneous imbibition data have been presented. The results demonstrate that reliable experimental data for spontaneous imbibition can be obtained for the cores of homogeneous porous rocks having a bulk volume of 0.3 cm^3.
- The measured data can be used for validating the predictive value of network models which employ micro-CT-based realistic networks where sample sizes are small.
- All the existing scaling laws, considered in this study, for spontaneous imbibition scale the experimental data for the same rock type satisfactorily, but with different values for dimensionless time.
- The normalized gas recovery was calculated using three different models reported. The models proposed by Ma *et al.* and Viksund *et al.* show best agreement with measured data. The data of the largest and smallest cores were successfully scaled for all three types of rocks.

Nomenclature

a	coefficient associated with capillary forces, M/T
A	cross sectional area, L^2
A_i	area open to imbibition in the *i*th direction, L^2
b	coefficient associated with gravity, M/T
D	core diameter, L
g	gravity constant, L/T^2
k_w	water or wetting phase permeability, L^2
k	absolute permeability, L^2
k_r	relative permeability, L^2
l_{Ai}	the distant traveled by the imbibition front from the open surface to no flow boundary, L
L	core length, L
L_C	characteristic length, L
m_w	mass of water imbibed, M
M^*	characteristics mobility ratio
N_{wt}	volume of water imbibed into the core, L^3
p_c	capillary pressure, M/LT^2
Q_w	imbibition rate of the wetting fluid, L^3/T
R	recovery by spontaneous imbibition in the unit of pore volume, fraction
R^*	normalized non-wetting phase recovery, fraction
S_{wf}	water saturation behind imbibition front, fraction
S_{wi}	initial water saturation, fraction
S_w	water saturation, fraction
t	imbibition time, T
$t_{D,MK}$	dimensionless time (Mattax and Kyte)
t_D	dimensionless time
ρ_w	density of water, M/L^3
μ_w	wetting phase viscosity, M/LT
μ_{nw}	non-wetting phase viscosity, M/LT
λ^*	characteristic mobility, ML^3/T
ϕ	porosity, fraction

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Table 1: Bulk volumes of the cores used in a number of spontaneous imbibition experiments reported.

Author	Smallest (cm^3)	Largest (cm^3)	Rock Type / Fluid System
Mattax & Kyte[6]	14.2	56.0	Alundum, sandstone / Oil–brine
Hamon & Vidal[7]	444.6	3865.0	Aluminum silicate cores / Oil-water
Cuiec *et al.* [8]	56.7	226.9	Outcrop chalk / Oil-brine
Zhang *et al.* [9]	13.3	116.8	Berea / Oil-brine
Tie *et al.*[10]	55.1	91.0	Berea, Mt. Gambier carbonate/Oil-brine
Li and Horne[11]	38.0	874.7	Berea, chalk, gray-wacke / Water-air
This Study	0.1	12.3	Berea, Bentheim, Mt. Gambier/Brine-air

Table 2: Physical properties and dimensions of the cores used and constant "c" values for Li and Horne model.

Samples	Properties	Berea	Bentheim	Mt. Gambier
	ϕ	0.22	0.23	0.54
	k (D)	1.10	2.89	2.80
	WI	0.85	0.80	0.84
A	L (cm)	2.40	2.56	2.59
	D (cm)	2.52	2.56	2.51
	c	1.17	1.11	0.96
B	L (cm)	2.40	2.56	2.59
	D (cm)	1.52	1.49	1.48
	c	1.17	0.96	0.70
C	L (cm)	2.40	2.56	2.59
	D (cm)	0.52	0.53	0.55
	c	1.27	1.13	0.71
D	L (cm)	1.52	1.54	1.50
	D (cm)	0.52	0.53	0.55
	c	1.49	1.65	1.03
E	L (cm)	0.51	0.52	0.51
	D (cm)	0.52	0.53	0.55
	c	1.36	1.25	1.36

Table 3: Petrophysical properties of the literature data used in this study.

Author	Rock	ϕ	k (D)	L (cm)
Li & Horne[11]	Chalk	0.362	0.005	7.5
	Graywacke	0.045	0.0006	3.52
Schembre *et al.*[26]	Berea	0.15	0.5	11.0
Li&Firoozabadi[27]	Berea	0.228	0.5	4.93
Li & Horne[28]	Berea	0.245	1.2	43.5
Hatiboglu *et al.*[29]	Berea	0.21	0.5	6.0

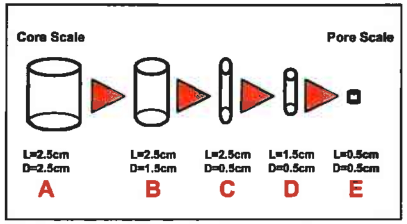

Fig. 1: Procedure of downscaling the core samples.

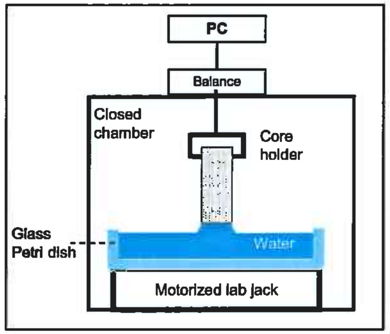

Fig. 2: Schematic of the spontaneous imbibition apparatus.

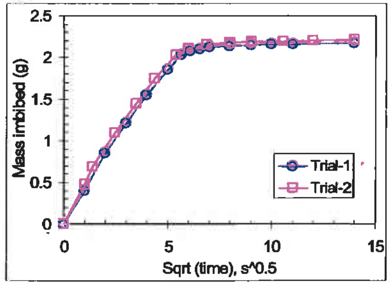

Fig. 3: Reproducibility test for the largest Bentheim core.

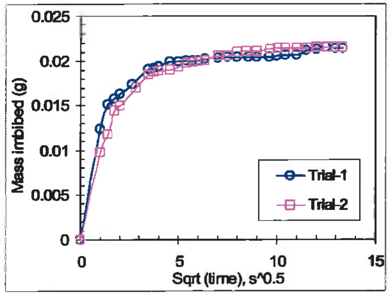

Fig. 4: Reproducibility test for the smallest Bentheim core.

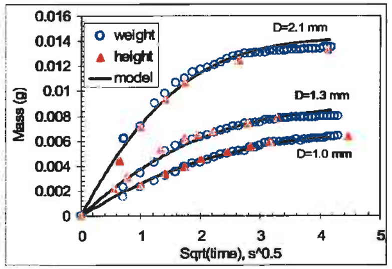

Fig. 5: Spontaneous imbibition of silicon oil into glass capillaries.

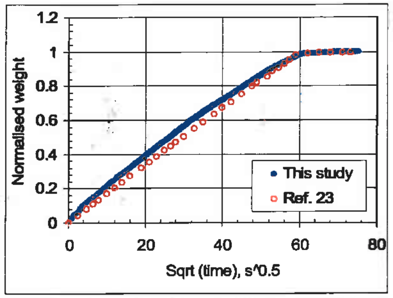

Fig. 6: Spontaneous imbibition of millipore water into Vycor glass rod.

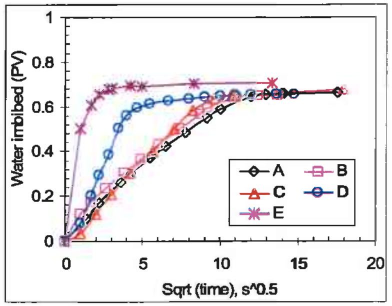

Fig. 7: Water imbibed versus square root of time for all Berea sandstone cores.

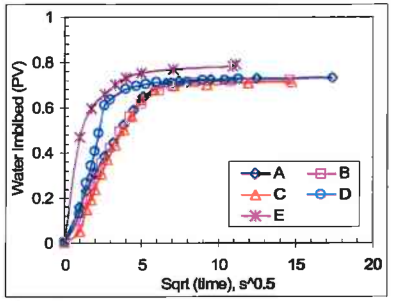

Fig. 8: Water imbibed versus square root of time for all Bentheim sandstone cores.

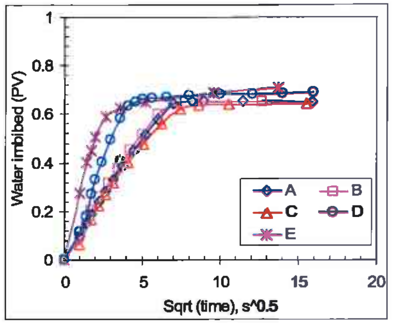

Fig. 9: Water imbibed versus square root of time for all Mt. Gambier carbonate cores.

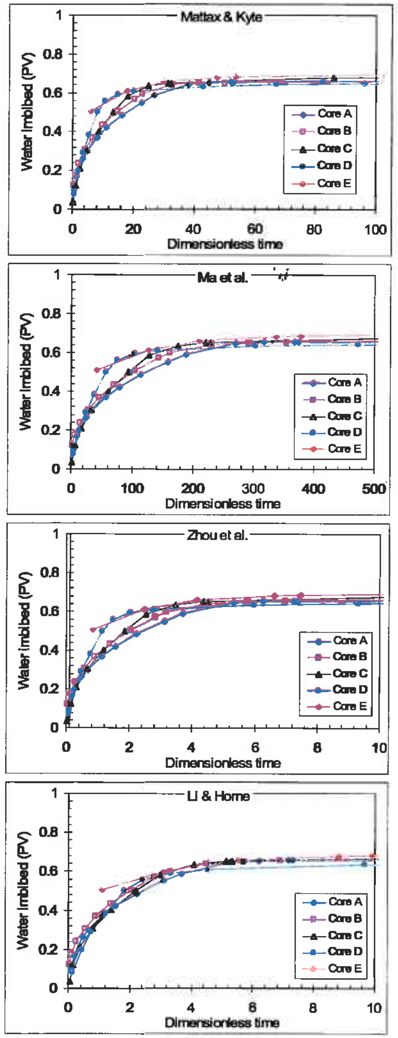

Fig. 10: Various scaling laws for spontaneous imbibition of water into air-saturated Berea cores.

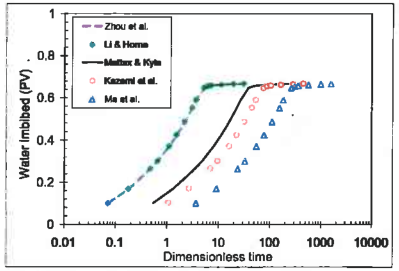

Fig. 11: Comparison of various scaling laws for spontaneous imbibition into Berea core A.

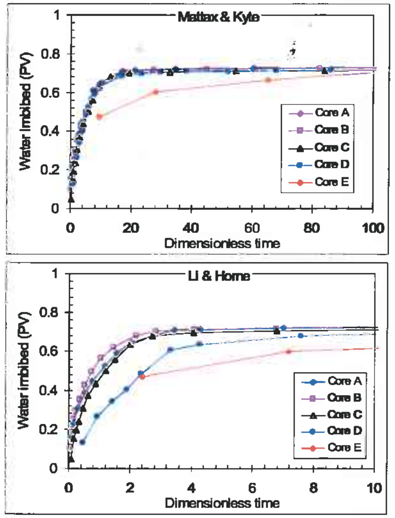

Fig. 12: Water imbibed versus dimensionless time for all Bentheim sandstone cores.

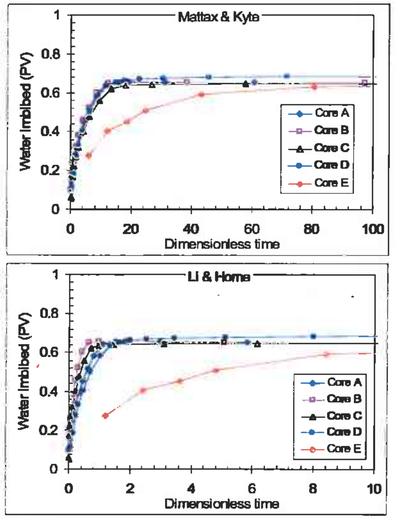

Fig. 13: Water imbibed versus dimensionless time for all Mt. Gambier carbonate cores.

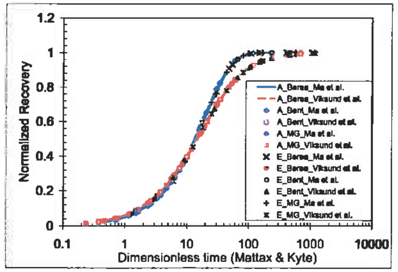

Fig. 14: A comparison of normalized recoveries using Eqs. 16 and 17 (Ma *et al.* and Viksund *et al.* models, respectively).

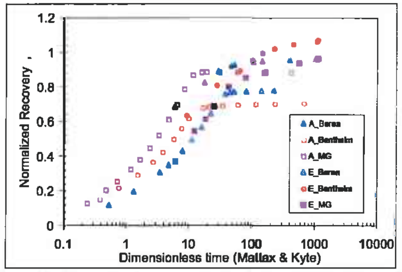

Fig. 15: Normalized recovery using Eq. 18 (Li and Horne model).

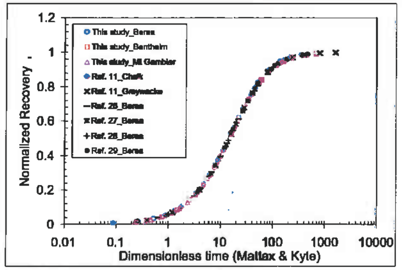

Fig. 16: Comparison of the experimental data (Core A only), scaled using the Viksund *et al.* recovery model, with those reported for spontaneous imbibition of water into air-saturated cores.