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Two phase relative permeability of gas and water in coal for enhanced coalbed methane recovery and CO$_2$ storage

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Abstract

Gas-water relative permeability behaviour of seven European coals of different ranks was characterised in order to enhance the scientific understanding of the fundamental processes of two-phase flow taking place within the macrostructure of coal. Laboratory experiments were carried out on cylindrical coal samples using the unsteady state method to measure gas-water relative permeabilities due to its operational simplicity. The impact of factors such as wettability, absolute permeability and overburden pressure on coal relative permeability were assessed. Considerable variation in the shapes of the relative permeability curves for different rank coals was observed, which was attributed to the heterogeneous nature of coal.

1. Introduction

Coalbed Methane (CBM) or Enhanced Coalbed Methane (ECBM) production using CO$_2$ injection is initiated through a resource evaluation process involving numerical simulations, making use of reservoir data that has either been estimated through empirical correlations and history matching of field data, or derived from laboratory tests on coals from a different basin altogether. As coal is a highly heterogeneous rock, any discrepancies in its reservoir characteristics can significantly impact the simulation results for a field site.

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When a virgin coalbed methane reservoir is first encountered, the entire cleat network is normally saturated with water and there are small or insignificant quantities of free gas present. The presence of water significantly hinders the flow of methane through coal seams and vice versa. Consequently, the effective permeabilities to both water and methane are reduced. Therefore, it is important to determine the effective permeability for the reservoir when two-phase flow is prevalent, and this effect is described quantitatively in terms of the coal's relative permeabilities to the gas and water phases.

Coals generally possess high irreducible water saturation in the cleats, which can be up to 80%. Their relative permeability to gas is therefore quite low and, according to Meaney and Paterson [1], it can be as low as 10% of the absolute permeability in some coals. Most of the early work in this field was carried out by Reznik et al. [2] who suggested laboratory tests for determining the air-water relative permeability behaviour of Pittsburgh coals. Relative permeabilities were measured at steady state conditions with both increasing and decreasing water saturations. However, water relative permeability values could not be measured directly, and had to be inferred from corresponding gas relative permeability data using Corey's relationships [3]. Dabbous et al. [4] extended this work by determining gas relative permeabilities at two different overburden pressures. These techniques were improved considerably by Puri et al. [5] who formulated a standard procedure for sample selection, handling, preparation and testing of coals.

In a similar way, Gash [6] conducted both steady state and unsteady state tests using tracer methods, and found that the two techniques yielded comparable gas-water relative permeability curves, within the experimental error with which saturations could be determined. Later on, Gash et al. [7] assessed the effect of cleat orientation and confining pressure on cleat porosity, permeability and relative permeability for Fruitland coals. An increase in the confining pressure from 450 psi (3.1 MPa) to 1,000 psi (6.9 MPa) caused the gas relative permeability to decrease less than the water relative permeability.

The shape of the relative permeability curves is dependent on whether the coal is wetted preferentially by water or gas, which in turn is a function of the lithotypes that constitute the coal. For instance, clarain and vitrain tend to prefer gas, while durain and fusain are more easily wetted by water. Moreover, in conventional gas reservoirs, the rock surfaces tend to be water-wet like the cleats in coalbeds, whereas in coal seams, the methane is adsorbed onto the matrix, therefore it may well be methane wet. Consequently, coals could potentially display a mixture of water wet, methane wet and intermediate wettability behaviour, depending on the degree of mineralisation. Indeed it is this heterogeneity of coal that is largely responsible for the variability in relative permeability curves. No relative permeability curves for European coal basins have been reported in the literature so far.

2. The origin of coals tested and sample preparation

Large coal blocks representative of coal ranks from High Volatile Bituminous to Anthracite were collected from opencast and underground coal mines in the United Kingdom, France and Germany as:
  - the *Schwalbach* seam from the Ensdorf underground colliery in Saarland, Germany
  - the *No.1* seam from the Warndt-Luisenthal (W-L) underground colliery in Saarland, Germany
  - the *Splint* seam from the Watson Head open cast site in Lanarkshire, Scotland
  - the *Tupton* seam from the Carrington Farm open cast site in Derbyshire, UK
  - the *Dora* seam from the Rumeaux underground colliery in Lorraine, France
  - the *9ft* seam from the Selar open cast site in South Wales, UK
  - the *7ft* seam from the Tower underground colliery in South Wales, UK

Before initiating the laboratory relative permeability measurements the coals were characterised for rank, porosity, absolute permeability and mechanical/elastic properties as reported later in Table 1. Sample selection procedures outlined by Hyman et al. [8] were adopted during the tests, together with recommendations for measuring relative permeability by Gash et al. [7].

Freshly cut core samples of 50 mm diameter were initially placed in a desiccator to help eliminate any residual gas from the samples. These were then vacuum dried at 60°C to remove free water in the cleats which could potentially initiate relative permeability effects. After about 24 hours of drying, the cores were weighed. This was followed by full saturation using degassed water and a vacuum pump. The cores were then re-weighed after 3 days of saturation to establish the pore volume and macroporosities.

3. Experimental set up and relative permeability measurements

The two most common experimental techniques used in determining relative permeability data are the steady state and unsteady state methods. Laboratory experiments presented here were carried out using the unsteady state method [9] due to its operational simplicity. In this method, the core is initially saturated with water, which is subsequently displaced by continuous injection of a gas. Saturations vary throughout the experiment and therefore equilibrium is never attained. The pressure differential and flow rates of the produced fluids are monitored as a function of time, and the corresponding relative permeabilities are deduced using Buckley-Leverett displacement theory [10]. The unsteady state gas flood attempts to replicate the displacement of water in the cleats by gas desorbed from the matrix.
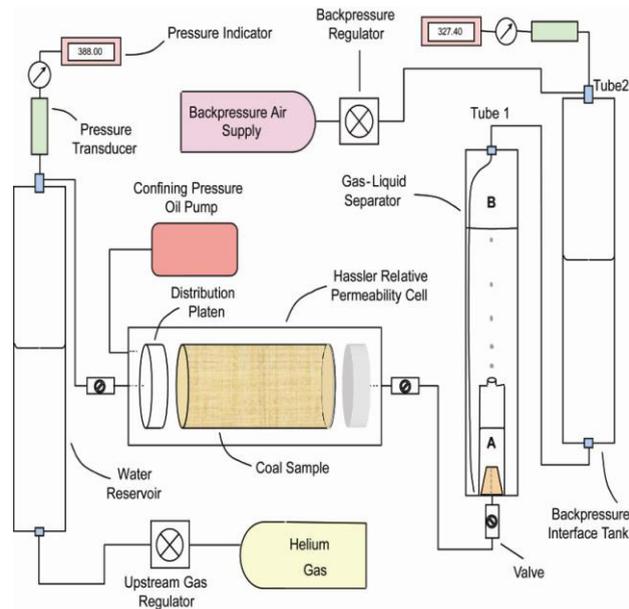

Fig. 1. The experimental set-up for relative permeability tests.

During the measurements, a gas-water separation unit and a backpressure device were connected in series to the outlet end of the Hassler cell core holder as illustrated in Fig. 1. The gas-liquid separation tube (Tube 2) was designed especially tall to a height of 1.5 m so as to accommodate as much gas as possible, yet sufficiently thin to minimise errors whilst reading fluid levels. The internal diameter and wall thickness of the tubes were 25 mm and 6 mm respectively. The Hassler cell was designed to withstand stresses of up to 100 MPa. Its end platens were fitted with seals consisting of Viton o-rings possessing a shore hardness factor of 90 to minimise deformation due to pressure. The gas-water

separator tube was partially filled with a low density paraffin oil, while the gas and water flow rates are measured by the main outer tube (Tube 1) and the small upturned syringe respectively.

A single saturated coal specimen was inserted into a rubber core sleeve, which is then loaded into the oil filled Hassler cell. A confining pressure of 1,000 psi (6.9 MPa) was applied to simulate the effect of overburden stress. For a number of coal types, the absolute and relative permeability tests were repeated at high (6.9 MPa) and low (4.1 MPa) confining pressures in order to assess the effect of overburden stress on the internal cleat structure and pore size distribution.

Injection of gas into the Hassler cell causes water to be forced out of the fully saturated core and simulates a drainage displacement process, as the saturation of the wetting phase decreases throughout the experiment. As water is produced, it accumulates in the small syringe forcing the oil column to move upwards. When gas production commences, it pushes the paraffin oil downwards in the tall tube (Tube 1) and any oil that is displaced is transferred to the second tube (Tube 2), which serves as an interface across which the backpressure is transmitted. Due to its non-adsorbing characteristics and smaller molecular size, helium was used as the injected gas in the experiments.

3.1. Relative permeability measurements

During the experiments, an overall pressure differential in the range of 50-60 psi (0.34 - 0.41 MPa) was applied across the core, based on an upstream gas injection pressure of 250 psi and a downstream backpressure of approximately 200 psi. The pressure gradient was selected so as to be large enough to minimise capillary end effects, but also sufficiently small compared with the total system pressure to render compressibility effects negligible.

Flow measurements were started once the inlet and outlet pressures had ceased to fluctuate. Data were recorded more frequently just after gas breakthrough when flow rates began changing more rapidly. Upstream and downstream pressures were also monitored at regular intervals. The use of sensitive Kenmac pressure regulators helped to achieve better control over the pressures at each end.

Gas flooding was continued until approximately 4 litres of helium gas had been flowed through the sample. This was done to ensure that the test was terminated only when the water relative permeability had become negligible and the gas relative permeability was stable. Once the separation system could no longer hold any more produced gas, the test was terminated.

4. Results and discussion

The Johnson, Bossler and Neumann (JBN) [9] method was used to calculate relative permeability curves from the unsteady state test data. To apply this procedure successfully, the system was allowed to stabilise over a one-month period prior to the experiments so as to minimise capillary end effects.

4.1. Relative permeabilities of coals tested

The experimental results and other relevant coal characteristics are summarised in Table 1. Examples of representative relative permeability curves derived from the laboratory tests are shown in Fig. 2 to 5 for each of the seven coal types. The relative permeability behaviour of the Splint coal was observed to be quite different from the other coals, having an abnormally high irreducible water saturation and steep relative permeability curves. The Splint samples were heavily fractured with large visible fractures that were responsible for the channelling of gas and water at high flow rates. Similar behaviour has been reported for sub-bituminous coals in the Powder River basin. The fact that Splint, Dora and Selar 9ft coals have irreducible water saturations at opposite ends of the saturation range typifies the variability that is so

common in coals. Selar 9ft coal is also mildly gas wet with an average equipotential flow point (cross point saturation) in the range of $0.55 > S_g > 0.60$, i.e. greater than 0.50. It is the only coal from the set which exhibited such behaviour as all other coals were water wet to differing degrees.

Table 1. Coal characterisation data obtained during the laboratory experiments and data analysis.

|	Coal Seam						
	Schwalbach	W-L No.1	Splint	Tupton	Dora	Selar 9ft	Tower 7ft
Volatile Matter (d.a.f) (%)	43.6	41.6	40.2	35.3	16.5	10.2	9.1
Fixed Carbon (d.a.f.) (%)	56.4	58.4	59.8	64.7	83. 5	89.8	90.9
Vitrinite Reflectance (%)	0.79	0.71	0.55	0.49	0.71	2.41	2.28
Moisture Content (%)	1.54	1.39	13.3	15.7	0.83	2.07	0.86
Coal Rank	High Vol. Bituminous B	High Vol. Bituminous B	High Vol. Bituminous B	High Vol. Bituminous A	Semi-anthracite	Anthracite	Anthracite
Young's Modulus, E (GPa)	$3.20 - 3.90$	$2.19 - 2.69$	$1.80 - 2.30$	$1.10 - 1.62$	$2.41 - 2.84$	$1.75 - 2.58$	$1.82 - 2.26$
Poisson's Ratio, ν	0.26	0.42	0.34	0.36	0.38	0.40	0.32
Average Critical Gas Saturation	0.35	0.32	0.15	0.23	0.33	0.40	0.25
Irreducible Water Saturation	0.22	0.19	0.68	0.36	0.15	0.17	0.34
Average Cross Point Gas Saturation	0.40	0.350	0.21	0.38	0.42	0.58	0.37
Absolute Permeability (mD)	0.90	0.52	0.73	2.15	5.52	9.51	2.93
Porosity (%)	0.63	1.76	1.80	1.35	1.38	0.96	0.12

(a) Selar 9ft – Sample 2

(b) Splint – Sample 2
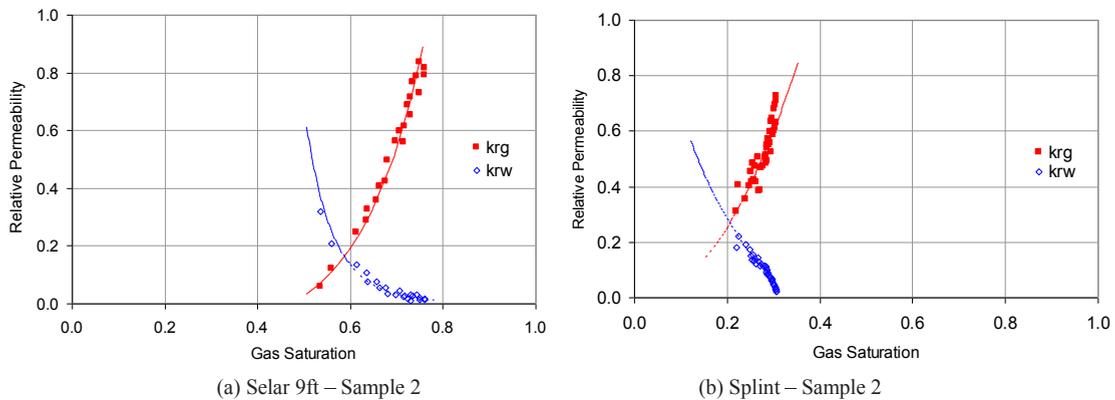
Fig. 2. Relative permeability curves for Selar 9ft and Splint coals.

Tower 7ft, Selar 9ft and Tupton coals generally appear to have more familiar curve shapes and are comparable to those determined by Gash et al. [7]. In particular, data from Tower 7ft and Selar 9ft, which have similar rank and elastic properties, display a greater coherence than Tupton coal, whose data are moderately dispersed. Some of the coals, notably Schwalbach, Dora and Warndt-Luisenthal No.1, exhibit convex shaped gas relative permeability curves and a relatively flatter water relative permeability profile.

All three coals originate from the Saar-Lorraine coal field at the border between France and Germany. In the case of Schwalbach, the extended water leg could be attributed to its robust mechanical properties and low permeability.

The convex shape of the curves suggests that gas flow is not occurring completely through the main cleat pathways. Instead, part of it is passing through the matrix or other units within the coal structure. Although water saturation is decreasing, the regions within the structure from which water is being driven out do not contribute significantly to retarding gas flow. On the other hand, if the curves are concaved upwards or straight lines, then the gas is able to drive the water more easily.

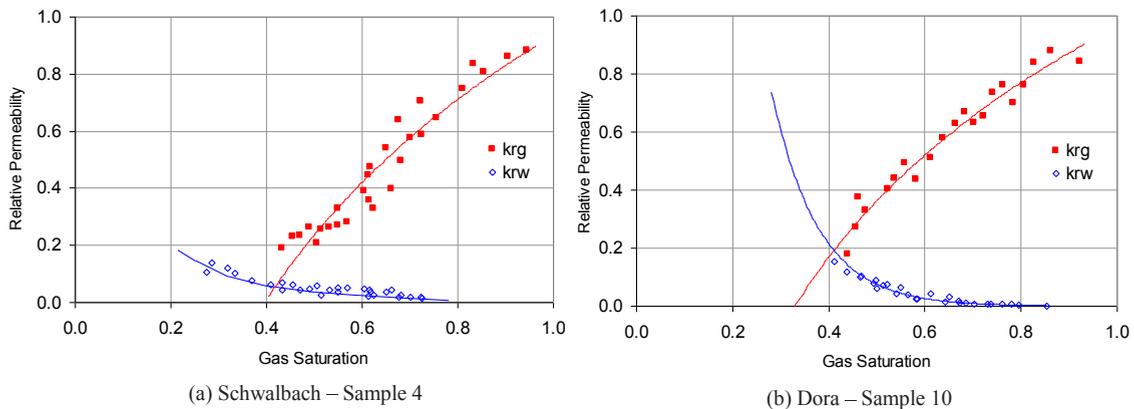(a) Schwalbach – Sample 4   (b) Dora – Sample 10

Fig. 3. Relative permeability curves for Schwalbach and Dora coals.

Post breakthrough water production was very small in each case, giving rise to generally low water relative permeabilities. Critical gas saturations appear to be spread out over a broad range of saturations but were generally found to lie in the 15-35% band, which is higher than those values suggested in the literature [1]. Irreducible water saturations were also high, ranging from 15-40% for all coal types except for Splint which was over 65%.

4.2. Effect of wettability on coal relative permeability

All the coals were found to be water wet to differing degrees by virtue of their cross point gas saturations being less than 0.50, except Selar 9ft which displayed moderate gas wettability. Splint coal was the most water wet with an average cross point saturation of only 0.21. The composition of a coal in terms of its mineral matter content and the dominant lithotypes influences the wettability, which in turn affects the relative permeability. The presence of more clarain and vitrain bands in Selar 9ft coal may explain its gas wetness. Similarly, coal samples from the Dora seam are considered to be more gas wet in comparison to Warndt-Luisenthal No.1 which is strongly water wet. This tendency towards intermediate gas wettability in the former is characterised by the following features as demonstrated in Fig. 4:

- An increase in gas saturation at the crossover point from 0.35 to 0.42.
- An increase in the cross point relative permeability itself from 0.11 to 0.19.
- An overall decrease in the gas relative permeability and increase in water relative permeability.
- An increase in the irreducible water saturation, i.e. the Swirr end point increases from 0.80 to 0.84.

It is worth noting that Dora coal is semi-anthracitic in terms of rank but also contains a significant amount of ash material constituting some 36.7% by weight.
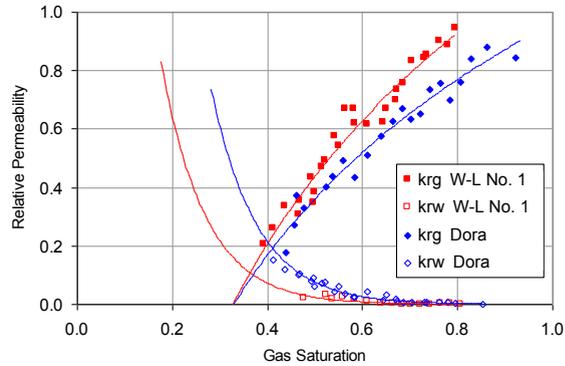
Fig. 4. Effect of wettability on relative permeability behaviour.

4.3. Effect of confining pressure on coal relative permeability

The only published studies to date that have reported the effect of confining pressure on coal relative permeability are by Dabbous et al. [4] and Gash et al. [7]. Their results have so far been inconclusive. Fig. 5 shows comparisons between relative permeability data obtained at two different confining pressures for Tupton and Tower 7ft coals respectively.
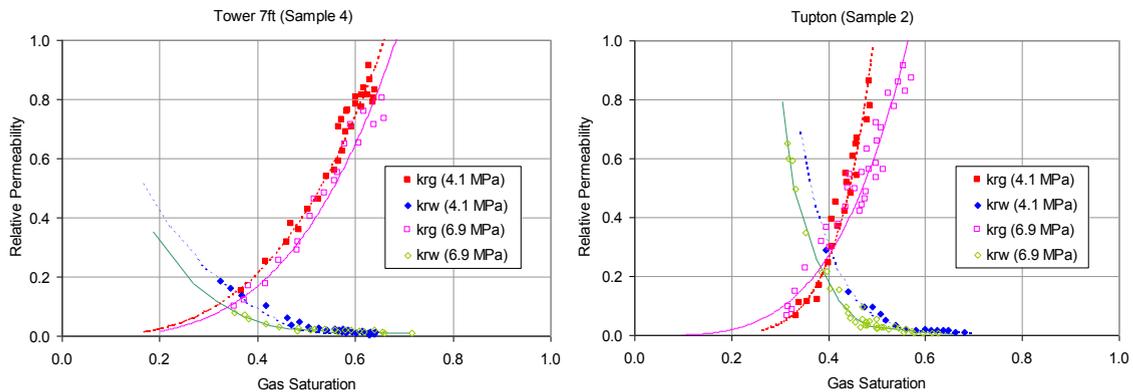

Fig. 5. Effect of confining pressure on relative permeability for Tower 7ft and Tupton coal samples.

The change in stress from 4.1 MPa to 6.9 MPa causes a small but noticeable shift in the curves towards lower relative permeabilities. The interpreted end point saturations are also reduced, with the irreducible water saturation in particular being higher due to the entrapment of water pockets. There is also a slight shift towards lower gas saturations, which is confirmed by Dabbous et al. [4] who measured gas relative permeabilities for Pittsburgh coals at overburden pressures of 1.38 MPa and 4.14 MPa.

5. Conclusions

Gas-water relative permeability experiments carried out on different ranks of European coals using an unsteady state method yielded critical gas saturations in the range of 15 to 35%. These were generally

higher than those values observed in previous studies. However, it is worth noting that critical gas saturations for coal have rarely been documented explicitly in the literature and therefore had to be inferred from relative permeability curves for the purposes of comparison. Irreducible water saturations ranged between 15 and 40%.

Considerable variability in the shapes of relative permeability curves was also observed, and was mainly attributed to coal heterogeneity, both in terms of composition and cleat-matrix configuration. Overall, the shapes of the relative permeability curves were governed more by the wettability characteristics of the coal seams rather than their rank or elastic properties. It was observed that, when the effect of the large cleats dominates, the relative permeability curves become straighter and narrower, while if the matrix effect is more predominant then the curves tend to be spread over a wider saturation range and are less linear. This trend was observed in the results where those samples containing a larger concentration of fractures parallel to the direction of flow tended to give rise to steeper curves resembling straight lines over a narrow saturation range. This was accompanied by an overall shift towards higher water saturations and corroborates the work of previous researchers such as Meaney and Paterson [1].

On the other hand, some of the curves obtained have displayed a very sharp increase in gas relative permeability at high gas saturations, while a much shallower decrease in water relative permeability is observed at lower values. Consequently, the water relative permeability effectively falls to zero very soon after breakthrough has occurred, confirming a high irreducible water saturation. This behaviour could represent a possible shift from the cleat contribution initially dominating to the matrix becoming more prevalent later on.

Helium was used during the relative permeability tests and it was assumed that gas did not adsorb onto the coal during drainage. In reality, however, the presence of adsorptive gases such as methane and CO_2 means that the adsorption process would be occurring, albeit much slower and over a long period, and could therefore affect coal permeability and relative permeability in the seams.

Relative permeabilities were found to decrease slightly with increasing confining pressure although the corresponding effect on absolute permeability was greater.

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