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Two phase relative permeabilities for gas and water in selected European coals

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HIGHLIGHTS

- Gas–water relative permeabilities of seven European coals were characterised.
- The impact of wettability and overburden pressure on relative permeabilities was assessed.
- Considerable variation in the shapes of the relative permeability curves for different rank coals was observed.

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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 and overburden pressure on coal relative permeabilities 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.

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. In order to evaluate the deliverability of coalbed methane wells it is important to determine the effective permeability for the reservoir throughout its production life (when two-phase flow is prevalent), and this effect is described quantitatively in terms of the coal relative permeabilities to the gas and water phases. Fluid flow through the cleat system also depends on the distribution of fluids in the cleats, which is related to capillary pressure. A clear appreciation of the internal pore structure of coal and its interaction with gas and water is required if one is to understand the mechanisms of two-phase flow in a complex porous media such as coal.

Water can exist in coal in a variety of forms, including free water in the cleats, chemically bound water of hydration, and water adsorbed onto the surface of the matrix blocks. For water-saturated coals, increases in gas relative permeability help to restrict water production and improve gas flow as the seam becomes progressively dewatered. During this process whereby water is withdrawn from the cleats, there is a change from water relative permeability dominating to gas relative permeability becoming more dominant. At the same time, coals generally possess high irreducible water saturations 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

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as 10% of the absolute permeability in some coals. However, it should be noted that the matrix, particularly the small micropores, are coated with methane, causing the matrix to be gas wet, despite the cleats being water wet and often possessing a high irreducible water saturation.

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.

A survey of the literature reveals that relatively little experimental data has been reported for coal relative permeability, and there are often large discrepancies between field and laboratory derived curves. There are still no generally accepted methods in the industry for laboratory measurement of relative permeability in coal. Similarly, few accepted standards are available for comparing such data. This is primarily due to the physical properties of coal, which make it difficult for accurate measurements to be taken. The principal reasons why relative permeability data are not easily obtainable include: the friable and brittle nature of coals; the low porosity of the cleat network, which requires the accurate measurement of very small volumes of water; and the stress dependent nature of coal permeability.

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 1000 psi (6.9 MPa) caused the gas relative permeability to decrease less than the water relative permeability.

Laboratory studies carried out by Meaney and Paterson [1] on coal taken from the Bowen Basin in Australia indicated that the separation of water and gas in the field due to gravity resulted in higher effective permeabilities than what was measured in the laboratory. This suggests that actual relative permeabilities in the field are likely to be higher where there is gravity segregation. For such flow systems it may be more appropriate to use straight-line relative permeability relationships since capillary effects are considered negligible in segregated flow.

More recently Shen et al. [8] investigated the relative permeabilities to gas and water in different rank coals selected from South Qinshui Basin, China under various gas/water saturations through water replacement with methane using an unsteady-state method. Contact angles in the coal–water–CO_2 system were measured by Sakurovs and Lavrencic [9] using CO_2 bubbles in water/coal systems at 40 C and pressures up to 15 MPa using five bituminous coals. Clarkson et al. [10] investigated the impact of some CBM reservoir properties on derived (from production analysis) relative permeability curves. In an effort to infer and quantify wettability alteration of coal surface during the ECBM process, Chaturvedi et al. [11] studied wettability of coal at scales ranging from the microscopic to the core. Chen et al. [12] proposed an improved relative permeability model for coal reservoirs. In a separate study [13], the model was applied to the experimental and field data reported in the literature.

In this study the gas–water relative permeability behaviour of different coal types is characterised in order to further our understanding of the fundamental processes of two-phase flow taking place within the macrostructure of coal. New relative permeability curves for a range of European coals of varying rank are presented and analysed. This is realised primarily through laboratory tests, where gas–water relative permeability curves are determined for coals, and the impact of factors such as wettability, absolute permeability and overburden pressure, on coal relative permeability, are assessed. It is hoped that the results will provide characterisation data that would enable CBM and ECBM simulators to better describe in situ reservoir conditions and evaluate the effect of carbon dioxide injection on gas productivity.

2. Relative permeability measurement using unsteady state method

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 [14] 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 [15]. The unsteady state gas flood attempts to replicate the displacement of water in the cleats by gas desorbed from the matrix.

2.1. Coal sample collection and 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

In order to preserve their natural moisture content and prevent oxidation during transport and storage, the blocks were wrapped

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