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# Effect of surface roughness and lithology on the water–gas and water–oil relative permeability ratios of oil-wet single fractures

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ABSTRACT

This paper discusses the effect of surface roughness on the water–gas and water–oil relative permeabilities of single fractures. After manufacturing 20 × 20 cm transparent replicas of fractures developed under tensional load, constant injection rate displacement experiments were performed. Saturation distribution against time was visually monitored and the residual phases were determined for seven fracture samples of different rock types. These values were then correlated to the fractal and statistical properties of the fracture surfaces. Fractures developed from less porous and larger grain size rock samples (marbles) showed "larger scale" heterogeneity, which caused residual phase saturation in the form of large pockets. Porous rocks with small grain sizes (limestones) showed "small scale" heterogeneity yielding residual saturations in small pockets. The fractal dimension obtained by the triangular prism method has more control on the residual saturation distribution than the other fractal and statistical parameters.

Subsequently, the relative permeability ratios were determined using the simplified Corey equation for fracture systems and the conditions causing deviations from the "cubic ratio" behavior were clarified qualitatively and quantitatively for four different displacement cases (water–gas, gas–water, oil–water, and water–oil).

In the liquid-liquid cases, the deviations were due to a combined effect of wettability and roughness. Highly granular (and porous) limestone samples, with the smallest grain size out of the seven samples, presented the biggest deviation from the "cubic ratio" in the water displacing oil and gas cases.

The semi-quantitative analysis presented in this paper is expected to give new insights into residual phase saturation development and the deviations of relative permeabilities from the traditionally accepted "cubic ratio" behavior.

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## Background

In a pioneering study, Romm (1966) presented the first data on fracture relative permeabilities (RP) after measuring oil–water relative permeabilities as a linear function of its saturation, which yields an X-shaped curve. Much later, attempts were made to estimate the shapes of the relative permeabilities of single fractures for gas–liquid (Pruess and Tsang, 1989; Fourar et al., 1993; Chen, 2005), and liquid–liquid (Wong et al., 2008; Shad and Gates, 2010) systems experimentally and computationally. A common point in those studies is that the method applied was steady-state, i.e., the two phases were allowed to flow simultaneously in a single fracture at different ratios until a steady-state is reached.

In one of the earliest attempts, Persoff and Pruess (1995) presented liquid–gas relative permeabilities measured on a rough fracture surface. They observed strong phase interference, i.e., the RP values were much lower than 1 at intermediate saturations, which contradicts the theory of straight line relative permeabilities ($k_{rw} + k_{ro} = 1$ at all saturations). Another critical observation made in that study was the existence of critical gas flow paths. After a quick invasion of gas in its own critical path due to high mobility, it flowed through its own preferred channel and its RP decreased rapidly after water started invading the model. At low saturations of water, gas RP took very low values (interference zone), reaching

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zero quickly. Water, then, started controlling the flow with its RP steadily increasing. Both observations were also supported by a computational model that was applied on a non-smooth fracture surface by Pruess and Tsang (1989, 1990).

In a sequence of papers, Fourar et al. (1993), Fourar and Bories (1995), and Fourar and Lenormand (2001) applied the theory of two-phase flow in pipes introduced by Lockhart and Martinelli (1949) and measured steady-state relative permeabilities for liquid–gas systems. After identifying different flow regimes as a function of superficial velocities of the phases, they obtained relative permeabilities as a function of relative permeabilities for smooth parallel plates. Their major observation was that the relative permeabilities do not follow a straight line behavior. Later, Nowamooz et al. (2009) applied this approach on a transparent replica of a rough walled rock fracture. They observed deviations from the cubic ratio for only one type of fracture surface (sandstone) and suggested using other fracture surfaces belonging to different rock types such as granite to generalize their observations. A major conclusion from these studies is that the sum of the relative permeabilities of liquid and gas is less than one indicating strong interference effect.

Meanwhile, Wong et al. (2008) measured oil–water relative permeabilities of smooth and rough fracture models following a similar computational approach and a rough fracture model (created by glass beads) proposed by Fourar et al. (1993). They observed a slight deviation from the straight line relative permeabilities for the smooth parallel plate model. They reported that the roughness also affects the oil–water flow pattern but this becomes insignificant at larger apertures. They did not report any RP data for rough surfaces.

Shad et al. (2008, 2010) studied the effect of oil viscosity and flow orientation on smooth parallel plates using the steady-state approach introduced by Fourar et al. (1993). They observed lubrication effect yielding RP values higher than 1 if the fracture is oil-wet.

Similarly, using their two smooth parallel plate model, Chen and Horne (2004) applied the steady-state method introduced by Fourar et al. (1993) to measure relative permeabilities. After visualizing different flow regimes, they introduced a “tortuous channel” model that causes reduction in relative permeabilities and deviation from X-shape curves. This study was extended by Chen et al. (2007) to clarify the effect of phase change on steam–water relative permeabilities of smooth and rough surfaces. They observed different flow patterns and regimes from air–water systems that have tendency to form their own flow paths blocking each other’s way. Steam nucleation developed due to roughness in the rough-walled models causing the development of initial immobile steam saturation as well as entrapment of steam bubbles that may be considered as residual saturation.

As seen, to date, most of the experiments were run on smooth parallel plates applying steady-state measurement technique. Even under these conditions, deviations from the straight line relative permeabilities (X-shaped) were observed mainly due to phase interaction depending on the flow rates of the fluid pairs. Some of the above mentioned studies used rough fractures prepared artificially, such as glass bead models (Fourar et al., 1993; Wong et al., 2008) and artificially roughened glass surfaces (Chen and Horne, 2006; Chen et al., 2007), and observed critical effects of the roughness on deviation from straight line relative permeabilities. Yet, the roughness effect requires more attention to clarify its effects on the flow patterns of immiscible fluids as well as immobile or residual saturation of the phases.

For this type of work, one needs more realistic fracture systems, ideally exact replicas of rock fractures. We are aware of a very limited number of studies that developed fracture replicas of original rocks fractured under stress and used in flow experiments. Among those, Nowamooz et al. (2009) and Radilla et al. (2013) used the same sample (Vosges sandstone) and performed steady-state RP measurements of liquid–gas systems. Both studies suggested that, for generalized results, different rock types yielding different fracture surfaces should be used. In a preceding study, Develi and Babadagli (2015) and Babadagli et al. (2015) performed visual experiments of single and multiphase (immiscible) flow on seven different fracture replicas of different rock types (marbles, granites, and limestones). In addition to these attempts, miscible displacement experiments were reported with visual analysis on rough fracture surface obtained from rocks (Auradou et al., 2001, 2006; Korfanta et al., 2015). Yet, more data is needed to correlate the roughness characteristics to liquid–gas and liquid–liquid relative permeabilities. This is needed not only for the shape of the relative permeabilities but also for residual saturations. Understanding residual saturation development, especially, requires unsteady-state experiments as also indicated by Chen and Horne (2006) and Chen et al. (2007).

Playing a critical role on multiphase flow and phase distribution, fracture surface characteristics should be determined to correlate the relative permeabilities to the fracture roughness (and aperture). This requires an initial attempt of mapping the fracture surfaces (Develi et al., 2001; Ogilvie et al., 2001a,b, 2002a). The next step is to quantitatively characterize the surface roughness in which fractal methods have been widely applied and tested (Brown, 1987, 1995; Dubuc et al., 1989; Pande et al., 1987; Miller et al., 1990; Huang et al., 1992; Schmittbuhl et al., 1995; Den Outer et al., 1995; Glover et al., 1998, 1999; Develi and Babadagli, 1998; Babadagli and Develi, 2001; Ogilvie et al., 2002b; Murata et al., 2002).

## Statement of the problem and solution methodology

Based on the attempts on the relative permeability (RP) measurements of single fracture systems over the last five decades as summarized above, the following can be highlighted as critical points for further investigations:

1. Displacement experiments are needed to clarify the residual (and immobile) phase saturations in a single fracture due to roughness.
2. Channel flow (preferred flow path) is controlled not only by the interference between two phases caused by variable flow rates but also the roughness. Hence, visual experiments on realistic fracture models are needed.
3. The shape of the fracture RPs may be in the form of straight lines (Romm, 1966) or follow the “cubic ratio” (Fourar et al., 1993; Fourar and Bories, 1995; Shad et al., 2010; Wong et al., 2008) with no residual saturations. Deviations from straight line relative permeabilities or more recently accepted Brooks and Corey (1966) type “cubic ratio” relationships were also observed due to phase interference on smooth parallel plate models or artificially roughened fracture samples. This should be tested on original fracture surfaces obtained from fracturing tests. To achieve this, visual experiments are needed.
4. Clarification is needed on the effect of wettability of the fracture surface (Babadagli et al., 2015) on the dynamics of the displacement process (the shape of the RP curves) and residual/immobile phase saturations.
5. Viscosity ratio plays a critical role on RP as the process takes place in a 2-D medium. Unsteady-state (displacement) type experiments are needed to clarify the effect of it on the shape of the RP curves as steady state experiments may not be able capture certain phenomena such as viscous fingering and how it is associated with the roughness.

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