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Relative permeabilities hysteresis for oil/water, gas/water and gas/oil systems in mixed-wet rocks

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Abstract

Accurate determination of relative permeability ($k_r$) curves and their hysteresis is needed for reliable prediction of the performance of oil and gas reservoirs. A few options (e.g., Carlson, Killough and Jargon models) are available in commercial reservoir simulators to account for hysteresis in $k_r$ curves under two-phase flow. Two-phase $k_r$ curves are also needed for estimating $k_r$ hysteresis under three-phase flow during water-alternating-gas (WAG) injection. Although, most oil reservoirs are mixed-wet, the existing hysteresis predictive approaches have been developed based on water-wet conditions. Experimentally measured data are needed to assess the performance of these methodologies under more realistic reservoir conditions e.g. low gas-oil IFT and mixed-wet systems.

This paper includes two parts. In the first part we review the most valuable works in the literature regarding the effect of hysteresis on two-phase relative permeabilities in different wettability conditions. As will be highlighted most of these data are generated on water-wet or slightly water-wet condition which are most likely not representative of the oil reservoirs. Even the generated two-phase relative permeabilities on mixed-wet and oil-wet conditions are not fully developed for the full hysteresis cycle and/or not for all the three possible systems (oil/water, gas/oil and gas/water) in one place. It is recently recommended by some of the valuable theoretical works in the literature that to enhance the predictions of three-phase hysteresis models, hysteresis for all possible two-phase systems shall be considered in the provided equations. As a result in the second part of this paper, we summarize comprehensive set of experimentally measured relative permeabilities for the two-phase systems of oil/water, gas/water and gas/oil. This set of data can be used with new three-phase hysteresis models such as that presented by Hustad and Browning (2010) to enhance the prediction of the WAG processes in non-water-wet systems.

Experiments were performed in 65mD sandstone with mixed-wettability.

For the gas/water system, the first set of fluid displacements began by water injection (imbibition: I) in the core saturated with gas and immobile water. This was followed by a period of gas injection (Drainage: D) which was followed by alternating periods of water and gas injections (IDIDI). In the second series, the core was initially 100% saturated with water and the experiment started with gas injection (D) followed by successive imbibition and drainage periods (DIDIDI). Similar sets of displacement experiments were performed for oil/water and gas/oil systems. The gas/oil system in our experiments represents extra low-IFT (near-miscible) system with an IFT value of 0.04 mN.m$^{-1}$. The measured pressure drop and fluid production data obtained during the experiments were then history matched to estimate $k_r$ values for each imbibition and drainage period for each pair of fluids.

In the oil/water system (DIDID injection sequence), $k_{rw}$ shows cycle hysteresis which is in contrast to the common observations made in water-wet systems in which $k_{rw}$ does not show hysteresis. In addition to $k_{rw}$, $k_{ro}$ also shows significant hysteresis for the 1st imbibition period compared to the 1st drainage period but after the 1st imbibition period the $k_{ro}$ hysteresis was not significant. In the gas/water system (IDIDI), both $k_{rg}$ and $k_{rw}$ decreased as the alternation between imbibition and drainage continued. The results show significant differences in the $k_r$ hysteretic behaviour in gas/water and oil/water systems. We demonstrate that the approach used in some of the three-phase simulations reported in literature, where the oil/water $k_r$ curves are
used instead of gas/water $k_r$ curves (which are not normally measured) is not valid for mixed-wet systems and can lead to significant errors in prediction by reservoir simulators. Irreversible hysteresis loops were observed in our experiments even for the gas/oil system (in spite of the ultra-low gas/oil IFT) whereby $k_{rg}$ values during each drainage period lied above the $k_{rg}$ of the preceding imbibition. Drainage $k_{ro}$ curves were significantly lower than their preceding imbibition $k_{ro}$. The observed $k_{ro}$ cycle hysteresis diminished after the 2nd or 3rd injection cycle.

The results suggest that in mixed-wet systems it is necessary to consider irreversible hysteresis loops for all phases, and hysteresis behavior of different systems (oil/gas, water/gas and water/oil) can be different. This behaviour is not predictable by the formulations such as Land, Carlson and Killough models which are currently exist in commercial reservoir simulators.
Introduction

In two-phase systems (for a water-wet condition), the entire wetting phase (water) remains continuous due to wetting layers and through the smaller pores. As the wetting phase saturation increases, it invades the next larger pores and traps some of the non-wetting phase (gas or oil) in the invaded pores. Since some of the pores of the size being occupied by the wetting phase contain some trapped non-wetting phase, at any particular wetting phase saturation, some of the wetting fluid must occupy pores of a larger size than it would have occupied if there was no trapped non-wetting phase in the porous medium. As a result, the wetting phase relative permeability for imbibition (water injection) increases compared to the drainage case (gas injection or oil injection (primary drainage)), and non-wetting phase imbibition relative permeability would be lower than that of drainage. The greater the amount of the non-wetting phase entrapment, the greater will be the reduction in the non-wetting phase relative permeability for imbibition process. This means that relative permeability to a fluid at a given saturation depends on whether that saturation is obtained by approaching it from a higher or lower value. This behaviour is known as the hysteresis effect. Therefore, relative permeability measurement experiments in the laboratory must be performed under representative conditions wherein each saturation is approached in the desired manner based on the processes (displacements) happening at reservoir.

For example (for a water-wet system), if the reservoir is depleted by decreasing the oil saturation and increasing the gas saturation, as in expanding gas-cap drive, the drainage relative permeability curves should be used. If however the reservoir is depleted by decreasing the oil saturation and increasing the water (or wetting phase) saturation, as in a water-drive mechanism, then the imbibition relative permeability curves must be applied. Most of the reservoirs are undergoing three-phase flow and as a result both drainage (gas saturation increases) and imbibition (water saturation increases) are required for reservoir simulations. In addition, some EOR processes such as WAG injection involve alternating (cyclic) injection of water and gas as well as three-phase flow and as a result three-phase hysteresis should also be accounted for. Two out of the three available approaches to simulate three-phase hysteresis in WAG injections are based on two-phase hysteresis (Shahverdi et al., 2011; Shahrokhi et al., 2014). In the first approach, a two-phase hysteresis model (such as Killough, Carlson or Jargon) is coupled with a three-phase k_r correlation (Stone-I, Stone-II or Baker). In the second approach (ODD3P model in Eclipse, Hustad and Browning (2010)), two–phase k_r under cyclic hysteresis are required for all the three pairs of fluids. Two-phase relative permeabilities are also required for the third approach (WAG-Hysteresis model in Eclipse, Larsen and Skauge (1998)). As a result, accurate determination of relative permeability (k_r) hysteresis is needed for assessment of these approaches as well as improving the prediction of the performance of many oil recovery processes including WAG injection. Even then, 3-phase relative permeability hysteresis models themselves suffers from limitations whatever the quality of the input 2-phase data (Fatemi and Sohrabi (2013c), Zuo et al. (2014); Egermann et al. (2014), Shahrokhi et al. (2014)).

Most of the hysteresis data in the literature have been obtained with saturations starting at endpoint values (i.e., irreducible water saturation or residual oil saturations for water/oil system). These data are usually dealing with the differences between bounding relative permeability curves. However, in most of the displacements happening in a real reservoir the direction of saturation change reverses at a number of intermediate saturations (known as scanning curves on k_r versus saturation plots). As a result, the data obtained from such displacements are not applicable to the modeling reservoir processes in which saturation of phases increase or decrease to an intermediate value, then change in the opposite direction. Examples include EOR methods such as water alternating gas (WAG) or Cyclic Steam Stimulation (CSS) injection.

In addition to saturation and saturation history, reservoir rock wettability also plays an important role in relative permeability and their hysteretic behaviour (Owens and Archer (1971), Morrow et al. (1973); McCaffery and Bennion (1974); Morrow 1990; Rao et al. 1992). Recently Fatemi and Sohrabi (2013a)
showed that under low IFT conditions, changing wettability from water-wet to mixed-wet can also affect the results of gas/oil displacements (recovery and relative permeabilities) even in the absence of any water. This extra low-IFT behaviour is in contrast with the effect of wettability observed for gas/oil systems under high IFT in the literature.

Fatemi et al. (2012a) provided an extensive literature review on the two-phase hysteresis models. Although, it is generally accepted that many oil reservoirs are mixed-wet (Jerauld and Rathmell, 1997; Salathiel, 1973; Delshad et al. 2003), however the majority of the existing relative permeability hysteresis functions have been developed for strongly water-wet porous media (Land, Killough, Carlson). According to the Salathiel (1973) and Delshad et al. (2003) in a mixed-wet system, the oil-wet pores correspond to the largest pores in the rock and the small pores remain water-wet. Few relative permeability models have been developed for mixed-wet porous media (Temeng, 1991; Moulu et al., 1999; Delshad et al., 2003; Kjosavik et al., 2002) and unfortunately none of them are available in commercial simulators such as ECLIPSE and CMG.

Experimentally measured data are needed to assess the performance of two-phase hysteresis models as well as the three-phase hysteresis approaches under more realistic operational and reservoir conditions e.g. low (near-miscible) gas-oil IFT and mixed-wet systems. This paper provides the two-phase relative permeability data set required for assessment of these approaches for the case of different WAG injection scenarios under low gas/oil IFT and mixed-wet conditions, WAG experiments under such conditions have been presented in previous publications (Fatemi and Sohrabi (2013b); Sohrabi and Fatemi (2012); Fatemi and Sohrabi (2015)). To the best of our knowledge this paper is the first work that addresses the issue of cycle hysteresis for up to 3 or 4 cycles and also investigates all three two-phase systems of gas/oil, gas/water and oil/water under mixed-wet conditions. In addition the gas/oil system used in this study represent near-miscible condition which is the case for most WAG injection scenarios (Christensen et al. (2001); Fatemi 2015).

The gas/water relative permeability data presented in this paper are also of interest to those investigating the effect of hysteresis in underground gas storage. Natural underground geologic traps have been utilized for storing gas and liquid hydrocarbons. These reservoirs are usually developed from known hydrocarbon reservoirs which have been abandoned. Gas storage reservoirs are utilized in many locations to seasonally store gas in summer months for periods of high demand in the winter. This generally involves the cyclic pressurization (drainage) and depressurization (imbibition if the storage reservoir overlies an aquifer) of the reservoir on an annual basis. (Bietz et al., 1996).

Processes in porous media that involve decreases in the saturation of the wetting phase are commonly referred to as “drainage.” Imbibition is commonly used to denote an increase in the wetting-phase saturation. Since the system under investigation here is a mixed-wet sample definition of the wetting and non-wetting phases is not as straightforward as in the case of water-wet system. As a result regardless of rock wettability, here we use the term “drainage” to refer to the decreases in water saturation for oil/water system, oil saturation in a gas/oil system or water saturation in a gas/water system. Similarly, the term “imbibition” here refers to the processes in which increase in water saturation in oil/water system, oil saturation in a gas/oil system or water saturation in a gas/water system takes place.

Review of Two-Phase Hysteresis Studies:
Gas/Water System:
Geffen et al. (1951) investigated the effect of saturation history on relative permeability bounding curves in gas/water systems under water-wet condition. They concluded that relative permeabilities are not a single valued function of saturation. It was observed that for water/gas (air) system, hysteresis effect was larger for gas compared to water.
Colonna et al. (1972) performed experimental work to systematically study the evolution of the hydrodynamic rock characteristics for a given history of alternated fluid displacements. Various combinations of drainage and imbibition cycles aimed at creating a series of situations resulting from the exploitation of a gas storage were studied on two large sandstone samples: (1) a Vosges sandstone and (2) a well consolidated Hassi R’Mel sandstone. Their results showed that the relative permeabilities of the non-wetting phase (gas) in the drainage displacement do not retrace those of the previous imbibition.

Evrenos and Comer (1969) performed coreflood experiments to capture multi-cycle drainage-imbibition processes in hydrophilic rocks (water-wet) used as gas storage reservoirs. The behaviours of $k_r$ curves for consolidated and unconsolidated sands were similar and imbibition relative permeabilities of both phases were not retraced in the subsequent drainage period. Oak (1991) measured two-phase relative permeabilities for water-gas (nitrogen) for an intermediate-wet (with respect to water and oil) sandstone. The water-gas data suggest that water is the wetting phase with respect to gas. Bietz et al. (1996) investigated the effect of saturation history for a gas/water system (the formation water and pressurized nitrogen gas) in three different core samples. From their investigation, it is evident that encroachment of water into the previously uninvaded portion of the reservoir can significantly reduce the relative permeability of the contacted region. They reasoned that this is due to the fact that the initial reservoir water saturation ($S_{wi}$) is often naturally lower than irreducible water saturation ($S_{wirr}$) (by gas injection). This phenomenon was very well depicted in high permeability, low permeability and dolomite cores (Figure 1), where the gasflood (drainage) relative permeability curves show the inability of the flowing gas phase to reduce the water saturation yielding significantly reduced gas endpoint relative permeability. It should be mentioned Bietz et al. (1996) did not investigate subsequent hysteresis cycles.

Figure 1: Gas/water relative permeabilities for three different samples, a) high permeability composite core; b) low permeability composite core and c) dolomite composite core (Bietz et al., 1996)
Oil/Water System:
Geffen et al. (1951) performed coreflood experiments on core samples with the native wettability of the reservoir (probably slightly water-wet) and investigated the effect of saturation history on relative permeability bounding curves in oil/water systems. It was observed that in the case of water/oil system, hysteresis effect was much larger for non-wetting phase (oil) compared to the wetting phase (water). Geffen et al. (1951) performed additional tests on the Nellie Bly oil/brine system by establishing partial oil saturations, then flooding the core with brine. Further experiments have shown that, this flow behaviour would be reversible and reproducible, provided the previous maximum oil saturation is not exceeded.

Geffen et al. (1951) noticed that, quantitatively, the flow characteristics of oil/water and gas/water systems are not in agreements but qualitatively, the effects of saturation history are the same. Differences in the wettability characteristics of the two systems are thought to be a contributing factor in the lack of quantitative agreement. Jones and Roszelle (1978) investigated saturation history dependency for oil/water system. Relative permeability to water was considerably reduced in the drainage period, but permeability to oil is relatively unchanged from imbibition values (slightly larger than drainage). Batycky and McCaffery (1978) investigated the effect of oil/water IFT on two-phase relative permeability hysteresis. They observed that at high IFT of 50 mN.m\(^{-1}\), both phases show some degree of hysteresis between imbibition and drainage relative permeabilities (dashed curves in Figure 2). As for the qualitative nature of the observed hysteretic behavior, \( k_{rw} \text{(Imb.)} > k_{rw} \text{(Drain.)} \) and \( k_{ro} \text{(Drain.)} < k_{ro} \text{(Imb.)} \). By reducing the IFT to 0.2 mN.m\(^{-1}\) (solid curves in Figure 2a), the hysteresis effect in the oil relative permeability curves reduced compared to the high IFT system, and there was no hysteresis in brine relative permeability. At the extra-low IFT of (approximately) 0.02 mN.m\(^{-1}\) (solid curves in Figure 2b), there was no hysteresis between the drainage and imbibition relative permeability of either phase.
Figure 2: oil/water relative permeability hysteresis for different IFTs; a) IFT = 50 mN.m$^{-1}$; b) IFT = 0.2 mN.m$^{-1}$ and c) IFT = 0.02 mN.m$^{-1}$ (after Batycky and McCaffrey, 1978)

Amaefule and Handy (1982) also investigated the effect of oil/water IFT on the relative permeabilities hysteresis behaviour (water-wet Berea sandstone cores). Oil/water relative permeability data for the high-tension (34 mN.m$^{-1}$) and extra-low (0.03 mN.m$^{-1}$) systems are presented in Figure 3. The hysteresis effect was much smaller at the low IFT than it was at the high IFT. The corresponding irreducible brine saturations decrease from 40% at 34 mN.m$^{-1}$, to 28% at 0.03 mN.m$^{-1}$. However, the residual oil saturation decreased from 20% for IFT of 34 mN.m$^{-1}$ to 4% at an IFT of 0.03 mN.m$^{-1}$. Unsteady-state results led to predictions of less oil recovery than steady-state data, for both high and low tensions.
Braun and Holland (1995), measured oil/water relative permeability cycle hysteresis for a water-wet outcrop rock sample as well as a mixed-wet reservoir core. They concluded that for the oil phase, imbibition and drainage relative permeability bounding curves differ significantly. The difference was much less pronounced for the water phase relative permeability. By comparing the two wetting conditions, they concluded that similar relative permeability hysteresis behavior for oil phase was observed for both wettability conditions (with secondary drainage curve lying below that for imbibition but merging with the imbibition curve near the endpoints). In the mixed-wet sample, hysteresis effect was more pronounced compared to water-wet sample. However, hysteresis effect in oil relative permeability was less in mixed-wet system compared to the water-wet one. In the case of water-wet system they observed that oil relative permeability dropped in secondary drainage compared to the imbibition. Nevertheless, the observed hysteresis effect between secondary drainage and imbibition was negligible compared the imbibition and primary drainage.

Braun and Holland (1995) also measured scanning curves as transitions between imbibition and drainage bounding curves in an outcrop sample (water-wet condition) and concluded that a notable characteristic of the oil relative permeability scanning curves is their reversibility at high oil saturations where it does not exhibits any hysteresis. Regarding cyclic hysteresis, they did not observe oil relative permeability hysteresis in change of direction from drainage to imbibition and vice versa. It should be mentioned that the range of saturation change for the \( k_{ro} \) measurement in their experiment was limited to just 10%, which usually is not expected to show much hysteresis anyway. Water relative permeability was found to be reversible over the entire ranges.

Hawkins and Bouchard (1992) work was focused on oil/brine systems (refined mineral oil and distilled water), in a synthetic core composed of uniform beads which they believed to have an oil-wetting preference. Their data were consistent with the literature data in that greater hysteresis was observed in the relative permeability of the non-wetting phase (in their experiments water).

Torabzadeh and Handy (1984) investigated an oil/water system at different IFT and observed hysteresis in relative permeability curves for both wetting and non-wetting phases. At any temperature (oil/water IFT) the effect appeared to be more pronounced for the non-wetting phase (oil). Hysteresis effect was more significant at lower temperatures (higher IFT's) and decreased with increasing temperature (decreasing IFT). The effect disappeared at 175 °C for the IFT\( _{o/w} \) = 0.015 mN.m\(^{-1}\). Unfortunately they just investigated DID injection scenario for the case of IFT\( _{o/w} \) = 0.117 mN.m\(^{-1}\) in which they observed...
that for both phases $k_r$ values for primary drainage are larger compared to the $1^{st}$ imbibition. $k_{rw}$ didn’t show significant hysteresis between 2$^{nd}$ drainage and 1$^{st}$ imbibition. However, $k_{ro}$ showed some reduction for the change of injection from 1$^{st}$ imbibition to 2$^{nd}$ drainage (although not significant).

Wang (1988) investigated the effect of wettability alteration on water/oil two-phase flow behavior in Berea sandstone and Loudon reservoir cores. In one test, a water-wet Berea core was made mixed-wet by aging the core with Loudon crude after it was driven to irreducible brine saturation. In the other test, a mixed-wettability preserved Loudon core was made to become more water-wet by extraction with toluene distillation. Figure 4a shows the relative permeability curves for the natural Berea Core B2 over two complete drainage/imbibition cycles. Subsequent tests in the second drainage and second imbibition showed no further hysteresis in either oil or water relative permeability; both were the same as those in the first imbibition path. Figure 4b shows oil/water relative permeabilities for the same core after aging towards mixed-wet condition. Although apparently there was no change in water phase relative permeability hysteresis behaviour, but the oil phase shows different hysteretic behavior, in which $k_{ro}$ shows much less hysteresis effect compared to the water-wet condition and $k_{ro}$ for drainage lies above the imbibition curve (contrary to the water-wet condition where $k_{ro}$ for drainage are larger than those of imbibition). It is worth mentioning that in theory the distinction between the wetting and non-wetting phases becomes less significant than in a strongly water-wet core.

Figure 4: Oil/water relative permeability hysteresis for Berea sandstone at water-wet (left) and mixed-wet (right) conditions (after Wang, 1988).

Figure 5a shows Wang (1988) relative permeability curves for Loudon Composite Core L1 in the preserved state. The water relative permeability data were reproducible in both drainage and imbibition directions. The oil relative permeability data showed hysteresis, with the imbibition curve being higher than the drainage curve (similar to what was observed in Figure 4b). But for later stages of the test ($2^{nd}$ drainage and $2^{nd}$ imbibition) measured $k_{ro}$ data were very close to those of the $1^{st}$ drainage. Figure 5b shows $k_{ro}$ and $k_{rw}$ hysteresis effect for the same core once the wettability has been changed towards more water-wet status. It is evident that $k_{ro}$ shows stronger hysteretic behaviour compared to the preserved state (Figure 5a), since $k_{ro}$ for the subsequent displacements ($2^{nd}$ drainage and $2^{nd}$ imbibition) drops compared to the $1^{st}$ imbibition.
Figure 5: Oil/water relative permeability hysteresis for Loudon Composite Core at reservoir preserved state (left) and after extraction by toluene (right) (after Wang, 1988).

Figure 6 shows the effect of wettability on the $k_r$ and $k_{rw}$ in Wang (1988) experiments. For both core samples $k_{rw}$ showed small change between the two wettability conditions ($k_{rw}$ curve and end point $k_{rw}$ for water-wet system are slightly lower compared to the mixed-wet condition). The major difference is in $k_r$ curves where $S_{orw}$ is less for mixed-wet system compared to the water-wet condition. As a result $k_{ro}$ values are larger at higher $S_w$ in the case of mixed-wet system compared to the water-wet condition. Note that the cross point of the $k_{ro}$ and $k_{rw}$ curves are shifted towards higher $S_w$ for mixed-wet system.

Eleri et al. (1995) investigated how relative permeability test methodology (steady-state versus unsteady-state) impacts relative permeability curves and their hysteresis behaviour for two-phase oil and water in intermediate-wet cores. It was observed that hysteresis occurs in both methods. The relative permeabilities at a given saturation for the phase increasing in saturation are higher than when the saturation of the phase is decreasing. But hysteresis is more pronounced in the unsteady-state relative permeability curves than in the steady-state curves. Eleri et al. attributed this observation to the viscous instabilities in their waterflood experiments.

Oak (1991) measured two-phase relative permeabilities for water-oil (Dodecane). The water-oil data suggest that the treated core was intermediate-wet, since both water and oil relative permeabilities are affected by the saturation history.
Lombard and Lenormand (1993) used sand-packs as porous media and evaluated secondary imbibition and secondary drainage oil/water relative-permeability curves. In water-wet system, they found significant hysteresis in oil relative permeability curves, with relative permeability to oil during secondary drainage (SD) remaining significantly lower than that of the former imbibition. They also observed a very small amount of hysteresis in water relative permeability curves. For oil-wet system, although the qualitative hysteretic behaviour of oil relative permeability was similar to that of water-wet conditions but the difference between imbibition and secondary drainage relative permeability was not significant. On the other hand, water relative permeability showed significant hysteretic behavior in the oil-wet system compared to water-wet condition.

Dixit et al. (1998a,b) used a three-dimensional (3D) network model to study oil/water relative permeability hysteresis phenomena. Dixit et al. (1998a) investigated strongly and weakly water-wet (corresponding to mild aging; $0^\circ < \theta < 90^\circ$) porous media. Dixit et al. (1998b) investigated mixed-wet (corresponding to moderate aging; $90^\circ < \theta < 180^\circ$ for oil-wet regions) porous media. Different combinations of pore-scale displacement mechanisms (viz., snap-off and piston-like displacement) as well as consolidated and unconsolidated porous media were simulated. They concluded that the nature of the observed hysteresis trends change dramatically depending to the combination of the displacement mechanisms and geometrical properties of the pore-network model. Dixit et al. (1998a,b) claimed that all experimentally observed trends in relative permeability hysteresis are reproducible under suitable conditions. In general for mild aging they have not observed any significant hysteresis for water phase in consolidated porous media, but $k_{rw}$ hysteresis was more significant for unconsolidated system. For both consolidated and unconsolidated systems they predicted some hysteresis for the oil phase. Under moderate aging conditions, in either of the consolidated and unconsolidated system, hysteresis was found to be significant for both oil and water phases.

**Gas/Oil System:**

Osoba et al. (1951) performed coreflood experiments on core samples with the native wettability of the reservoir. Their results for bounding relative permeability curves in oil/gas (kerosene/helium) system showed that the relative permeability for both phases are subject to hysteresis; Their measured relative permeability values showed hysteresis for both oil (wetting) and gas (non-wetting) phases. Oil relative permeability for imbibition was higher than drainage, while for gas, drainage relative permeability was higher than imbibition ones. Hysteresis effect was larger for non-wetting phase (gas) compared to the wetting phase (oil).

![Figure 7: Gas/Oil relative permeabilities hysteresis (after Osoba et al., 1951).](image-url)
Naar et al. (1962) experimental work on oil and gas (air) system (Figure 8) showed that consolidated rocks and unconsolidated porous media exhibited different hysteretic behaviour. At a given saturation, the imbibition non-wetting permeabilities for a rock were smaller than its drainage relative permeabilities. The contrary happened for unconsolidated samples where imbibition non-wetting permeabilities were larger than drainage ones. A similar difference was observed for the wetting phase. Imbibition permeabilities were larger than drainage ones for a consolidated rock but smaller than drainage permeabilities for an unconsolidated medium.

In addition to these two extremes (consolidated and unconsolidated), Naar et al. (1962) also investigated the effect of saturation history for poorly consolidated sandstone (as an intermediate condition). Comparing the permeability curves of the poorly consolidated sandstone (Figure 9) with the curves presented in Figure 8, shows the tendency of the poorly consolidated medium to behave as an unconsolidated medium. As can be seen, the oil relative permeability hysteretic behaviour is similar to the unconsolidated glass spheres while the gas relative permeability hysteresis is qualitatively similar to that of the consolidated sandstone.

Figure 8: Relative permeability curves for (a) consolidated sands (b) unconsolidated glass spheres (after Naar et al., 1962)

Figure 9: Gas/oil relative permeabilities for poorly consolidated sandstone (after Naar et al., 1962).
Although in their original work Naar et al. (1962) have not presented any relative permeability cycle hysteresis, they claimed that significant difference was observed for both the consolidated and unconsolidated samples, when drainage and imbibing processes were repeated. This means that after an imbibition when the wetting fluid is drained and then imbibed again in a consolidated rock, the relative permeability retraces the imbibition curves only. However, when these processes were applied to the unconsolidated sand, the flow behavior retraces in succession imbibition and drainage relative permeability curves. Figure 10 shows a schematic representation of the Naar et al. (1962) comments about cyclic hysteresis in consolidated and unconsolidated rocks.

Haniff and Ali (1990) related the hysteresis effect to the difference in advancing and receding contact angles and concluded that at complete wetting situations where the contact angle is zero, the advancing and receding contact angles are the same and hysteresis effects should be absent. Their experimental study on fluid flow and residual saturations in a methane-propane gas condensate fluid system showed that at a gas/oil IFT of 0.001 mN.m$^{-1}$ no hysteresis effect was observable in the relative permeability curves (Figure 11). On the other hand, experiments performed at IFT values of 0.2 mN.m$^{-1}$ (at partial wetting condition where the advancing and receding contact angles are finite and different) show significant hysteresis effects (although the drainage displacement was not extended) in relative permeability curves. Unfortunately Haniff and Ali (1990) did not investigate hysteresis for 0.001 < IFT$_{g/o}$ < 0.2 mN.m$^{-1}$.

![Figure 10: Schematic representation of kro and krg hysteretic behaviour in water-wet system; left) consolidated and right) unconsolidated porous medium (after Dixit et al., (1998a,b))](image1)

![Figure 11: Effect of oil/gas IFT on the two-phase relative permeability hysteresis. left) IFT = 0.2 mN.m$^{-1}$; right) IFT = 0.001 mN.m$^{-1}$ (after Haniff and Ali, 1990).](image2)
Oak (1991) measured two-phase relative permeabilities for oil-gas (dodecane/nitrogen) for an intermediate-wet (respect to water/oil system) sandstone. A strong hysteresis effect was found in the gas relative permeability curves, suggesting that gas is the non-wetting phase.

Methodology
From the provided literature review, it is obvious that except Oak (1991) most of the previous works are just focused on one of the two-phase systems (i.e. gas/oil, gas/water or oil/water). In addition they have not investigated cyclic hysteresis which is especially important in the case of WAG injection. In this section we summarize our methodology to investigate the cyclic hysteresis effect for all three possible two-phase systems under mixed-wettability condition.

Core and Fluids
Table 1 lists physical properties of the core sample used in this study. The brine used in the experiments was synthetic brine made of Sodium Chloride (NaCl) and Calcium Chloride (CaCl₂) in de-gassed distilled water. We first established immobile water saturation in the core (by displacement) and then changed the core wettability from water-wet to mixed-wet by aging using an appropriate crude oil sample. This process is expected to make the core mixed-wet with the parts in contact with immobile water to be water-wet and other parts non water-wet. The calculated Amott-Harvey index from two spontaneous imbibition measurements and two forced displacement measurements showed lumped neutral-wet condition (Fatemi, 2015). The process of $S_{\text{win}}$ establishment resulted in $S_{\text{win}}=18\%$ obtained by accurate material balance and x-ray scan analysis. After the ageing period, the core went through another period of cleaning to make sure that the ageing crude had been displaced from the core and would not contaminate the test fluids. Details of the immobile water establishment, wettability alteration, cleaning the core after wettability and x-ray analysis can be found elsewhere (Fatemi and Sohrabi, 2013a; 2013b). Regarding the capillary pressure consideration and its inclusion in history matching refer to Shahrokhi et al. (2014).

The hydrocarbon fluid system used in the experiments consisted of an equilibrium binary mixture of methane ($C_1$) and n-butane ($n-C_4$). The test fluids (oil and gas) were pre-equilibrated at the conditions of the experiments (1840 psia and 100 °F) to minimise mass transfer between fluids during the displacement experiments. Oil and gas phases were also pre-equilibrated with brine (the same brine which was used for the establishment of immobile water saturation which is also used during water injection) to make sure that immobile water saturation would not be stripped from the pore spaces by the injection of these fluids. The critical point of the oil/gas mixture was 1870 psia and 100 °F and the experiments were conducted at 1840 psia and 100 °F, which is very close to the critical point of the system. The oil/gas IFT was 0.04 mN.m$^{-1}$ at this condition (Table 3) and hence, the gas/oil system was nearly miscible (Fatemi and Sohrabi, 2013b). For more information on rock and fluids properties, immobile water establishment, wettability alteration refer to Fatemi and Sohrabi (2013b).

Table 1: Physical properties of the core sample used in the experiments.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Permeability (mD)</th>
<th>Length (cm)</th>
<th>Diameter (cm)</th>
<th>Porosity (frac.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>65</td>
<td>60.5</td>
<td>5.08</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Table 2: Physical properties of synthetic brine at 100°F (38°C).

<table>
<thead>
<tr>
<th>Salinity (mg/L)</th>
<th>Density (gr/L)</th>
<th>Viscosity (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>992.96</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Table 3: Measured fluid properties for gas and oil phases at 100°F (38°C).

<table>
<thead>
<tr>
<th>Pressure (psia)</th>
<th>ρ_g (kg.m⁻³)</th>
<th>ρ_o (kg.m⁻³)</th>
<th>μ_g (mPa.s)</th>
<th>μ_o (mPa.s)</th>
<th>IFT (mN.m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1840</td>
<td>211.4</td>
<td>317.4</td>
<td>0.0249</td>
<td>0.0405</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Experiments: Gas-Water System**

**Gas/Water DIDIDI Injection Scenario:**
This series of tests started with a gas injection (drainage, D) into the core fully saturated with water, and was then followed by a water injection period (imbibition, I). The periods of gas and water injections were repeated and in total three injection cycles, DI-DI-DI, were carried out. During the brine injection periods, no gas was produced after water breakthrough (BT). This is contrary to our observations for gas/oil systems, in which gas production continued after the oil BT (although at very small rates). We attribute this difference between the behaviour of gas/water and gas/oil systems to a stronger snap-off mechanism and hence stronger trapping of the gas by water in gas/water system compared to gas/oil system. Figure 12 shows how the change of water saturation (gas saturation is one minus water saturation) at different stages of this series of gas/water displacement (DIDIDI) tests.

**Figure 12:** Average brine saturations during different stages of water/gas DIDIDI hysteresis test (65 mD, mixed-wet core).

**Gas/Water IDIDI Injection Scenario:**
We first established the immobile water saturation, and then started this series of tests with a brine injection (Imbibition: I) into the core saturated with 82% gas and 18% S_wim. This brine injection period was followed by a gas injection period (Drainage: D). The periods of water and gas injections were repeated and in total three water injections and two gas injections were carried out one after another. This series of fluid displacements is referred to as IDIDI. Figure 13 shows core average water saturation for different water and gas injection periods of this test. For more details of the gas/water DIDIDI and IDIDI injection scenarios refer to Fatemi and Sohrabi (2012).
Experiments: Gas-Oil System

**DIDID Injection Scenario:**
This series of tests started with a gas injection into the core saturated with oil and 18% immobile water saturation. The gas injection period (Drainage, D) was followed by an oil injection period (Imbibition, I) and the gas and oil injection periods were repeated until in total three gas and two oil injection periods had been carried out one after another. Therefore, this series of fluid displacements is here referred to as DIDID. Figure 14 shows average oil saturation inside the core for different oil and gas injection periods of this test.

**IDIDI Injection Scenario:**
This series of displacements started with an oil injection (Imbibition, I) into the core saturated with gas and 18% immobile water saturation. This injection period was followed by two cycles of successive injections of gas and oil. Based on the order of the oil and gas injection periods, this experiment is referred to as IDIDI. Figure 15 shows average oil saturation inside the core during the different oil and gas injection stages of this test. For details of the gas/oil IDIDI and DIDIDI injection scenarios refer to Fatemi et al. (2012a).
Experiments: Oil-Water System

**DIDID Injection Scenario:**
The objective of this series of displacements was to investigate the effect of hysteresis on the behavior of oil/water relative permeability under mixed-wettability conditions. The experiment started with an oil injection into the core completely (100%) saturated with brine. This was followed by two imbibition/drainage cycles. The experiment is referred to as DIDIDI.

Figure 16: Water average saturations change inside the core during different cycles of two-phase water/oil DIDIDI hysteresis test (65 mD, mixed-wet core).

**Primary Waterfloodings (65 mD)**
To obtain imbibition bounding relative permeabilities curves for oil/water system. Water-injection experiments (for both wettability conditions) were carried out with immobile water in the core ($S_{wi}=18\%$) and 82% oil. Brine was injected through the core at 25 cm$^3$.hr$^{-1}$. Brine injection continued for some time after the breakthrough until the rate of oil production became practically zero.

**Results and Discussion**
A black-oil coreflood simulator (SENDRA) was used in this study to history match the core flood results (pressure drop across the core and production data) in order to obtain $k_r$ curves. Figure 17 shows comparison between history matching and experiment which is important for reliable estimation of the relative permeabilities curves. To further validate the observed trends in relative permeability values, for all injection cycles $k_{ori}/k_{rwi}$ ratio has been plotted as a function of normalized wetting saturation. This is performed due to the fact that unsteady-state $k_r$ values are suffering from the non-uniqueness. This means that different set of $k_r$ values
might be obtained for the same experiment and they all might match the history of the coreflood (more or less). Yet, the good point is that the $k_{nw}/k_{rw}$ ratio for an unsteady-state experiment would be unique for a specified experiment and as a result for all such $k_r$ sets. This means that if the $k_{nw}/k_{rw}$ ratio is different for two un-steady state experiments then one can argue for sure that real $k_r$ values for these two experiment would not be the same anyway. It should be mentioned that the inverse of this statement is not correct. In addition during the course of history matching we used the estimated parameters of the previous injection period as the initial guess to answer whether the parameters from the previous scanning curve can match the new injection period. For more discussion and details refer to Fatemi et al (2012b).

Figure 17: history matched data (pressure drop and oil production) in the case of 1st drainage period in the DIDID series (65mD, Mixed-Wet, $S_w=18$).

**Hysteresis Effect in Gas-Water System**

**Gas/Water Bounding Relative Permeabilities**

$k_r$ values of the 1st drainage period (gas injection) in the DIDIDI series and the 1st imbibition period (water injection) in the IDIDI series are in fact representative of bounding drainage and imbibition curves respectively. Figure 18 shows bounding curves for the imbibition and drainage relative permeabilities for the studied water-gas system. Both gas and water phases show hysteresis effect. The observed hysteresis is much larger for non-wetting phase (gas) compared to that of the wetting-phase (water). Imbibition relative permeability values for water are larger than drainage values, and the gas relative permeabilities values for imbibition are smaller than those obtained in drainage direction displacement. Water phase $k_r$ shows more hysteresis effect for lower water saturation values and for high enough $S_w$ values (above 0.78) the trend of $k_{rw}$ shows that there is not much difference between imbibition and drainage values. Contrary to this, the non-wetting phase (gas) $k_r$ shows stronger hysteresis dependency at high $S_w$ values (low $S_g$), and the trend of $k_r$ curves shows that the imbibition and drainage $k_r$ values are approaching each other for small $S_w$ values.
Figure 18: Water and gas bounding relative permeabilities (water/gas system).

**Gas/Water Scanning Relative Permeability Curves: DIDIDI Experiment**

Figure 19 shows the cyclic hysteresis effect obtained for water phase relative permeability in the DIDIDI experiment. The process starts with bounding drainage curve (1st gas injection) in which water saturation decreased from 1 to 0.54. At this point, the drainage process stopped and imbibition (water injection) started. Changing the direction of flow, water relative permeability follows a new curve (blue curve) which lies slightly above the previous drainage period. As the alternation between imbibition and drainage cycles continues all water relative permeability curves (except 3rd water injection) are practically equal to each other and the bounding drainage relative permeability. So in the case of DIDIDI process, it is reasonable to conclude that water phase relative permeability does not show much cyclic hysteresis.

Figure 19: Water phase relative permeability hysteresis (gas/water system, DIDID experiment).
Figure 20 shows the cyclic hysteresis effect on the gas phase relative permeability in the DIDIDI experiment. The displacements start with the bounding drainage curve (1st gas injection; red triangles) in which water saturation decreased from 1 to 0.54. During this process the gas relative permeability increased from 0 to around 0.08. It should be mentioned that 0.08 is also the value obtained from Darcy equation at the end point of the experiment (semi steady-state condition). At this low relative permeability value, the gas phase is still strongly mobile due to its much less viscosity compared to water ($\mu_g/\mu_w=0.03$). At this point, the drainage process stopped and the imbibition (water injection) started. Changing the direction of injection to imbibition, the gas relative permeability follows a new path (blue curve) which lies between the former drainage curve (bounding drainage) and the bounding imbibition curve (1st water injection of IDIDI experiments, which is shown by dashed curve). The imbibition process stopped at water saturation of around 0.77 and another drainage displacement started in which water saturation decreased to about 0.5 (red circles). The relative permeabilities of the 2nd drainage lie above the former imbibition displacement. Comparison of Figure 19 and Figure 20, shows that the cyclic hysteresis effect is more pronounced for the gas phase relative permeability than the water phase. Another important feature is that the hysteresis loop made by $k_{rg}$ in the 1st imbibition and the 2nd drainage periods, is not closed. The gas relative permeabilities of the subsequent imbibition period (2nd water injection; blue circles) follow a path, which is the same as 1st water injection. Figure 20 shows that as the alternations between imbibition and drainage continue the gas relative permeability drops at different drainage stages. This means that $k_{rg}$ for the 1st drainage is higher than the 2nd drainage cycle, and the lowest values are those of the 3rd gas injection period. The same Figure also shows that for different imbibitions, $k_{rg}$ values are practically equal to each other. As the cyclic injection continues, the cyclic hysteresis effect becomes smaller for the later stages of the experiment compared to the earlier ones. This means that the reduction of $k_{rg}$ values for the 3rd gas injection cycle (compared to the 2nd gas injection) is much less than reduction factor for the 2nd gas injection cycle (compared to the 1st gas injection). In addition to this, the hysteresis loops by 3rd drainage and 3rd imbibition, is smaller than that formed by the 1st drainage and the 1st imbibition. This shows that as expected cyclic hysteresis is more important for earlier stages of the experiment. Possibly the most important hysteresis effects exist for the change of injection from the 1st drainage into the 1st imbibition, as well as change of injection from 1st imbibition into the 2nd drainage.
Figure 20: Evolution of gas phase relative permeability hysteresis (gas/water system, DIDIDI experiment).

Figure 21: Semi-log plot of gas phase relative permeability hysteresis (gas/water system, DIDIDI experiment).
Gas/Water Scanning Relative Permeability Curves: IDIDI Experiment

Figure 22 shows the water relative permeability curves obtained from the IDIDI displacements. The general hysteresis behaviour of the water phase for this series of the experiments is somehow different from what was observed for the DIDIDI injection scenario (where there was not much hysteresis). Here the displacements started with a bounding imbibition curve (1st water injection; blue curve) in which the water saturation increased from 0.18 (immobile water saturation) to 0.73. At this point, the imbibition process was stopped and drainage (gas injection; red) started. The water relative permeability values of the drainage scanning curve do not follow the values of the previous imbibition displacement. The results show $k_{rw}$ reduction for the 1st drainage compared to the previous imbibition. The 1st drainage continued until the water saturation decreased to 0.48. At this point, another imbibition displacement started and its relative permeability followed a new path (light blue curve) which lies below the previous drainage displacement. It should be mentioned that the end point relative permeability of water (at $S_{grw}$) for each imbibition are calculated directly from Darcy equation at the semi-steady state condition (when there was no more gas production and the only mobile phase was water).

The water relative permeability hysteresis loop formed by 1st drainage and 2nd imbibition is not closed at this stage of the experiment. This means that relative permeability at the turning point ($S_w = 0.73$) in which the flow direction changed from 1st imbibition to 1st drainage, is not the same as the previous drainage relative permeability (at the same saturation). At the end of the 2nd imbibition, another drainage displacement started (pink curve). The results show that the 2nd drainage scanning curve follows those of the previous imbibition displacement (2nd imbibition). In fact, after the 2nd imbibition, the cycle hysteresis effect is vanished for the later stages of the experiment. The $k_{rw}$ of the 2nd imbibition and all subsequent ones are very close to the bounding drainage relative permeability values. As a result, as the alternation between imbibition and drainage continues the cycle hysteresis effect becomes less important as the $k_{rw}$ are approaching those of the bounding drainage $k_{rw}$. The most important hysteresis effect is between 1st Imbibition and 1st drainage, and of less importance is between 1st drainage and 2nd imbibition.

It is worth mentioning that the observed hysteretic behaviour in 1st cycle (1st drainage + 1st imbibition) of the IDIDI gas/water hysteresis study is similar to those reported by Bietz et al. (1996).
Figure 22: Evolution of water phase relative permeability hysteresis (gas/water system, IDIDI experiment).

Figure 23 and Figure 24 show gas relative permeability obtained from the IDIDI experiments. The general hysteresis behaviour of the gas phase is not quite similar to what was observed for the DIDIDI experiments. The process starts with the bounding imbibition curve (1st water injection; dark blue) in which the water saturation increases from 0.18 to 0.73. During this displacement, the gas saturation drops from 0.82 to 0.27. At this point, the imbibition process was stopped and a drainage displacement (gas injection; red) started. The relative permeability of the drainage scanning curve does not follow the values of the previous imbibition displacement. $k_{rg}$ values of the 1st drainage are below those of the bounding imbibition curve. The 1st drainage displacement continued until the water saturation decreased to 0.48. This is in contrast with Figure 21 where in the case of DIDIDI experiment, all $k_{rg}$ imbibition and drainage scanning curves lie between imbibition and drainage bounding curves. At water saturation of 0.48, another imbibition displacement started. The relative permeability of this imbibition displacement follows a new path (light blue curve) which lies slightly below the previous drainage displacement. At the end of 2nd imbibition, another drainage displacement began (pink curve). Again, the scanning drainage curves do not follow those of the previous imbibition displacement (although the difference is very small). This can be explained by the fact that for the 2nd drainage, trapped gas saturation (initially in place at the start of the cycle) is slightly higher than the 1st drainage. This entrapment process is not reversible during the following drainage displacement and restricts the flow. Again, the conclusion is that the gas relative permeabilities do not make closed hysteresis loops. As the alternation between imbibition and drainage continues, the cycle hysteresis effect becomes less important. The same as the water phase, most important hysteresis effect for the gas phase was observed between 1st Imbibition and 1st drainage, and of less importance between 1st drainage and 2nd imbibition. After the 2nd imbibition cycle, the cycle hysteresis effect on $k_{rg}$ is vanished for the later stages of the experiment.
Figure 23: Gas phase relative permeability hysteresis between 1st imbibition and 1st drainage (gas/water system, IDIDI experiment); \( k_{rg} \) values for the 1st drainage are less than those of the bounding imbibition curve.

Figure 24: Evolution of gas phase relative permeability hysteresis (gas/water system, IDIDI experiment).

Figure 25: Water and gas phase relative permeability for different stages of IDIDI experiment (semi-log plot).
Comparison of Figure 20 (k_{rg} for DIDIDI test) and Figure 24 (k_{rg} for IDIDI test) shows that for the DIDIDI test, the k_{rg} for each drainage stage is higher than the former imbibition stage, while for the IDIDI, as the alternation between imbibition and drainage continues, the k_{rg} for each stage is smaller than that of the previous stage and bigger than that of the subsequent period. This means that k_{rg} hysteretic behaviour for gas/water system in our mixed-wet core is a function of injection scenario, i.e. IDIDID or DIDIDI. No work in the literature suggests saturation history dependency for k_{rmw} in two-phase systems (for extensive assessment of hysteresis models including Killough and Carlson models refer to Fatemi and Sohrabi, 2012).

**Hysteresis Effect in Gas-Oil System**

**Gas/Oil System Bounding Relative Permeabilities**
k_{r} values of the 1st drainage period in the DIDID series and the 1st imbibition period of the IDIDI series are in fact representative of bounding drainage and imbibition curves respectively. Figure 26 shows bounding curves for the imbibition and drainage relative permeabilities for the oil-gas system (in presence of S_{wi}). Our results here clearly show that even at near-miscible conditions of our experiments (IFT= 0.04 mN.m^{-1}), there are significant hysteresis effects for both the non-wetting-phase (gas) and the wetting-phase (oil). It should be mentioned that in most of the available studies in the literature steady-state (SS) technique have been used to investigate the effect of IFT on hysteresis between imbibition and drainage bounding curves. However in this study we have used unsteady state (USS) approach. Comparisons performed in the literature such as Eleri et al., (1995) shows that USS shows usually larger hysteresis effect compared to the SS approach. Nevertheless, we believe that USS approach is more representative for displacements during WAG injection. The observed hysteresis is much larger for non-wetting phase (gas) compared to wetting-phase (oil). Imbibition relative permeability for oil is larger than drainage values, and the gas relative permeabilities for imbibition are less than those obtained for the drainage cycle.

**Gas/Oil Scanning Relative Permeability Curves: DIDID Experiment**

Figure 27 shows the evolution of cycle hysteresis effect on the oil phase relative permeability in the DIDID experiment. For the sake of completeness, the imbibition bounding curve (1st oil injection of IDIDI) has also been shown by the dashed lines. The process starts with bounding drainage curve (1st gas injection) in which normalized oil saturation has decreased from 1 to 0.2. Changing the direction of flow, oil relative permeability follows a new curve (red line) which lies between the previous drainage curve (bounding drainage) and the bounding imbibition curve. It should be mentioned that the relative permeability data from the former drainage period would not match this imbibition displacement. Oil relative permeabilities of 2nd drainage lie below those of the previous imbibition displacement. Scanning drainage relative permeability starts from the previous imbibition curve and sharply approaches the bounding drainage curve, and then follows the same (or quite close) values as the bounding drainage curve. As a result, it can be stated that relative permeabilities move rapidly toward the drainage bounding curve but slowly toward the imbibition bounding curve. Relative permeabilities of the subsequent imbibition (2nd oil injection; red triangles) follow those of the previous drainage for a large saturation interval, which shows that hysteresis effect is less at this stage of the experiments. An important observation here is that at normalized oil saturation of around 0.73 which is the turning point (change of displacement direction from 1st imbibition to 2nd drainage) for this hysteresis loop (2nd drainage and 2nd imbibition), the oil relative permeability is not equal to the values of the former drainage curve (at the same saturation). This means that successive imbibition and drainage cycles do not necessarily make a closed hysteresis loop. Figure 27 shows that for the last stage of this experiment (3rd gas injection; light green curve) there is no k_{ro} hysteresis compared to the 2nd imbibition displacement.
Figure 28 shows the cycle hysteresis effect observed on the gas phase relative permeability in the DIDID experiment. For the sake of completeness, similarly to the oil phase case, the imbibition bounding curve (1st oil injection of IDIDI) is also shown by dashed line in this Figure. The displacements started with the bounding drainage curve (1st gas injection; blue) in which normalized oil saturation has decreased from 1 to 0.2. As is obvious from comparing Figure 27 and Figure 28, the hysteresis effect is more pronounced for gas phase relative permeability than oil phase. Gas relative permeabilities of the subsequent imbibition (2nd oil injection; red triangles) would follow a new path, which is more or less parallel to the bounding imbibition and 1st scanning imbibition curves. As the initial gas saturation for this imbibition period is less than $S_{gi}$ for the 1st imbibition displacement, trapped gas saturation would be also less. Contrary to the oil phase relative permeabilities, $k_{rg}$ values make a closed loop cycles for successive imbibition and drainage cycles. Figure 28 shows that for the last stage of this experiment (3rd gas injection; light green), the gas relative permeability does not follow the values of the former imbibition displacement. The same as the previous drainage scanning curve, the 3rd drainage relative permeability starts from the previous imbibition curve and sharply approaches to the bounding drainage curve, and then follows the same (or quite close) values as the bounding drainage curve.

Figure 26: Oil and gas bounding relative permeabilities (gas/oil system, 65 mD, mixed-wet).
Figure 27: Evolution of oil relative permeability hysteresis (gas/oil system, DIDID experiment).

Figure 28: Evolution of gas relative permeability hysteresis (gas/oil system, DIDID experiment).
**Gas/Oil Scanning Relative Permeability Curves: IDIDI Experiment**

Figure 29 and Figure 30 shows the oil relative permeability curves obtained from the IDIDI displacements. The Figure also shows the drainage bounding curve (1st gas injection in DIDID series). The general hysteresis behaviour of the oil phase is the same as what has been already discussed for the DIDID experiments. Figure 31 and Figure 32 shows the gas relative permeability derived from the IDIDI experiments. For the sake of completeness, the drainage bounding curve (1st gas injection of DIDID) is also shown. The general hysteresis behaviour of the gas phase is also the same as what has been already discussed for the DIDID experiments. For assessment of Killough, Carlson and Beattie et al. hysteresis models and more details for gas/oil system refer to Fatemi et al. (2012a).

![Graphs showing oil and gas relative permeability curves](image)

Figure 29: Evolution of oil phase relative permeability hysteresis (gas/oil system, IDIDI experiment).
Figure 30: Semi-log plot of the evolution of oil phase relative permeability hysteresis (gas/oil system, IDIDI experiment).

Figure 31: Evolution of gas phase relative permeability hysteresis (gas/oil system, IDIDI experiment).
**Hysteresis Effect in Oil-Water System**

**Oil/Water Scanning Relative Permeability Curves: DIDID Experiment**

Figure 33 and Figure 34 show the cycle hysteresis effect on water phase relative permeability in this series of experiments. The displacements started with bounding drainage curve (1<sup>st</sup> oil injection) in which water saturation has decreased from 1. At this point, the drainage process has stopped and imbibition (water injection) started. Changing the direction of flow, water relative permeability follows a new curve (blue curve) which lies below the $k_{rw}$ for the former drainage period. For the 2<sup>nd</sup> oil injection period, $k_{rw}$ lies above those of the 1<sup>st</sup> imbibition, yet below those of 1<sup>st</sup> drainage (bounding drainage curve). As the alternation between imbibition and drainage periods continues, each drainage $k_{rw}$ curve lies above those of its former imbibition period. The $k_{rw}$ for different drainage periods are practically equal to each other and very close to the bounding drainage relative permeability. Regarding to the $k_{rw}$ in imbibition periods, the differences are not so much for higher oil saturation (low water saturations) but as oil saturation approaches lower values (end of imbibition period), water relative permeability for 3<sup>rd</sup> imbibition is higher than 2<sup>nd</sup> imbibition period, which in turn is larger than 1<sup>st</sup> imbibition period. This is due to the residual oil saturation which increases as the alternating injection continues.

Figure 35 and Figure 36 show the cycle hysteresis effect on the oil phase relative permeability in this series of experiments. The displacements started with the bounding drainage curve (1<sup>st</sup> oil injection). During this process the oil relative permeability increased from 0 to around 0.1. At this low relative permeability value, the gas phase is strongly mobile due to its much less viscosity compared to water ($\mu_o/\mu_w=0.06$). At this point, the drainage process stopped and the imbibition (water injection) started. Changing the direction of injection to imbibition, oil relative permeability follows a new curve (blue curve) which lies below the former drainage curve (bounding drainage). The Imbibition process stopped at water saturation of around 0.70 and another drainage displacement started in which water saturation decreased. The $k_{ro}$ curve for the 2<sup>nd</sup> oil injection period is very close to those of the former imbibition period. As the cyclic injection continues, the oil relative permeability continues to drop but generally the hysteresis effect is not significant after the 1<sup>st</sup> imbibition.
Figure 33: Evolution of hysteresis effect on water relative permeabilities (oil/water system, DIDIDI, 65 mD, mixed-wet).
Figure 34: Evolution of hysteresis effect on water relative permeabilities (semi-log plot, oil/water system, DIDIDI, 65 mD, mixed-wet).
Figure 35: Evolution of hysteresis effect on oil relative permeabilities (oil/water system, DIDIDI, 65 mD, mixed-wet).
Figure 36: Evolution of hysteresis effect on oil relative permeabilities (semi-log plot, oil/water system, DIDIDI, 65 mD, mixed-wet).

It is worth mentioning that the observed hysteresis behaviour in our oil/water system in mixed-wettability is similar to those reported by Torabzadeh and Handy (1984) and Wang (1988) experiments on preserved state core samples as well as pore-network simulations by Dixit et al. (1998a,b) for mixed-wettability condition. However we observed larger hysteresis effect for $k_{rw}$ which is probably due to wettability differences and higher IFT$_{o/w}$ in our experiments.

**Conclusions**

**Gas/Water System:**

- The results show that for the non-wetting phase (gas), relative permeability of the scanning drainage would not follow those of the former imbibitions. This is contrary to the assumptions made in Carlson, Land and Killough hysteresis models and shows the importance of including models with non-reversible hysteresis loops such as Beattie et al. and Kjosaevik et al. in commercial simulators.
Contrary to the prediction of existing $k_r$ hysteresis models, we observed that although the same saturation as the former imbibition turning point is achieved in drainage periods, end-point relative permeability of gas would be less than the previous drainage. Current two-phase hysteresis models assume they are the same (except Beattie et al. model).

**Gas/Water System: (IDIDI)**
- Water (wetting phase) relative permeability shows hysteresis in alternating imbibition and drainage cycles. Our results show that $k_{rw}$ values drop in successive change of saturation direction from imbibition to drainage and vice versa. The hysteresis in $k_{rw}$ becomes less as the number of alternation increases (later cycles).
- As the alternation between imbibition and drainage cycles continues, gas relative permeability for drainage and imbibition cycles keeps decreasing. In our three-cycle water and gas injections, $k_{rg}$ was higher for the 1st water injection and was lowest for the 3rd water injection cycle. Generally, $k_{rg}$ cyclic hysteresis for this series of experiments was not significant after 1st drainage.

**Gas-Water System: (DIDIDI)**
- Generally, water (wetting phase) relative permeability did not show much hysteresis during alternation between imbibition and drainage cycles (especially for higher water saturations). Compared to the $k_{rw}$, cycle hysteresis is more pronounced for $k_{rg}$.

**Gas/Oil System:**
- Despite a very low IFT (0.04 mN.m$^{-1}$) between the oil and gas, the $k_r$ curves show significant hysteresis.
- Hysteresis is much less for wetting phase (oil) compared to the non-wetting phase (gas).
- As the alternation of imbibition and drainage cycles continues, the hysteresis effects on oil relative permeabilities diminish.
- From the experimental data we observed that the oil and gas $k_r$ curves show hysteresis in drainage direction compared to the preceding imbibition cycle.
- Based on the results, we suggest that more flexible hysteresis models such as that of Beattie et al. should be considered and included in commercial simulators.

**Oil/Water System:**
- Water relative permeabilities show hysteresis for alternation between imbibition and drainage periods. Contrary to the usual behaviour of the wetting-phase in the water-wet or oil-wet system, in our mixed-wet rock, we observed that water relative permeabilities in imbibition direction are less than those of former drainage period. Water relative permeabilities do not show significant difference for drainage periods. This means that $k_{rw}$ are on top of each for different drainage periods.
- Oil relative permeability shows significant hysteresis for the 1st imbibition compared to the 1st drainage period. Although after that, the oil relative permeability is generally decreasing with alternation between imbibition and drainage periods, but still it is fair to claim that there is no significant hysteresis after 1st imbibition period.
- For our mixed-wet rock, although relative permeabilities of oil/water and gas/water systems are very close to each other for the 1st drainage periods (1st oil injection compared to 1st gas injection), the difference between their hysteretic behavior are very different for the later cycles. This means that current suggestion in literature to use oil-water relative permeabilities instead of gas-water set (in case of unavailability of gas-water kr) might be fine for the 1st drainage period, but for cases with cyclic imbibition and drainage displacements (such as WAG process) it would cause significant errors on the predicted three-phase relative permeabilities and predicted
injectives and productions.

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References


- Review of the previous experimental studies regarding hysteresis effect in oil/water, gas/water and gas/oil systems.

- Reporting the novel set of experiments performed to study all these three systems for a single core sample with mixed wettability.

- Obtaining sets of relative permeabilities for these three systems by history matching the experimental data.

- These sets of relative permeabilities can be used for investigation and simulation of three-phase flows including hysteresis effect, such as those occur in WAG injection.