AN EXPERIMENTAL STUDY OF NEAR CRITICAL GAS CONDENSATE RELATIVE PERMEABILITY OF CARBONATES

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ABSTRACT

Typical gas condensate fields contain a gas/liquid system during depletion. Such systems are difficult to model experimentally because they exhibit near-miscible behavior at high pressure and temperature (typically: $P_{critical} > 300$ bar and $T_{critical} > 100°C$). One way to simplify laboratory experimentation is to use a binary retrograde condensate fluid and to adjust temperature to control miscibility. A series of relative permeability test were conducted on a moderate-permeability carbonate core using methanol/n-hexane at near miscible conditions in the presence of immobile water. Potassium carbonate was added to the water to prevent miscibility with methanol. The experiments used a pseudo-steady-state technique under conditions similar to the near well region of a carbonate gas-condensate reservoir. The flow of gas and condensate at different force ratios (capillary and Bond numbers) was investigated. It was observed that relative permeability depended on fluid composition and flow rate as well as initial condensate and water saturations. As the wetting phase (condensate) flow rate increased or interfacial tension decreased, relative permeability versus wetting phase saturation curves shifted to the left.

INTRODUCTION

The effect of near-criticality on relative permeability is still an unsolved issue in reservoir engineering. Experimental studies published in the literature indicate a trend from immiscible to miscible relative permeability curves as the interfacial tension (IFT) approaches zero. There are conflicting views on which mechanism controls the change in relative permeability. Many authors argue that low IFT affects relative permeability through the ratio between viscous and capillary forces, as denoted by the capillary number (Ameafule and Handy, 1980). Most of these authors, however, suggest that there is a threshold interfacial tension below which capillary-number dependence is important (Henderson et al., 1996). Relative permeability data is usually interpreted in terms of the IFT alone (Asar and Handy, 1988). In two cases, this was done in view of the fact that a transition from partial wetting to complete wetting, as predicted by Cahn (1977), may affect the mobility of both phases (Schechter and Haynes, 1992). The influence of such a transition cannot be described in terms of the capillary number, because it is induced by a change in IFT between the near-miscible phases.

According to current understanding of the flow behavior in gas condensate systems, at least two flow regimes may be considered: one corresponding to conditions away from the critical point, where IFT's are relatively high, and another to conditions near the critical point, where IFT's are very low (Williams and Dawe, 1989). Far from the critical point, the relative permeability curves show considerable curvature and appreciable residual saturations. Near the critical point, IFT reaches very low values and relative permeability curves become progressively straighter, with residual saturations diminishing. In the limit of zero IFT, the curves become straight lines, residual saturations vanish, and relative permeabilities sum to unity for all saturations. This observation is supported by experimental studies (Bardon and Longeron, 1980).

Condensate relative permeability is still a topic of discussion, especially for carbonates for which there is limited published work. Most of the literature focuses on sand packs and sandstones. The objective of this work is to provide conclusive experimental evidence of the effect of interfacial tension, flow velocity and presence of immobile water saturation on near-miscible relative permeability of carbonates.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

A methanol/n-hexane binary liquid mixture of 33.5°C critical solution temperature at atmospheric pressure and critical methanol fraction of 0.56 was selected for these tests. Below 33.5°C, the mixture segregates into methanol rich and n-hexane rich liquid phases. Methanol, being denser and more viscous, represents the wetting liquid hydrocarbon phase in approximating a gas-condensate system. Test equipment included constant displacement pumps, a Hassler-type core holder, a separator, and an automated fractional collector. A thermostatic air oven controlled temperature to within 0.01°C. Consequently, fluid properties remain constant within 0.1% whereas the interfacial tension changes within 1.5%. A carbonate core plug from a depleted gas field (North Marmara, Turkey) was tested. The core plug was relatively homogeneous apart from occasional small vugs. CT scans revealed no visible fissures or fractures. This core plug was used in all experiments (Table 1). Prior to each test, the core was saturated and flushed with methanol rich phase to remove any residual n-hexane. Oven temperature was set to achieve the desired IFT. Methanol rich phase was equilibrated with the n-hexane rich phase. Finally, n-hexane rich mixture was injected into the core at the desired rate (Table 1). Between experiments, the core plug was dried for two days in a 60°C oven to remove traces of methanol and n-hexane. For tests with initial water saturation, the core was first flooded with water that contained 5% by weight K_2CO_3 to ensure immiscibility of methanol in water. A few crystals of $K_2Cr_2O_7$, CuSO4•5 H_2O and a spatula tip of methyl red were added to the produced liquid to color the water and methanol differently so that phase separation could be visualized. Data was interpreted using a variant of the JBN method (Marle, 1981).

RESULTS

Relative permeability of the n-hexane rich phase, representing the gas phase, was particularly sensitive to velocity, and increased with increasing velocity at both values of

IFT, as shown in Figures 1 and 2. As velocity changed from 1.07 m/day to 2.14 m/day, methanol rich phase, representing the condensate phase, did not exhibit any rate sensitivity at high IFT's; however, as IFT decreased to 0.01 m N/m, condensate relative permeability increased slightly.   When irreducible water saturation was present, sensitivity of the gas phase relative permeability was more pronounced compared to condensate relative permeability sensitivity.   The condensate relative permeability change, however, was more than the zero irreducible water saturation cases.   An explanation for this result is that capillary pressures in the presence of connate water are systematically higher than the ones without water (Longeron et al., 1994). The presence of a second liquid phase induces an "over capillarity" that depends on IFT and increases with gas saturation. This effect is negligible for gas saturations below 20% PV and is at a maximum near residual oil saturation (Longeron et al., 1994).

These results can be interpreted using the condensate number that is defined as the summation of capillary and bond numbers (Calisgan et al., 2006) even though first it increases and then decreases as the resistance to flow reaches a maximum at intermediate saturations during the experiment.   Nevertheless, to distinguish between different experiments, an average condensate number is assigned as shown in Table 1.   As the condensate number increases, the relative permeability of the gas phase increases.   For drainage gas/condensate relative permeabilities, Henderson et al. (2000) reported that the relative permeability of the gas phase was particularly sensitive to velocity, and increased with increasing velocity at both values of IFT.   Condensate phase relative permeabilities exhibited a degree of rate sensitivity for three tests at an IFT value of 0.14 mN/m, with the velocity ranging from 18.5 to 74 m/day.   Similarly, Blom and Hagoort (1998) reported that for low IFT experiments conducted using glass beads, the effect of increasing the superficial velocity by a factor of 2.5 was considerable.   These results show that gas condensate flow is similar in carbonates, sandstones, and glass bead packs.

Experiments performed at higher temperature (32.8°C) give relative permeability curves to fluids of lower IFT.   The effect of varying IFT is summarized in Fig. 3 (S_{wirr}=0) and Fig. 4 (S_{wirr}=0.245).   A clear dependence of relative permeability on interfacial tension, regardless of presence of irreducible water saturation, is observed.   Non-wetting phase relative permeability increases gradually as interfacial tension decreases by a factor of 39.33.   At very low IFT, the non-wetting phase relative permeability approaches a unit-slope line for which non-wetting relative permeability is simply equal to the non-wetting phase saturation.   Wetting phase relative permeability was affected only at IFT values below 0.059 m N/m.   The measured wetting phase relative permeability is quite low, so it is difficult to mark differences between the experiments.   Perhaps the condensate number was not high enough to show appreciable differences.   These results point to a threshold interfacial tension as was reported previously by Bardon and Longeron (1980), Ameafule and Handy (1982), Henderson et al. (1996) and Jerauld (1997).   The irreducible wetting phase saturation changes at IFT values below 0.059 m N/m when there is no immobile water saturation.   However, when there is an immobile water phase the wetting phase irreducible saturation does not change.

DISCUSSION

Relative permeability accounts for the loss of effective flow area because part of the saturation no longer contributes to the conductivity when a second or third phase is present. Moreover, it accounts for the increased tortuosity of flow paths due to the presence of the additional phase(s). In this regard, both a decrease in IFT and an increase in flow velocity result in an increased permeability, suggesting that gas/condensate relative permeability data can be interpreted in terms of a balance between viscous, capillary and gravity forces. An increase in viscous compared to capillary forces causes a change in phase distribution in the pores such that flow path tortuosity decreases, reducing non-conductive saturation. Under capillary-dominated flow conditions, if the magnitude of the viscous forces is high enough, short cut locations, where one of the phases impedes a shorter way for the other mobile phases, may form. Thus, mobilized yet isolated blobs that may contribute to the residual saturation may form. It has been previously observed that when one fluid strongly wets the porous medium, it forms a continuous network covering the entire solid surface (Dullien et al., 1989). Consequently, when the pressure drops below the dew point pressure and a small amount condensate is formed in such an environment, it may remain as a lens, i.e., a thick layer of finite extent, spread as a thin film until it is uniformly distributed over the water surface, or spread as a monolayer (Adamson, 1976). The condensate spreads over the water surface completely when the spreading coefficient is equal to or greater than zero. If the condensate does not spread uniformly over the water surface it may form lenses and thus affect the whole system. Such lenses may lead to large values of critical condensate saturation in the reservoir. Coskuner (1997) reported isolated lenses in high pressure glass micro model experiments conducted using methane/n-pentane mixture. These results prove that the capillary number alone can not be used to describe this complex behavior, justifying the use of both capillary and bond numbers in the form of condensate number.

CONCLUSIONS

A new experimental procedure that allows the measurement of relative permeability to near-miscible fluids in the presence of immobile water saturation is developed. Gas/condensate relative permeability experiments conducted using methanol/n-hexane binary fluid sample in a carbonate sample showed marked resemblances to experiments conducted in sandstones and glass bead packs. The results show a strong dependence of non wetting phase relative permeability on interfacial tension and superficial velocity. In the presence of immobile water saturation this dependence is more pronounced. Relative permeability to the non-wetting phase is affected at lower values of the condensate number.

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Table 1. Testing fluid, core plug properties and experimental conditions.

| Test	T (°C)	IFT (mN/m)	Q (cc/hr)	Nca	Swi, fraction	Test Fluid	Methanol – n-Hexane
1	32.8	0.01	100	8.62E-6	0		56 % - 44 %
2	32.8	0.01	75	6.46E-6	0	**Methanol density**	0.8 g/cc
3	32.8	0.01	50	4.31E-6	0	**Hexane density**	0.66 g/cc
4	30.1	0.059	100	1.52E-6	0	**Well**	N. Marmara - 1
5	30.1	0.059	50	7.59E-7	0	**Plug depth**	1155.1 m
6	18	0.3933	100	2.48E-7	0	**Core length**	6.82 cm
7	18	0.3933	50	1.24E-7	0	**Diameter**	3.78 cm
8	18	0.3933	100	2.48E-7	0.245	**K air**	18.56 md
9	18	0.3933	50	1.24E-7	0.243	**Grain density**	2.7 g/cc
10	32.8	0.01	100	8.62E-6	0.242		
11	32.8	0.01	50	4.31E-6	0.245		
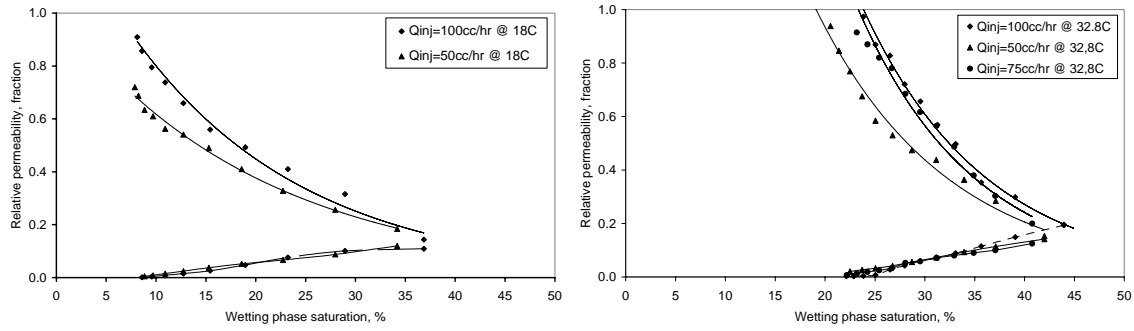
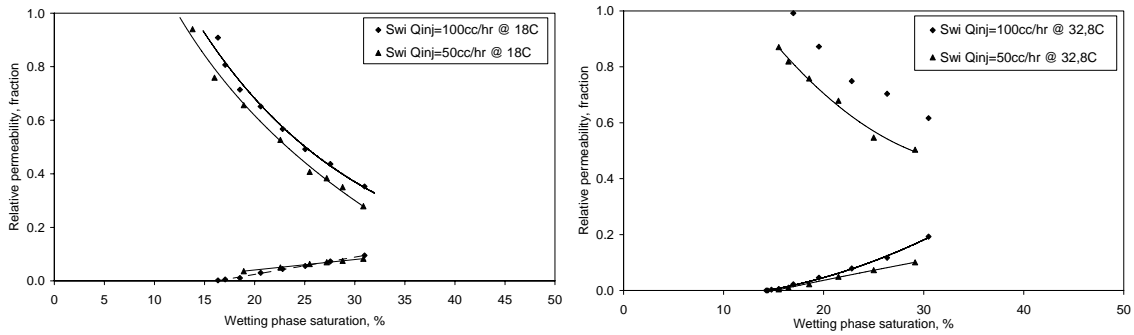Figure 1. Effect of flow rate at different IFT (Left: 0.3933, Right: 0.01 m N/m); Swi=0.

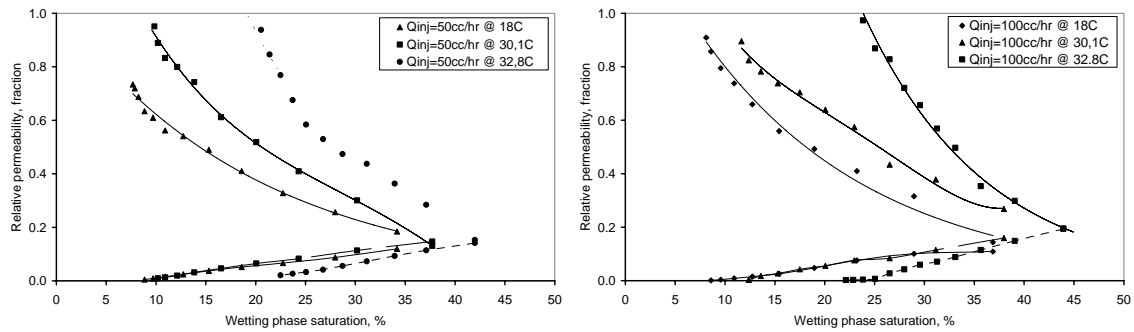Figure 2. Effect of flow rate at different IFT (Left: 0.393, Right: 0.01 mN/m); with Swir.

Figure 3. Effect of IFT at different rates (Left: 50 cc/hr, right: 100 cc/hr); Sw=0.
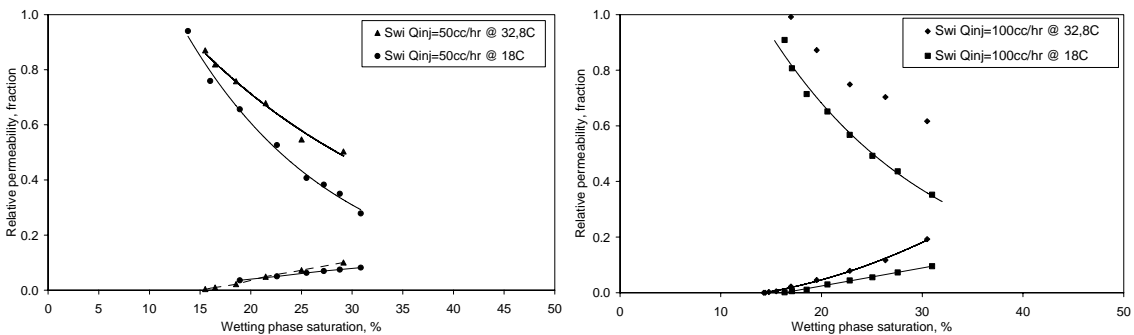

Figure 4. Effect of IFT at different rates (Left: 50 cc/hr, Right: 100 cc/hr); irreducible water saturation.