Reducing Mechanical Formation Damage by Minimizing Interfacial Tension and Capillary Pressure in Tight Gas

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Abstract. Tight gas reservoirs incur problems and significant damage caused by low permeability during drilling, completion, stimulation and production. They require advanced improvement techniques to achieve flow gas at optimum rates. Water blocking damage (phase trapping/retention of fluids) is a form of mechanical formation damage mechanism, which is caused by filtrate invasion in drilling operations mostly in fracturing. Water blocking has a noticeable impact on formation damage in gas reservoirs which tends to decrease relative permeability near the wellbore. Proper evaluation of damage and the factors which influence its severity is essential to optimize well productivity. Reliable data regarding interfacial tension between gas and water is required in order to minimize mechanical formation damage potential and to optimize gas production. This study was based on the laboratory experiments of interfacial tension by rising drop method between gas-brine, gas-condensate and gas-brine. The results showed gas condensate has low interfacial tension value 6 - 11 dynes/cm when compared to gas-brine and gas-diesel which were 44 - 58 dynes/cm and 14 - 19 dynes/cm respectively. In this way, the capillary pressure of brine-gas system was estimated as 0.488 psi, therefore diesel-gas system was noticed about 0.164 psi and 0.098 psi for condensate-gas system. A forecast model was used by using IFT values to predict the phase trapping which shows less severe phase trapping damage in case of condensate than diesel and brine. A reservoir simulation study was also carried out in order to better understand the effect of hysteresis on well productivity and flow efficiency affected due to water blocking damage in tight gas reservoirs.

1. Introduction

1.1. Water Blocking/Water Phase Trapping

Howard Johnson estimated that 10% of the world’s proven reserves of hydrocarbons some $200 \times 10^9$ BOF in low permeability reservoirs. Even in successfully fractured completions, the formations susceptible for water blocking (phase trapping) which one of the major mechanism of reduced productivity near wellbore[1]. A considerable effort required to diagnosing and evaluating its effects[2]. Due to filtrate invasion, the introduction of an additional immiscible or an increase existing phase saturation with porous media.
can cause deleterious relative permeability effects which can substantially impact the permeability and relative permeability of oil and gas[3]. According to the simulation and modelling result performed in the study of tight sand reservoir concluded that the importance of water blocking (liquid phase trapping) is one of the major damage due to relative permeability and capillary pressure effects[4].

1.2. Mechanism of Water Blocking

Figure 2 shows a schematic of the establishing water blocking within a low permeability gas reservoir application. For the better understanding, this mechanism was divided into three stages[5].

| Stage 1 (Initial condition) | Stage 2 (After Water Based Filtrate Invasion) | Stage 3 (After cleanup) |
|-----------------------------|---------------------------------------------|------------------------|
| It can be observed in the initial desiccated condition, the pre-existing Swi existing in porous media. Majority of the cross sectional area is available for gas flow which tends to high initial relative permeability. | After flushing with water based filtrate (i.e. drilling mud filtrate, completion fluid, kill fluids etc) results in the establishment of a high water saturation tends to be establishment of a high saturation of water. | Subsequently the drawdown of the reservoir results in the affected zone reverting to the irreducible water saturation dictated by the capillary mechanics of the system rather than back to the potentially very low initial water saturation. |

The irreducible saturation of water is greater than initial water saturation(Sirr > Swi) , this results a notably restriction in the cross sectional area available for fluid flow observed in Figure 1 and causes reduction in relative permeability to gas. Figure 2 shows a schematic of these mechanisms.
1.3. Factors Which Affects Severity of Water Phase Trapping
The factors were highly influenced on the water blocking damage such as interfacial tension, capillary pressure, rock wettability, fluid type and fluid composition[6, 7].

2. Methodology

2.1. Collection of Samples

2.1.1. Fluid Samples
The fluid samples were collected from the Melaka refinery PETRONAS Penapis Sdn Bhd Sungai Udangan Melak, Bintulu. Three samples was undergoes for the experimental study of interfacial tension and its effect on phase trapping in tight gas reservoirs.

2.1.2. Gas Sample
The nitrogen was used to imitate the produced gas after fluid invaded near wellbore in the tight gas reservoirs.

2.2. Interfacial Tension Measurement
The Vinci Interfacial Tension Meter (IFT-700) was used for the IFT measurement by using rising drop method in different temperature and pressure of following samples. The density of fluids at high temperature was required as input. Anton Par Density meter model DMA4500 was used to measure the density of these fluids at high temperature, shown in Table 2. Three Gas-liquid systems were used in the interfacial tension measurement at high temperature and pressure conditions.

- Brine-Nitrogen
- Condensate-Nitrogen
- Diesel-Nitrogen

![Figure 2. Water blocking-relative permeability relations][3]
Table 2. Density of liquids at 70 °C

| Fluid      | Density |
|------------|---------|
| Brine      | 0.9915  |
| Diesel     | 0.8198  |
| Condensate | 0.7012  |

3. Capillary Pressure Influences on Phase Trapping Damage

Interfacial tension a dominant factor of capillary pressure and they were also directly proportional to each other. The Interfacial tension between the damage fluid and produced fluid is high; it leads high capillary pressure which is caused the more serious phase trapping damage. In order to control the phase trapping, it is required to reduce capillary pressure this will helpful to displace the trapped fluid towards the wellbore by the reservoir drawdown. The relationship of capillary pressure and interfacial tension are given in the form of following equation[8],

\[
P_c = \frac{2\sigma \cos \theta}{r^2} A
\]

Where,

\( P_c \) = Capillary pressure, psi

\( \sigma \) = interfacial tension, dynes/cm

\( \theta \) = contact angle, degree

\( r \) = pore throat radius, microns

\( A \) = 145 x 10^{-3} \text{ (constant, to convert in psi)}

4. Correlations to Predict the Potential Severity of Aqueous Phase Trapping

In various stages of development of well, an evaluation of the potential severity of aqueous phase trapping into the formation is essential. The following tool provides a set of equation that is easy to use and helpful to evaluate the damage severity. The potential sensitivity of reservoir to the development of phase trap can also be predicted[3].

Many aqueous phase trap tests which have been carried out to over a wide range of permeabilities, gas reservoir and sub irreducible oil saturation applications. The regression analysis is a base of these equations generally for the phase trap tests. Aqueous phase trapping index (APTi) uses by focusing initial formulation and establish a new methodology to diagnose the problem related to aqueous phase
trapping. The permeability and initial water saturation values are the key factors of this basic equation which have two strongly characteristics for oil and gas reservoirs[3]. The APTi formulation generally said to be a conservative estimate, which was given by Equation 2.

\[
APTi = 0.25 \log 10 (k_a) + 2.2 (S_{wi})
\]  

(2)

where:

\(APTi\) = aqueous phase trap index
\(k_a\) = uncorrected average formation air permeability (mD)
\(S_{wi}\) = initial water saturation (fraction)

The above equation is valid for the ranges of absolute permeability and intial water saturation values, shown in Table 3.

**Table 3. Range of Validity[3]**

| Parameter | Value    |
|-----------|----------|
| Ka        | 5000mD   |
| Swi       | 0 - 1.00 |

The prediction criteria depend on the APTi value and refer the Table 4 for evaluation of damage potential.

**Table 4. Interpretation of APTi[3]**

| Parameter       | Value                                      |
|-----------------|--------------------------------------------|
| APTi > 1.00     | Formation unlikely to exhibit significant permanent sensitivity to aqueous phase |
| 0.80 < APTi < 1.00 | Formation may exhibit sensitivity to aqueous phase trapping |
| APTi < 0.80     | Formation will likely exhibit significant sensitivity to aqueous phase trapping |
5. Phase Trapping co efficient – A Forecast Method
The coefficient of phase trapping was introduced to evaluate potential damage of the water phase trapping by considering influences of initial water saturation, reservoir pressure, interfacial tension between fluids, liquid properties and pore structure on water phase trapping[9].

\[ PTC = \frac{k \Delta p}{\varnothing \mu_m \Delta_{wir}} \]  \hspace{1cm} (3)

Where,
- \( k = \) permeability, \( \mu m^2 \)
- \( \varnothing = \) porosity, fraction
- \( \Delta p = \) the biggest difference pressure for the driving fluid, kPa
- \( \mu_m = \) the viscosity ratio to the trapping phase and oil/gas,
- \( Swi= \) initial water saturation
- \( Swirr= \) irreducible water saturation (not movable)

The outcomes of the interfacial tension and capillary pressure was observed low in condensate-gas system, so it leads to low severity of phase trapping in the tight gas reservoirs. However, it required to use forecast model in order to predict the potential of damage. The prediction of phase trapping was taken place by applying phase trapping co-efficient (PTC) dimensionless factor, table 05 presented the criteria of prediction of phase trapping damage.

| Table 5. Prediction criteria of phase trapping[9] |
|-----------------------------------------------|
| PTC | Damage Severity |
|-----|----------------|
| PTC < 0.05 | None |
| 0.05 ≤ PTC < 0.3 | Weakly |
| 0.3 ≤ PTC < 0.5 | Weakly to medium |
| 0.5 ≤ PTC < 0.7 | Medium to intensely |
| PTC ≥ 0.7 | Intensely |

6. Result and Discussion
The measurement of interfacial tension between the damage fluid and produced fluid at different pressure and temperature was examined. The result shows that the interfacial tension of gas-condensate was low as compared the diesel and brine system. The values of IFT were measured 6 to 11 dynes/cm, mentioned in the Figure 5.
However the highest values of IFT was found in the brine-gas system stated from 44 to 59 dynes/cm, shown Figure 3. The diesel-gas system had moderate values of IFT that was noted as 14 – 19 dynes/cm varies with temperature and pressure, see Figure 4.

**Figure 3.** Interfacial tension of brine-gas system at different temperature and pressure

**Figure 4.** Interfacial tension of diesel-gas system at different temperature and pressure
The capillary pressure was estimated with the help of Equation 1 by substituting the value of interfacial tension of each fluid. As the capillary pressure is directly proportional to the interfacial tension so the high value of \( P_c \) exist in the case of brine-gas system which is visualized by the Figure 6. However the moderate and low values of capillary pressure are presented in the Figure 7 and 8 respectively.

**Figure 5.** Interfacial tension of condensate-gas system at different temperature and pressure

**Figure 6.** Capillary pressure vs Interfacial tension of brine-gas system at different temperature conditions
Figure 7. Capillary pressure vs Interfacial tension of diesel-gas system at different temperature conditions

Figure 8. Capillary pressure vs Interfacial tension of condensate-gas system at different temperature conditions

With the help of Equation 3, PTC was estimated by considering interfacial tension of three gas-liquid systems, shown in Table 6. In this way, it is concluded that condensate-gas system has low potential to phase trapping damage and displaced efficiently by gas produced which results improve in well productivity.

| Fluid      | PTC  |
|------------|------|
| Brine      | 0.66 |
| Diesel     | 0.48 |
| Condensate | 0.42 |
7. SCAL Reservoir Simulation
Furthermore, simulation approach used to simulate the core flooding in the tight core samples in order to evaluate the permeability damage caused by phase trapping. Sendra (Weatherford) software used for SCAL reservoir simulation which made for revealing relative permeability and capillary pressure from two-phase and multi-phase flow experiments performed in the SCAL laboratory. The following results based on the simulation by using tool Sendra Software. The Figure 9 shows the relationship between the relative permeability $K_r$, water saturation $S_w$ and capillary pressure $P_c$ in tight permeability core sample by using Corey’s & Burdine Correlation. The $K_{rg}$ and $P_c$ were decreasing with increment in $S_w$. Corey & LET correlation was used in the Figure 10 in Sendra Simulation[10] in which $K_{rg}$ was declined gradually with $S_w$ value raises and $P_c$ was also reduced during middle region of curves.

![Figure 9](image1.png)

**Figure 9.** Relationship between $K_r$, $S_w$ and $P_c$ using Corey & Burdine Correlation[10]

![Figure 10](image2.png)

**Figure 10.** Relationship between $K_r$, $S_w$ and $P_c$ using LET Correlation[10]
8. Conclusion
The interfacial tension less with low capillary pressure which has low tendencies to block mechanism and required core flooding to validate its effect. On the basis of IFT results, condensate has less severity to phase trapping in the low permeability and tight core samples as compared diesel and brine. Core flooding is required to evaluate the damage potential by injecting these fluids, estimate irreducible saturation which caused trapping of gas production and reduced well productivity. Proper evaluation and diagnosis of water blocking damage by laboratory experiments tends to be an effective prevention for the reduction of formation damage and optimized productivity of gas in low permeability reservoirs

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