Introduction

There has been a growing interest in production from unconventional gas reservoirs as conventional reservoirs are approaching their last stages of production. Therefore, extensive research has been dedicated to unconventional reservoirs.

Tight and shale gas reservoirs which have low to ultra-low permeability, are amongst the most common unconventional resources. Generally, the pore sizes of shale and tight reservoirs are in the range of 1-200 nm (Cipolla et al., 2009). Fluids within nano-scale pores are in a state between bulk materials and single atoms or molecules. Several studies have suggested that the thermodynamic properties of fluids in nano-pores are different from their bulk values due to what is known as fluid confinement (Gelb and Gubbins, 1999). When the size of the pores within the porous media is large compared to the size of the molecules, the interaction between wall surface and the molecules are negligible compared to the interaction among molecules. Therefore, fluid properties within such pores are considered not to be affected by the pore walls of the porous media. However, when the size of pores reduces and becomes in the range of nanometer, the size of the pore space is not much larger than fluid molecules; as a result, the properties of the fluids are affected by fluid-wall interactions. It has been proposed that nano-pores of unconventional reservoir rocks induce a high interfacial tension between fluid and walls of nano-pores, that lead to such complex phase behaviour. In other words, the elevated interaction among the molecules of the fluid plus the influence of pore walls on the molecules may change the apparent physical properties of the fluid such as: critical pressure and temperature, density, viscosity, surface tension, etc. Generally, such deviations in confined spaces have been attributed to increase in capillary forces, electrostatic interactions, van der Waals forces, and fluid structural changes. However, such theories have not yet been validated with reliable experimental data.

Confinement affects the phase and flow behaviour of gas-condensate fluids in unconventional rocks. It is suggested that gas condensate mixtures in nano-pores exhibit behaviour similar to a wet or dry gas system and in general tend to behave as leaner gas-condensate systems due to the effects of confinement (Devegowda et al., 2012). However, the nature and extent of confinement is not yet fully explored whilst optimum production from such reservoirs needs a thorough understanding of the confinement. There are some limited experimental procedures and methods proposed to study the effect of confinement on the fluid phase behaviour in gas condensate reservoirs (salahshoor and Fahes, 2020; Barsotti et al., 2019). However, there are no experimental data studying such effects using real unconventional core samples. Therefore, there are conflicting theories for the impact of confinement for gas-condensate fluids within unconventional rocks. In this study, for the first time, a novel method for measuring the dew point pressure of two gas condensate samples with different richness within a low permeability conventional core sample and two shale core plugs is presented.

Method

The method consists of measuring the effective permeability of the rock at different pressures. During the steady state displacement process within the rock saturated with gas, and when a liquid phase is formed, additional pressure drop is generated, which reduces the effective permeability of the core. In the proposed method, the pressure at which this change is noticed is considered as the dew point of the fluid sample within a porous media.

To generate results on the extent of confinement, accurate information on the bulk phase behavior of gas-condensate systems, in particular, accurate dew point (bulk) pressure is necessary. Therefore bulk dew point pressure is also needed to be measured.

Our unconventional displacement rig facility specifically designed for working with tight and shale rocks was used for the permeability measurement tests conducted here. This facility allows to generate reliable data when working with low-permeability-low-porosity unconventional rocks which requires working with low flowrate and low dead volume. A schematic diagram of core flooding set up for permeability measurement is shown in Figure 2.

The proposed steady-state permeability measurement procedure consists of the steps described as follows.
1. Inject the gas condensate mixture at a pressure above the bulk dew point into the core. The volume of injected mixture should be more than 1.5 times of the core pore volume to ensure that the core is fully saturated with the fluid.
2. Let the fluid inside the core to stabilize.
3. Decrease the pressure of the core to the target pressure point.
4. Inject nitrogen gas till steady state is achieved at which time the pressure difference and rate data are used in the Darcy Law to calculate the effective permeability. The volume of injected nitrogen should be more than 5 times (5-10 in our experiments) of the core pore volume to ensure that the core is fully saturated with the nitrogen. Nitrogen has been used to minimize the absorption effect and more importantly because nitrogen does not evaporate the condensate remained in the porous medium.
5. Repeat the above procedure for another pressure points.

![A schematic diagram of the core flooding apparatus used for permeability measurements.](image)

Two different gas condensate samples with MLDO of 13.3% and 25.6%, respectively, was used. The bulk dew point pressure (Pdew) of these two lean and rich fluids in the PVT cell was measured as 2392 and 2493 psi, respectively.

Initially, dew point pressure was measured at different pressures within a low permeability conventional rock with a permeability of 3.2 mD. This is the absolute permeability of the core sample which is measured using nitrogen without having gas condensate fluid inside the core. The dew point pressure measurement data for this core sample are presented in Figure 3. It is noted that the measured effective permeability is very close to the absolute permeability value at first two pressure points of 2500 and 2410 psi. However, when the pressure is dropped to 2360 psi the effective permeability value is dropped considerably from 3.2 to 2.6 mD indicating the presence of the condensate as the second phase within the 2360-2410 psi range, which covers the measured bulk Pdew of 2392 psi. These results suggest that because there is no difference between the bulk and porous medium Pdew, the confinement effects in this low permeability conventional rock under investigation is negligible.
Another similar experiment was performed this time on a shale core sample with an absolute permeability of 1.7 microdarcies and using the same leaner fluid. Figure 4 shows the dew point pressure measurement data for this experiment. The first two measured effective permeability points are very close to the absolute permeability value of 1.7 μD. However, when the pressure is dropped to 2450 psi, the measured effective permeability reduces from 1.7 μD to 1.5 μD indicating the presence of condensate inside the core. Based on these results, Pdew in this shale core sample is within the range of 2450-2500 psi. However, this range of pressure does not cover the measured bulk Pdew of 2392. There is a difference of at least 58 psi between the measured bulk Pdew and Pdew inside the porous medium, which is attributed to the confinement effects in this shale core sample. It should be noted that getting more accurate results for quantifying the extent of the confinement effects on Pdew requires more measured effective permeability data point within the 2450-2500 psi range.

To consolidate the findings and the proposed method, another shale core sample with an absolute permeability of 4.0 μD and the richer fluid was used. Figure 5 demonstrates the dew point pressure measurement data of this experiment. At 2600 psi and 2581 psi, the effective permeability was
measured to be 3.94 and 3.97 microdarcies which are very close to the measured absolute permeability. However, the permeability dropped to 3.81 microdarcies when the pressure was dropped to 2562 psi. This reduction in effective permeability suggests that condensate was formed in the core within the range of 2562-2581 psi. Hence, the confined Pdew is identified to be in the range of 2562-2581 psi which is at least 69 psi higher than the measured bulk Pdew of the richer gas condensate fluid, which is 2493 psi.

![Figure 5](image.png)

**Figure 5** Permeability versus pressure data measured during the core flood test conducted on a shale core sample with the permeability of 4.0 microdarcies using the richer gas condensate fluid

**Conclusions**

This study, for the first time, proposes a novel method for examining the effect of confinement on the dew point pressure of two different gas condensate mixtures inside two shale core samples. For this purpose, a rig facility specifically designed for working with unconventional rocks was used to measure effective permeability at different pressures. The dew point pressure is measured as significant drop in the measured effective permeability due to the presence of a second phase is noted. The results indicate that dew point pressure increases due to confinement by at least 58 and 69 psi for the leaner and richer fluids, respectively, confirming the effect of fluid confinement. Similar experiments performed on a low permeability conventional rock did not show any confinement effect confirming the integrity of the method. Additional experimental data are required to further quantify more accurately the effect of confinement on dew point pressure, which is currently under way. Such experiments data, also provide invaluable data to verify the theoretical theories already proposed or support any new such works, which is also part of this research future work program.

**References**


