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EXPERIMENTAL ANALYSIS OF GAS CONDENSATE FLOW IN POROUS MEDIA

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Abstract. Gas production will increase over the next years due to the increasing energy demand around the world. The global tendency looking for cleaner energies makes gas a great option due to its relative low cost and low pollution when compared to oil. During retrograde gas production, as the reservoir pressure falls, a liquid phase is formed and may block the flow path of the gas near the wellbore, decreasing the gas relative permeability. The reserve estimation and strategy for production needs to take this condensate blocking phenomena into account.

Experiments applying the Pseudo-Steady State Method to evaluate how the liquid dropout affects gas production was conducted in two rock samples, a sandstone and a carbonate, in order to evaluate the effect of porous media morphology on the relative permeability of retrograde gas.

The results prove that the relative permeability increased when the flow rate increased until they reached a peak and then started to drop. The condensate formation was sharper in the sandstone sample due to its more homogeneous consolidation.

Keywords: gas condensate, relative permeability, condensate formation, core flooding

1. INTRODUCTION

Gas production will increase over the next years due to the increasing energy demand around the world. Figure (1) shows the global tendency looking for cleaner energies making gas a great option due to its relatively low cost and low pollution when compared to oil. The new frontiers searching for reservoirs will find gas reservoirs with high pressure and high temperature, which can exhibit a gas condensate (retrograde gas) behavior.

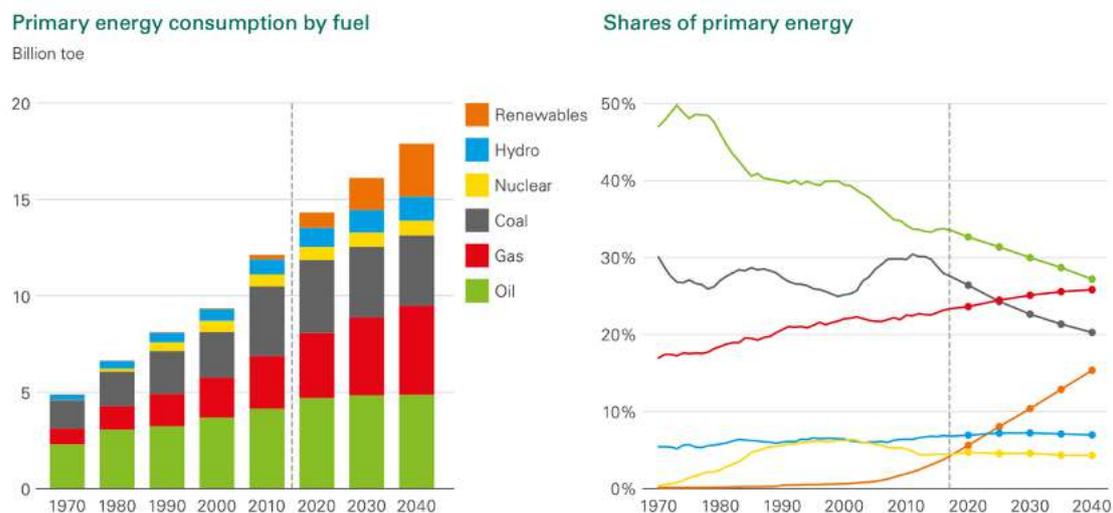


Figure 1. Primary energy consumption and its shares by fuel. Source: BP Energy Outlook 2019.

Figure (2) shows a phase diagram of a mixture that can be observed in a reservoir. The conditions to have a gas conden-

sate reservoir require a reservoir temperature between the gas mixture critical point temperature and its cricondentherm temperature. Fan *et al.* (2005) work shows the complexity which is a gas condensate reservoir.

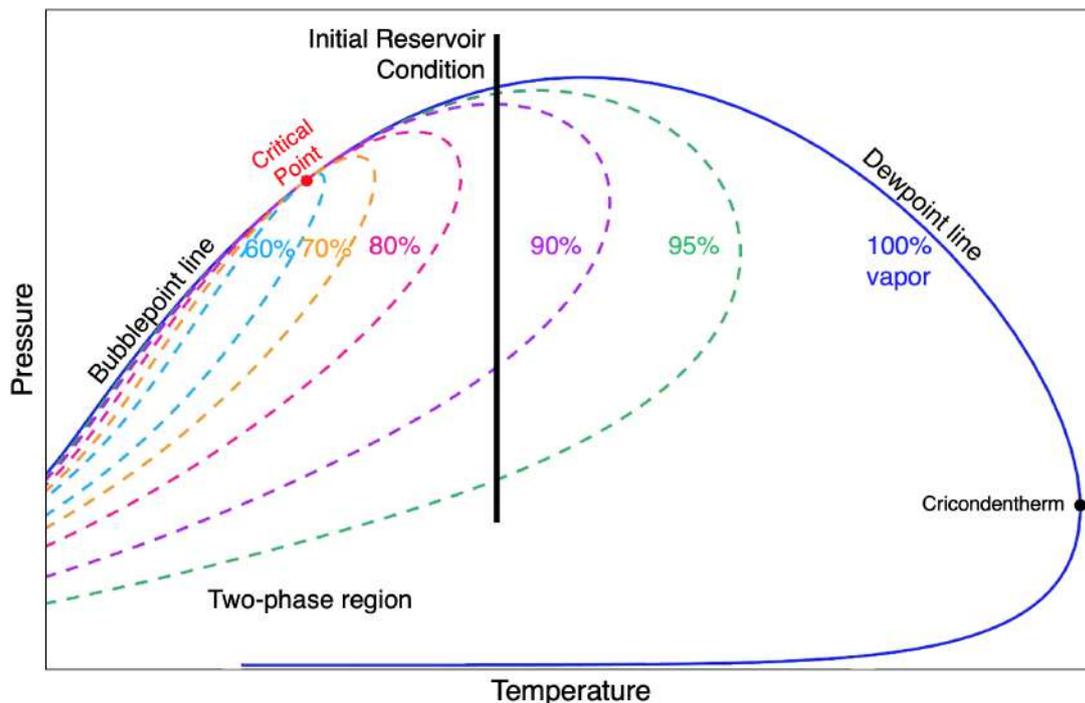


Figure 2. Phase Diagram.

During gas condensate production, as the reservoir pressure falls, a liquid phase is formed and may block the flow path of the gas near the wellbore, decreasing the gas relative permeability. The reserve estimation and strategy for production need to take this condensate blocking phenomena into account.

Experiments were conducted to evaluate the condensate blocking phenomena and to better understand how it affects the gas relative permeability. The Pseudo-Steady State Method (PSSM) developed by Mott *et al.* (1999) was chosen as the method to experimentally determine the gas relative permeability at different conditions.

2. EXPERIMENTAL SYSTEM

The experiment's goal is to simulate the condensate gas flow through a rock sample to evaluate its gas relative permeability using the Pseudo Steady State Method in a core flooding system. To conduct the experiments two rock samples and a gas condensate fluid were required.

Figure 3 shows the experimental setup which is a closed system and was composed by two cylinders, one for the mixture at high pressure and high temperature and the other one for the produced gas, a phase separator, responsible for accumulating the liquid dropout, a core holder, responsible for keeping the rock sample with an overburden pressure, two pumps (ISCO D-Series Pumps), one for each cylinder, and an oven to keep the experiment at high temperature. To evaluate the pressure difference toward the sample there is two pressure transducers (T1 and T2) (VELKI 400 and 100 bar).

Cylinder B is responsible for storing the gas mixture at a pressure higher than the dewpoint pressure and a temperature between the critical point temperature and the cricondentherm temperature. It will inject the gas mixture which will pass through V1 to the reducing valve which is responsible for decreasing the pressure from this point. This new pressure is lower than the dewpoint pressure and it has now gas and liquid flowing through the system. The gas and liquid will go through V2 and reach the core holder which is responsible for keeping the rock sample with an overburden pressure (T3). To measure the pressure difference on the rock sample there are two pressure transducers for that (T1 and T2). Both fluids will exit the core holder and reach the phase separator where the condensate (liquid) will be retained and the gas will continue its way to the cylinder A, passing through V4 and V5, and be stored there. After cylinder A is full of gas the experiment is interrupted. To restart the experiment (Experiment Procedure) it is necessary to adequate the gas and the condensate to the previous gas mixture (Refill Procedure).

After the experiment, the relative permeabilities of the gas and the liquid can be determined through the pressure and flow rates data, as shown ahead.

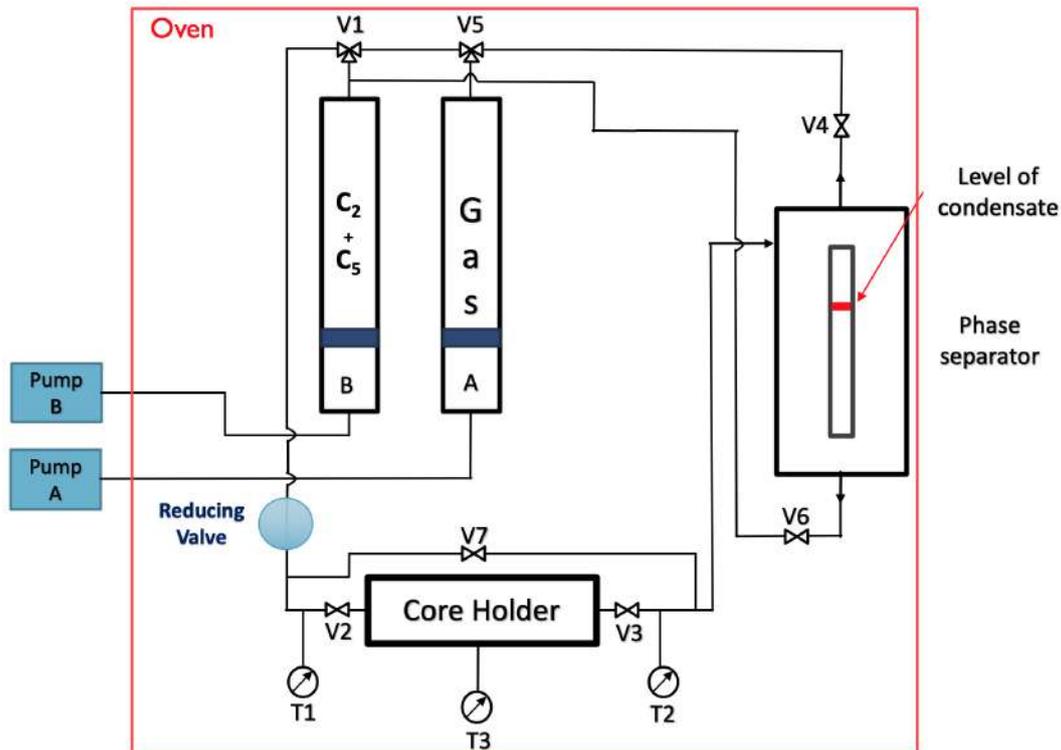


Figure 3. Experimental Setup.

2.1 Rock samples

To better analyze the effects of the rock sample matrix in the relative permeability of a gas condensate system two different types of rock were used. A sandstone with a homogeneous pore matrix and a carbonate with a heterogeneous pore distribution. Table (1) shows the characteristics of the two samples. They have similar sizes, near porosity and different absolute permeability as shown in Figure (4). Two devices were used to determine the sample's absolute permeabilities and porosities. The porosity device (UltraPore-300) was used 5 times for each sample providing a 0.1 standard deviation for both rocks. And the permeability device (Ultraperm 600) requires 4 different inlet pressures but the same pressure difference to provide a reliable result.

Table 1. Cores characteristics.

	Sandstone	Carbonate
Diameter (cm)	3.79	3.75
Length (cm)	9.50	9.80
Porosity (%)	17.9	15.0
Permeability (mD)	86.0	160.0
Total Volume (cm ³)	106.1	108.1
Pore Volume (cm ³)	19.0	16.2

2.2 Gas condensate mixture

The gas mixture used in the experiments was expected to have a retrograde behavior under the pressure and temperature lab equipment work limits. A combination of 85% ethane and 15% n-pentane (in mols) was the mixture used in the experiments. Figure (5) shows the mixture phase diagram.

The binary composition has a critical point temperature of 79.4°C and a cricondentherm temperature of 91.1°C. The experiments were conducted at 80°C (176°F). At this temperature, the mixture has a critical point pressure of 944.5 psi.

2.3 Initial conditions

To ensure the same experimental protocol with the sandstone and the carbonate samples the reducing valve setting was not altered. Table (2) shows the produced gas flow rate used in both experiments. The range cover two order of



Figure 4. Experiment samples, Sandstone (left) and Carbonate (right).

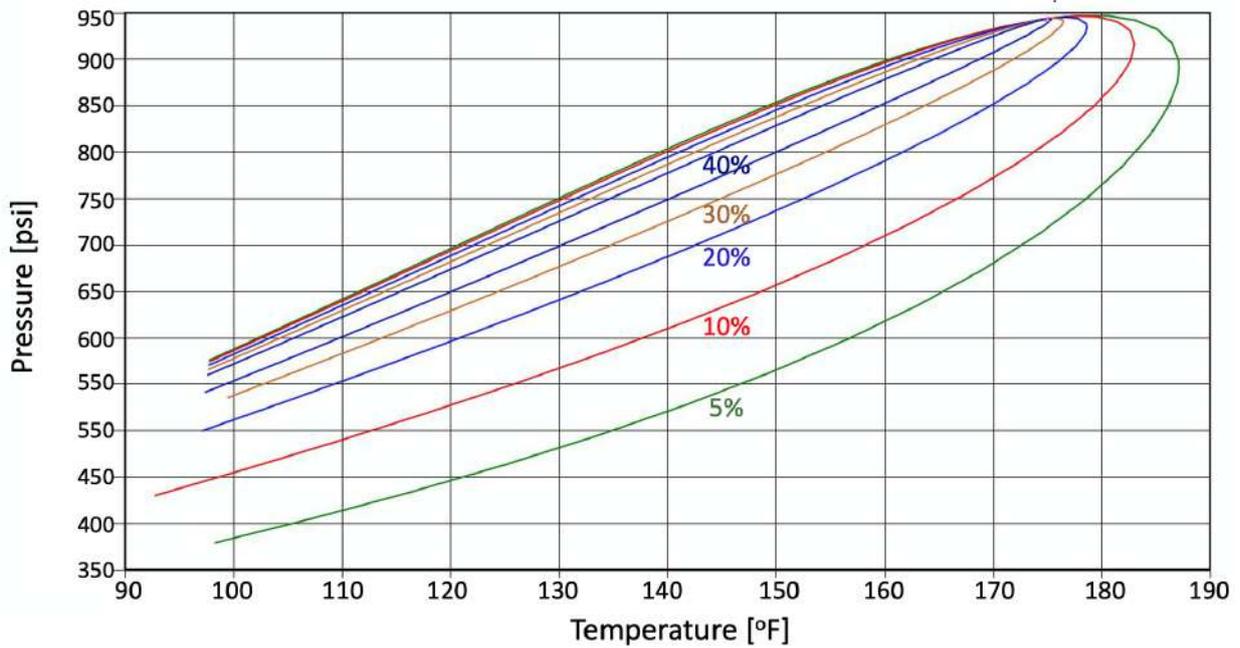


Figure 5. Mixture Phase Diagram, Winprop by CMG.

magnitude, which allowed for the analysis to be done under low and high flow rates conditions.

Table 2. Production gas flow rate (Pump A).

Gas flow rate (ml/min)								
1.33	2.31	4.00	6.93	12.0	20.78	36.00	62.36	108.00

During the experiments, cylinder B was kept in constant pressure using pump B. This pressure was higher than the dewpoint pressure to ensure that this cylinder was filled with gas only. Cylinder A is responsible to control the production gas flow rates as shown in Tab. 2.

Table (3) shows the initial pressure in both experiments, the stabilized pressure, and the liquid dropout. The stabilized pressure is the average pressure (T1) when the experiments reached the steady-state regime and the liquid dropout related

to this pressure.

Table 3. Experimental conditions.

	Sandstone	Carbonate
Initial Pressure (psi)	985.0	985.0
Stabilized Pressure (psi)	928.2	913.5
Dropout (%)	28.1	23.8

2.4 Experimental protocol

The experimental procedure was composed of two stages: the Refill procedure, and the Experimental procedure. Considering the experimental setup is a closed system, it is necessary, after running the Experimental Procedure, to turn the produced gas and liquid into a single phase mixture again what is done during the Refill Procedure during the Experiment Procedure, data necessary to calculate the relative permeability of gas and liquid is required. Figure 6 shows the experiment setup built inside the oven.



Figure 6. Experimental setup built inside the oven.

2.4.1 Refil procedure

The first step is to turn the oven on to 80°C and then wait for the whole system temperature and pressure to stabilize. The next step is to open the valves V3, V4, and V5 to fully connect the downstream circuit. The pressure on cylinders A and B is increases to 1200 psi to insure there is only gas in the system. After the system pressure stabilizes, it is necessary to open the valve V6 to connect the upstream and downstream circuits. After that, the system will only contain gas and then the procedure to transfer the mixture from cylinder A to cylinder B can begin. To maintain the system pressure above the dewpoint pressure, the cylinder B is set to work at constant pressure (1200 psi). Cylinder A injects the gas mixture at a constant flow rate. After the transfer process is complete it is necessary to close valve V6 to disconnect the production and injection lines. To reduce the pressure to 865 psi in the production line pump A was used. Finally, valves V1 and V2 were opened to connect the injection cylinder to the production line.

2.4.2 Experimental procedure

At the end of the Refill procedure, cylinder B is full of the gas mixture at a pressure superior to the dewpoint line pressure and will be kept at constant pressure during the Experimental procedure. At this moment, cylinder A is almost empty and it controls the experiment production gas flow rate using pump A. After starting pump A, cylinder B starts to inject the gas mixture to keep the initially set pressure. The experiment stops when cylinder A is full of gas and it is necessary to stop pumps A and B, turn the oven off, and close all the valves.

2.4.3 Data analysis method

The experimental data obtained, i. e., pressure, temperature and flow rates allow for the relative permeability calculation is done with mass conservation law taking a control volume around the reducing valve, according Eq. (1).

$$m_G^{(1)} = m_G^{(2)} + m_L^{(2)} \quad (1)$$

In terms of flow rate (Q) and densities (ρ) becomes Eq. 2:

$$Q_G^{(1)} \cdot \rho_G^{(1)} = Q_G^{(2)} \cdot \rho_G^{(2)} + Q_L^{(2)} \cdot \rho_L^{(2)} \quad (2)$$

At this point, the gas injection flow rate is known from the Pump B flow rate, the gas production flow rate is the flow rate that was set in the Experimental Procedure, and the Q_L is the unknown.

Equations (3), (4), and (5) were obtained after using Winprop to determine each fluid density equation.

$$\rho_G^{(1)} = (0,2843 \cdot P_G^{(1)} - 44,448) \cdot 10^{-3} \quad (3)$$

$$\rho_G^{(2)} = (0,3909 \cdot P_G^{(2)} - 195,27) \cdot 10^{-3} \quad (4)$$

$$\rho_L^{(2)} = (-0,5816 \cdot P_G^{(2)} + 829,14) \cdot 10^{-3} \quad (5)$$

At this moment it is possible to calculate the gas and the liquid relative permeability according to Eq. (6) and (7).

$$k_r G = \frac{Q_G^{(2)} \mu_G L}{A \Delta P K} \quad (6)$$

$$k_r L = \frac{Q_L^{(2)} \mu_L L}{A \Delta P K} \quad (7)$$

3. RESULTS

Figures (7) and (8) show the pressure difference in the sandstone experiment and the carbonate experiment, respectively. The steady-state regime was reached in every gas flow rate on both experiments, but the sandstone experiment showed some residual increment for the 62.4 and 108.0 ml/min flow rates. Due to the carbonate porous throat distribution and its higher permeability (160 mD), it reached a lower pressure difference than the sandstone, which has a more uniform pore throat configuration.

Figure (9) shows the sandstone and carbonate gas relative permeabilities as a function of the gas flow rate. For a low gas flow rate, there were low values of gas relative permeability for the two rock samples. As the gas flow rate increases, the gas relative permeabilities rises as some blocking liquid is washed way ny the gas as the gas velocity increases as well.

The carbonate sample reached higher values than the sandstone due to the higher permeability and pore throats distribution which is composed of large and small pore throats which favored preferential paths formation.

At higher gas flow rates values the gas relative permeability starts to reduce due to inertial effects, is confirmed by one phase experiments performed afterwards.

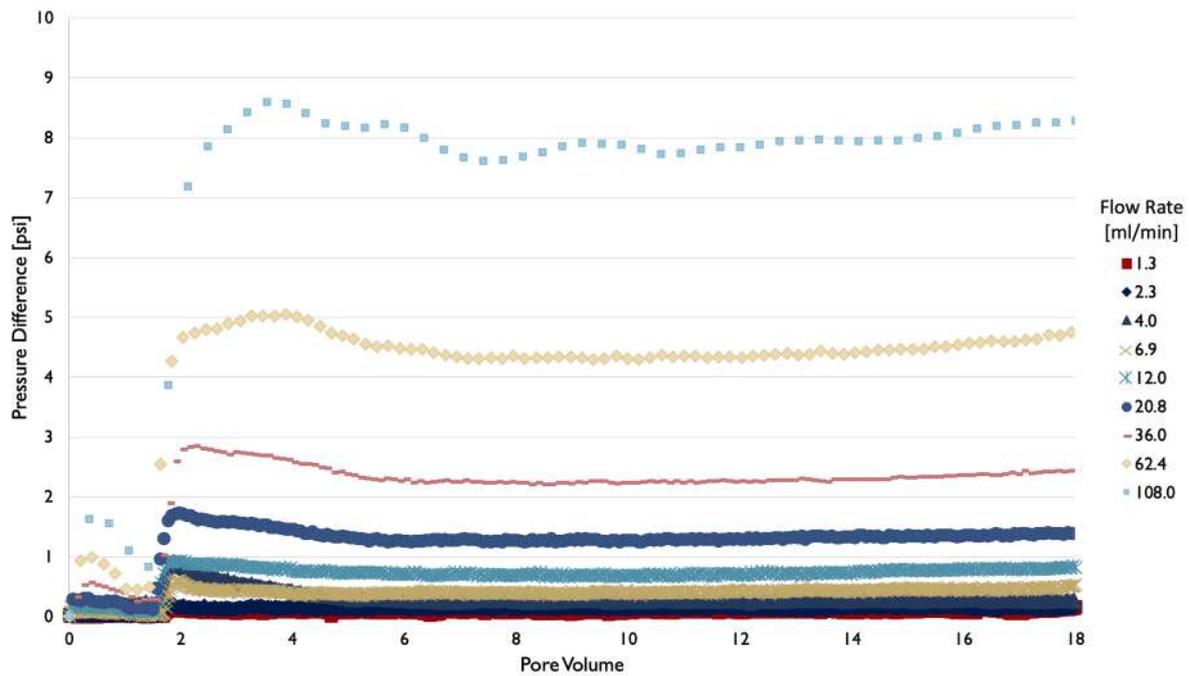


Figure 7. Sandstone pressure difference.

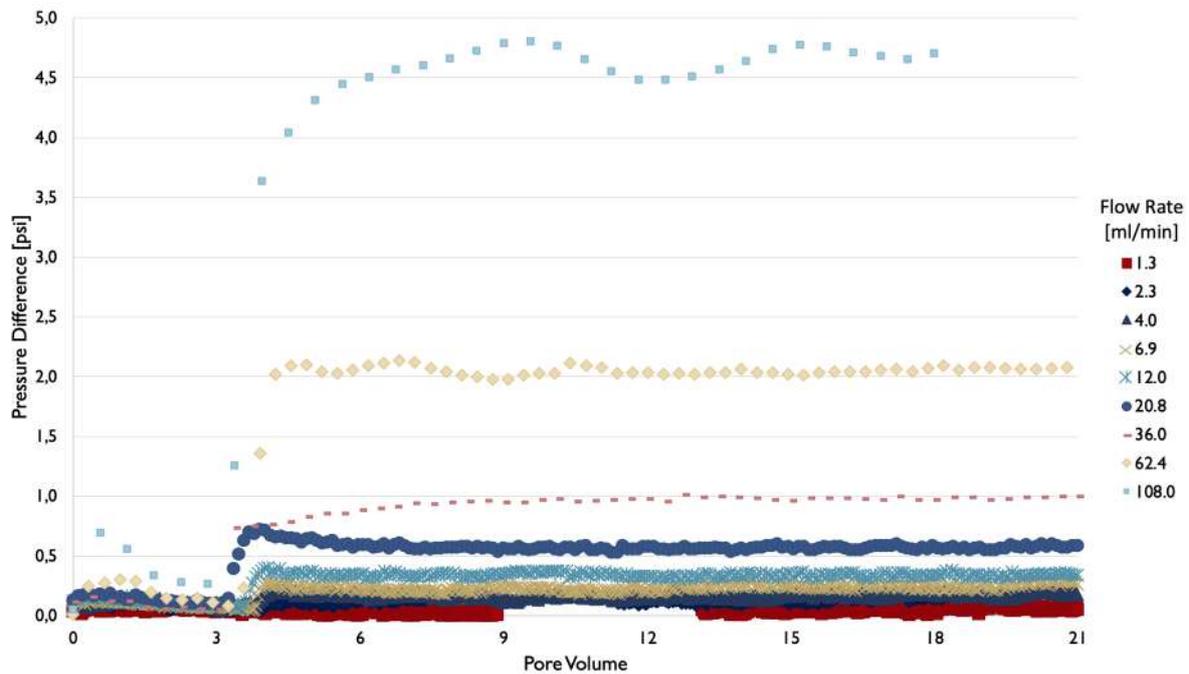


Figure 8. Carbonate pressure difference

4. FINAL REMARKS

It was possible to evaluate the gas relative permeability as a function of gas flow rate, pressure level, and porous media morphology. It shows that the carbonate has a higher relative permeability due to its heterogeneous consolidation where it creates preferential paths for the mixture to flow. Higher flow rates weaken the condensate blockage on both cores. For very high flow rates, the relative permeability was decreased in both samples due to inertial effects.

5. ACKNOWLEDGEMENTS

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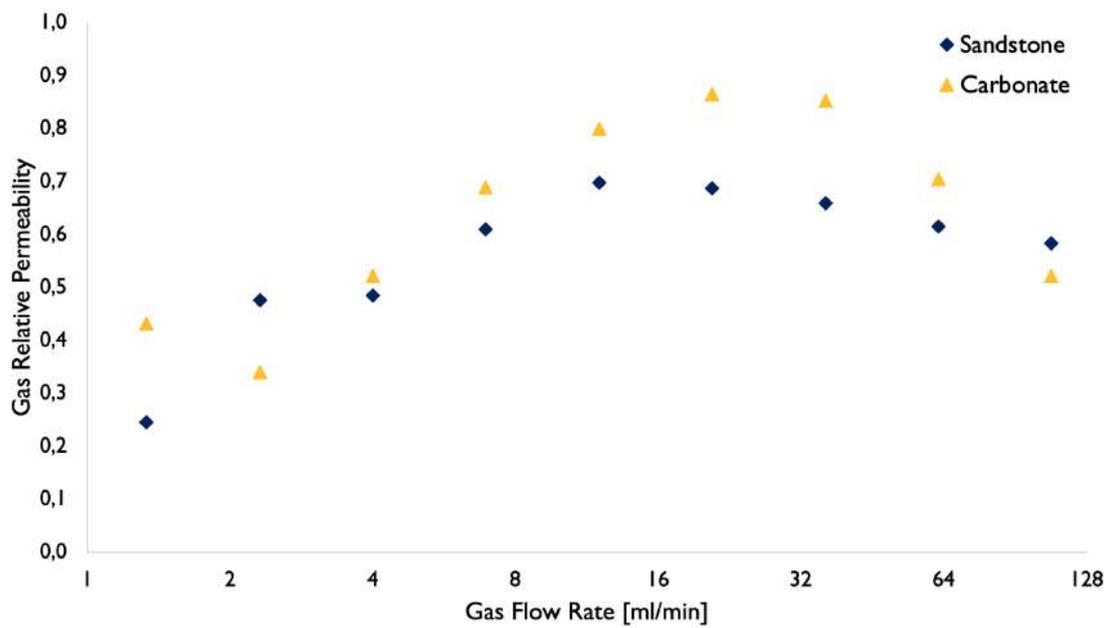


Figure 9. Gas relative permeability.

6. REFERENCES

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