SPE-187523-MS

Measurement of the Marcellus Shale Properties

M. Elsaig, S. Black, K. Aminian, and S. Ameri, West Virginia University

This paper was prepared for presentation at the SPE Eastern Regional Meeting held in Lexington, Kentucky, USA, 4-6 October 2017.

Abstract

Even though the advances in horizontal drilling and hydraulic fracturing techniques have unlocked the gas contained in Marcellus shale, the quantification of the petrophysical properties remain challenging due to complex nature of the shale. Shale permeability is commonly measured by the unsteady state methods, such as pulse-decay or GRI methods, because the shale has a permeability in nano-Darcy range. The permeability values by determined by these techniques have been found often to have large margin of uncertainty as a result of inconsistent experimental protocols and the complex interpretations methods.

In this study, petrophysical properties of the Marcellus shale core plugs were measured using an innovative laboratory setup, referred to as Precision Petrophysical Analysis Laboratory (PPAL). PPAL is designed to accurately measure the petrophysical properties of ultra-low permeability core plugs under the reservoir conditions. PPAL measurements are performed under steady-state isothermal conditions flow conditions and the analysis of the results do not require complicated interpretations. The key advantage of the PPAL is the capability to measure the permeability and porosity of the shale core plugs under a wide range of confining and pore pressures. In addition, the impact of gas adsorption (or desorption) on the measurements can be monitored. The core plugs used in this study were made available through the Marcellus Shale Energy and Environment Laboratory (MSEEL), a dedicated field laboratory in the Marcellus Shale. MSEEL has been established to undertake field and laboratory research to advance and demonstrate new subsurface technologies and to enable surface environmental studies related to unconventional energy development. The filed site is owned and operated by Northeast Natural Energy, LLC and contains several horizontal Marcellus Shale wells. In addition, a vertical well has been drilled specifically for obtaining core, log, and other data for scientific purposes (science well).

The results of the core plug permeability measurements indicated that that the permeability values decline as the gas (pore) pressure increases. Reliable values of the absolute permeability can be obtained by the application of the double-slippage correction for all pore pressure ranges but more specifically for pore pressures below 900 psia. Klinkenberg correction on the other hand, can only provide reliable values for the absolute permeability when the pore pressures are above 900 psia. The determined absolute permeability values were found to be impacted by the net stress. The analysis stress data with the aid of Walsh plot provided the estimates of the fracture (fissure) closure pressure. The closure pressure was found to be dependent on the absolute permeability.

Introduction

Marcellus Shale is the most prolific shale gas producer in the United States. The application of innovative horizontal drilling practices in combination with the massive hydraulic fracturing treatments have been successful to unlocked considerable reserves of natural gas in the Marcellus Shale. Shale is an organic-rich, naturally fractured formation containing both free gas stored in the limited pore space of the shale matrix and the adsorbed gas on the organic material. The shale formations are often characterized by ultra-low permeability (nano-Darcy range) as a result of the pore sizes which are only a few nanometers in diameter. The ultra-low permeability formations, such as Marcellus Shale, present many challenges for resource assessment and development. In order to estimate the gas resources, predict the reserves, and optimize the hydraulic fracturing treatments, reliable values of the shale key petrophysical properties including permeability and porosity are necessary. The quantification of the shale petrophysical properties however is challenging because the conventional technique often do not provide reliable values.

In this experimental study, the permeability of the Marcellus shale of the Marcellus shale core plugs were measured using a laboratory set-up that was designed and assembled for fast and robust shale core plug porosity and permeability measurements under steady-state conditions. This laboratory set-up has a resolution of one millionth standard cubic centimeters per second for gas flow rate and one hundredth cubic centimeters for pore volume measurement. The automated temperature control insures that the measurements are performed under isothermal conditions. The permeability and porosity can be measured under a wide range of net stress by applying confining pressure on the shale core plug. The objective of this study was to determine the accurate permeability values for Marcellus Shale samples and investigate the impact pressure (both pore and confining) on measured permeability values.

Background

A laboratory set-up, referred to as PPAL (Precision Petrophysical Analysis Laboratory), has been recently shown to provide accurate and repeatable measurements of the shale petrophysical properties (Zamirian et al., 2015 and Elsaig 2016). The detailed description of the apparatus and its operating principal have been presented previously (Zamirian et al., 2014a, 2014b). One of the key advantage of the PPAL is the ability to conduct the experiments on the shale core plugs under a wide range of both pore pressures. This would allow accurate determination of the absolute permeability. When the permeability of a rock sample is measured by the flow of a gas, the measured permeability values increase as the gas pressure decreases. Klinkenberg (1941) suggested that the momentum carried by the gas molecules hitting the pore walls result in higher gas velocities at low pressures and the flow regime is slip flow. This phenomenon is referred to as the gas slippage effect. Klinkenberg demonstrated that the permeability of porous media to gases is a linear function of the reciprocal of the mean pore pressure. This linear relationship is used to determine the absolute permeability of a rock sample when a gas used to measure the permeability (Klinkenberg correction). Klinkenberg theory however ignores the momentum that gas molecules carry to the bulk fluid which is generally insignificant in conventional formation with the permeability in millidarcy range. When average pore sizes are smaller than 10 nm which is typical of shale formations, the flow regime is transition flow and the Klinkenberg correction is no longer valid. This phenomenon can lead to measured permeability values that are higher than those predicted by Klinkenberg theory at low pressures and is referred to as the gas double slippage effect. Fathi (2012) used that a Lattice Boltzmann simulator to demonstrate that under transition flow conditions permeability of porous media to gases is a linear function of the reciprocal of the mean pore pressure-squared. This linear relationship can similarly be used to determine the absolute permeability of a rock sample containing small pore sizes (double slippage correction). Figure 1 illustrate the application of both Klinkenberg and double slippage corrections to the Marcellus Shale core plug sample 1 permeability values measured by PPAL using Helium (Elsaig 2016). As it can be observed the application of the Klinkenberg correction results in a negative value (-19 nano-Darcy) for the absolute permeability while the application of the double slippage correction provides a reasonable value for the absolute permeability (124 nano-Darcy).

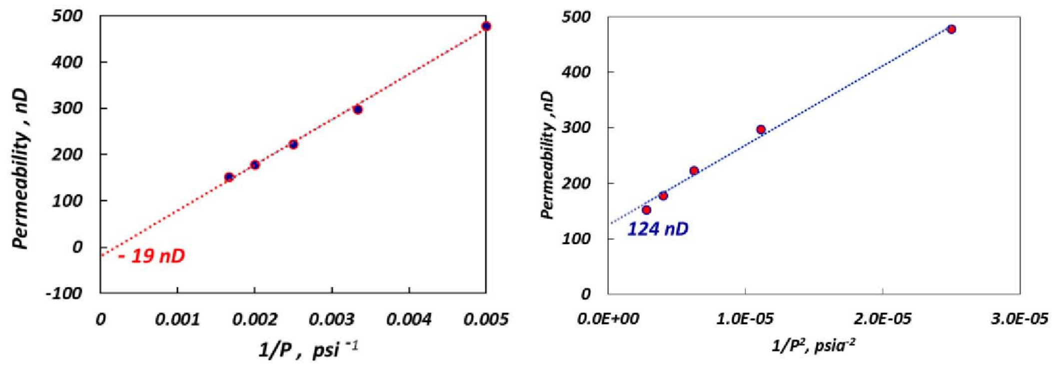

Figure 1—Absolute Permebility Evaluation for Sample 1 Measured Permeability Values (after SPE 184042)

Recently, Mathur et al (2016) concluded from experimental studies that the Transition flow is prevalent in the shale core plugs at pore pressures below 250 psia while the Slip flow is prevalent at pressures above 1000 psia. Our previous investigation with Marcellus Shale core plug sample 1 (Elsaig 2016), clearly indicated that for pore pressures in the range 200-500 psia Transition flow is prevalent.

Another advantage of the PPAL is the ability to conduct the experiments on the shale core plugs under a wide range of confining pressures. This would allow accurate determination of the permeability under a desired net stress. Shale is a naturally fractured formation. The natural fractures tend to be more sensitive to stress than the matrix. Therefore, the fractures begin to close down first as the stress increases, resulting in a major reduction in the permeability. After all the fractures are closed, the permeability reduction is caused by the matrix compression alone. Walsh (1981) suggested that a linear relationship exists between $(k/k_o)^{1/3}$ and $ln(P/P_o)$ where k is the permeability measured at a specific stress (P), and k_o is the permeability measured at the lowest stress (P_o). The differences in the compressibility of the fracture and the matrix result in two straight lines with different slopes on the Walsh plot. Therefore, the Walsh plot can be used to determine the stress at which the more compressible medium (fracture) is completely closed (Closure Pressure). Figure 2 illustrate the Walsh plot for the absolute permeability of the core plug sample 1 (Elsaig 2016) measured at 7 different net stress values (1300-7000 psi). As can be observed two straight lines are present confirming the presence of the fractures in the core plug. The fracture closure stress, determined from the point where two straight lines intersect, is 4,770 psi.

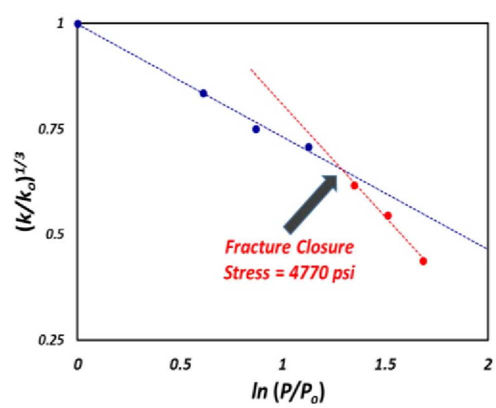

Figure 2—Closure Pressure Evaluation for Sample 1 (after SPE 184042)

Objectives and Methodology

The objectives of this study were:

1. To determine the absolute permeability of the Marcellus Shale core plug samples by applying the appropriate gas correction (slippage or double-slippage).
2. To determine the range of the pore pressure over which each gas correction (slippage or double-slippage) is applicable.
3. To investigate the impact of stress on the on the measured permeability values and determine the fracture closure stress.

Precision Petrophysical Analysis Laboratory (PPAL) was utilized to measure the permeability of several Marcellus shale core plugs, obtained from a vertical well drilled specifically for the laboratory research and other scientific purposes (science well) on the site of the Marcellus Shale Energy and Environment Laboratory (MSEEL). MSEEL is a field site and dedicated laboratory in the Marcellus Shale unconventional production region of north-central West Virginia. The filed site is owned and operated by Northeast Natural Energy, LLC and contains several horizontal Marcellus Shale wells. MSEEL provides a unique opportunity to undertake field and laboratory research to advance and demonstrate new subsurface technologies and to enable surface environmental studies related to unconventional energy development. During this study the permeability experiment were performed on two Marcellus Shale core plug samples (Samples 2 and 3). The permeability of the Marcellus Shale core plug sample 2 was measured under a wide range of gas (pore) pressures from 300 to 1200 psia while maintaining the net stress constant at 4000 psi. The permeability of the Marcellus Shale core plug sample 3 was measured under different (pore) pressures and several net stress values.

Results and Discussion

The measured permeability values for the Sample 2 as a function of the pore pressure are illustrated in Figure 3. It is clear from Figure 3 that the measured permeability values exhibit a declining trend as the gas pressure increases. To evaluate the absolute permeability of the sample both Klinkenberg and double slippage corrections were applied. Figures 4 and 5 illustrate both the Klinkenberg and double slippage corrections to the sample 2 measured permeability values. As it was observed previously for the core plug sample 1, the application of the Klinkenberg correction results in a negative value for the absolute permeability while the application of the double slippage correction provides a reasonable value for the absolute permeability. However, it is apparent from both Figures 4 and 5 that the permeability values exhibit two different trends for pore pressures below and above 900 psia.

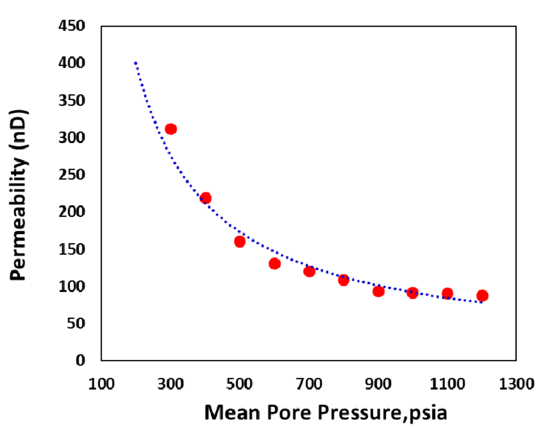

Figure 3—The Measured Permeability Values at Different Pore Pressures under Constant Stress

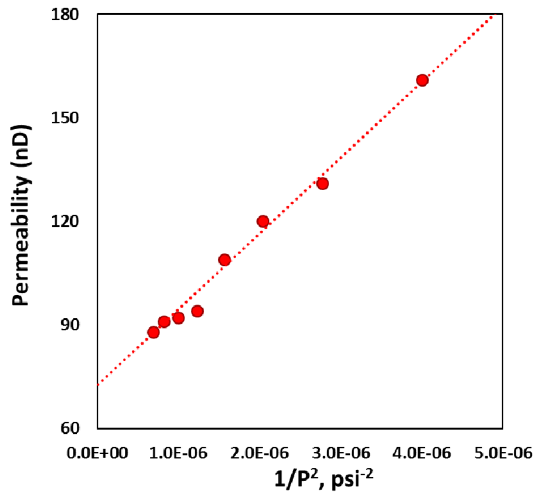

Figure 4—Absolute Permebility Evaluation by Double Slippage Method for Sample 2

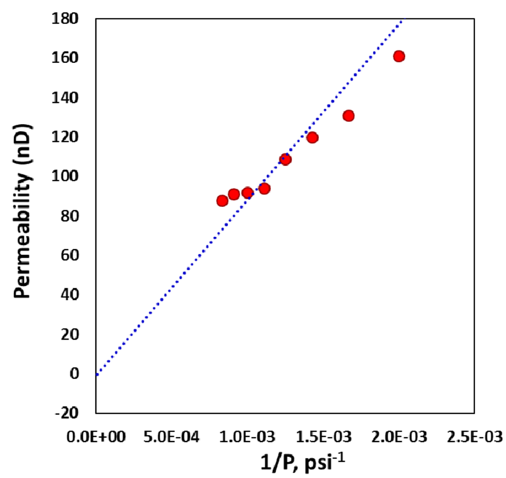

Figure 5—Absolute Permebility Evaluation by Klinkenburg Method for Sample 2

To further investigate this behavior, the Klinkenberg correction was applied to the measured permeability values for pore pressures over 900 as illustrated in Figure 6. It is apparent that the application of the Klinkenberg provides reasonable and consistent values for the absolute permeability. This indicates that the Slip flow is prevalent in the Sample 2 at pore pressures above 900.

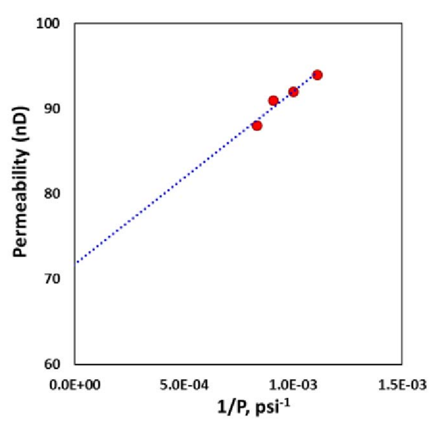

Figure 6—Absolute Permebility Evaluation by Klinkenburg Method for Pore Pressure above 900 psia

The measured permeability values for Sample 3 at different pore pressure from 500 to 1100 psia at net stress values of 3000 and 5000 as function of the reciprocal of the mean pore pressure-squared (double slippage correction) are illustrated in Figure 9. As it can be observed both set of measurements provide reliable values for the absolute permeability. Furthermore, it appears that the Transition flow is prevalent in the Sample 3 for pre pressures up to 1100 psia. It could be surmised that Sample 3 has lower absolute permeability than Sample 2, and as a result smaller pore sizes, is subject to Transition flow even at the higher pore pressures.

Figure 8 illustrates the Walsh plot for Sample 3. Two separate straight lines appear to be present which leads to the fracture closure stress of 3244 psi. This closure pressure is significantly lower than the values previously estimated for Marcellus core plugs (Zamirian et al., 2015 and Elsaig 2016). This lower closer pressure can be also related to the fact that Sample 3 has lower absolute permeability and as a result smaller pore sizes.

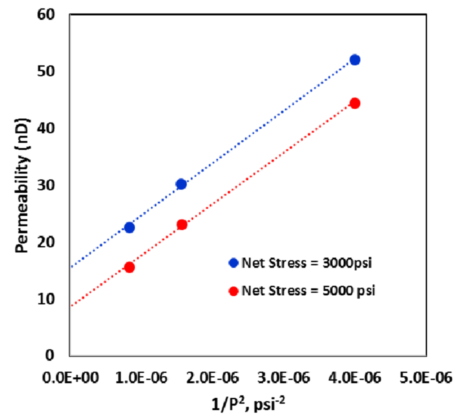

Figure 7—Absolute Permebility Evaluation by Double Slippage Method for Sample 3

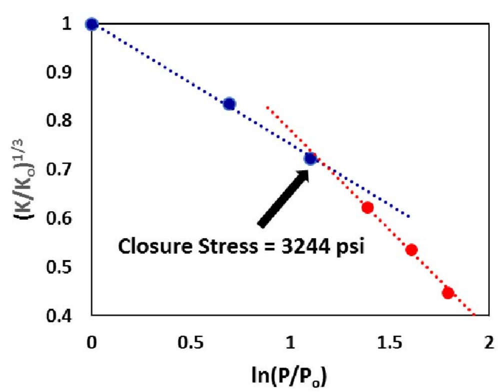

Figure 8—Walsh Plot for Sample 3

Conclusions

1. The permeability of several Marcellus Shale core plugs were successfully measured under a wide range of pore and confining pressures.
2. The gas double-slippage correction provided consistent and reliable values for the shale absolute permeability over a wide range of pore pressures but more precisely for pore pressure below 900 psia.
3. The Klinkenberg correction can provide reliable values for the shale absolute permeability only when the pore pressures are above 900 psia.
4. The pore sizes and as consequence the permeability of the sample can impact both flow regime (i.e. Transition or Slip flow) and the closure pressure.

References

1. Elsaig, M, Aminian, K., Ameri, S., Zamirian, M., 2016. "Accurate Evaluation of Marcellus Shale Petrophysical Properties." Paper SPE 1844042 presented at the Eastern Regional Meeting, Canton, OH, September 13-15.
2. Fathi, E., Tinni, A., and Akkutlu, Y., 2012. "Shale Gas Correction to Klinkenberg Slip Theory." Paper SPE 154977 presented at the Americas Unconventional Resources Conference, Pittsburgh, Pennsylvania, 5-7 June.
3. Klinkenberg, L.J., 1941. "The Permeability of Porous Media to Liquid and Gases." Paper presented at 11th mid-year meeting, Tulsa. API Drilling and Production Practices, New York, pp 200-213.
4. Mathur, A., Sondergeld, C.H., Rai, C.S., 2016. "Comparison of Steady-State and Transient Methods for Meauring Shale Permeability." SPE Paper 180259 presentred at SPE Low Perm Symposium, 5-6 May, Denver, Colorado.
5. Walsh, J.B., 1981. "Effect of Pore Pressure and Confining Pressure on Fracture Permeability." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics*, **18**(5): 429-435.
6. Zamirian, M., Aminian, K., Ameri, S., Fathi, E., 2014a. "New Steady-State Technique for Measuring Shale Core Plug Permeability." SPE 171613 Paper presented at the Unconventional Resources Conference, Calgary, Canada, 30 September-2 October.
7. Zamirian, M., Aminian, K., Ameri, S., 2014b. "A Fast and Robust Technique for Accurate Measurement of the Organic-rich Shales Characteristics under Steady-State Conditions." SPE 171018 Paper presented at the Eastern Regional Meeting, Charleston, West Virginia, 21-23 October.
8. Zamirian, M., Aminian, K., Ameri, S., 2015. "Measurement of Key Shale Petrophysical Properties." Paper SPE 174968 presented at the SPE ATCE, Houston, Texas, 28-30 Septemebr.