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Uncertainties in Permeability Measurements of Shales

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Summary

Matrix permeability is believed to control the long term performance of shale gas wells (Heller et al., 2014). There are several different methods for measuring shale permeability such as steady-state, pulse-decay, and crushed rock permeability. However, each method gives different results, sometimes orders of magnitude different (Ghanizadeh et al., 2015). In addition to the testing methodology, the flow regime influences the apparent permeability and flow behavior of gas. Gas flow regime is a function of knudsen number which relates to gas pressure and pore radius. Therefore, measured apparent permeability varies with the test conditions. The mean effective stress also changes the effective pore radius which in turn changes permeability and flow regime (Moghadam and Chalaturnyk, 2014). The testing method, pore pressure, and the confining stress of the tests are therefore the three immediate sources of uncertainty when measuring the permeability of shales.

In this work, we have conducted a theoretical analysis of gas flow regime at different conditions. Flow regime maps have been developed to provide a guideline in order to determine the dominant flow regime under lab or reservoir conditions. The aim of these flow regime maps is to assist in analyzing lab results and reservoir simulations. The results indicate that for most shales the gas flow regime lies under the slip or transition flow regime, even at pressures as high as 30 MPa. This indicates that slippage needs to be considered in all lab tests, regardless of the pressure, as well as in reservoir simulations. Klinkenberg (1941) established that gas permeability increases linearly with the reciprocal of pressure. His work has been traditionally used to infer the absolute permeability (liquid permeability) from gas permeability results. However, it has been observed that Klinkenberg-corrected permeability in shales can overestimate permeability by a few orders of magnitude (Moghadam and Chalaturnyk, 2014). The true relationship between apparent gas permeability and pore pressure in shales remains unclear, and the definition of absolute permeability is obscure at best.

Steady-state gas permeability tests have been done on three Montney samples and one sample from the Clearwater shale formation. The experiments are conducted at various pore pressures and mean effective stresses using methane and nitrogen. Results confirm the complex behavior of apparent permeability versus pore pressure and mean effective stress. Mean effective stress changes the pore radius and hence

the permeability, but this reduction in permeability leads to an increase in Knudsen number and therefore enhances the apparent permeability. As a result, the change in mean effective stress in shales affects the slip flow parameters as well as the permeability. The experimental results and the theory suggest that permeability reduction as a result of an increase in mean effective stress can be entirely canceled out by enhancement caused by slippage.

In addition to mean pore pressure, experimental results show a rate sensitivity in the values of apparent permeability. At a constant mean pore pressure and mean effective stress, permeability is observed to increase with increasing flow rate, reaching a constant value at higher rates. This effect has never been discussed before in shales and the theory is lacking, casting a shadow of doubt around the non-steady-state testing methods.

Effective stress coefficient for permeability (similar to Biot's coefficient in poroelasticity) is an important parameter that is necessary for calculating the effective stress, and relating permeability measurements to reservoir conditions. In order to calculate this coefficient, permeability measurements should be conducted at various mean effective stresses and pore pressures. However, due to the uncertainty in the slip flow parameters and absolute permeability values for gas, it is very difficult to extract the effective stress coefficient from permeability results. Both slippage and effective stress influence the results, but calculating the contribution of each would need unjustifiable assumptions given the current knowledge.

An extensive set of experimental data (preferably steady-state measurements) is needed in order to understand the flow of gas in shales. The influence of testing method, pore pressure, flow rate, and effective stress need to be addressed by both theory and praxis. The basic definition of gas permeability needs to be revisited in order to set up new standards (concerning testing pressure, rate, and stress state) in order to obtain meaningful and comparable permeability measurements.

References

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