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EFFECTS OF NON-DARCY FLOW AND PORE PROXIMITY ON GAS CONDENSATE PRODUCTION FROM NANOPORE UNCONVENTIONAL RESOURCES

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ABSTRACT
Transport properties and mechanisms as well as phase behavior under nanoscale confinement exhibit significant deviations from their bulk behavior. Phase behavior due to the significant effect of molecule-wall interactions as well as molecule-molecule interactions changes in nanopores. Additionally, in nanopores, when the mean free path of molecules is in the order of the pore radius, non-Darcy flow occurs. This phenomenon causes an increase in effective permeability of the flowing fluid. In this study, we focus on analyzing and determining the effect of phase behavior and transport properties change due to pore proximity on production from a shale gas condensate reservoir. Also, by Applying second-order Klinkenberg’s equation, effect of non-Darcy flow on production from the simulated reservoir is analyzed. Additionally, the effect of different connectivities between pore sizes on production is studied.

A shale gas condensate reservoir with an Eagle Ford gas condensate as the reservoir fluid is modeled. The fluid contains 80% of light (C1-C3), 10% of intermediate (C4-C6), 10% of heavy components (C7+). The pore volume of the reservoir is divided into regions based on pore size distributions obtained from MICP experiments on Eagle Ford shale samples. Random and series connectives between pores are considered.

Results indicated that when considering the decreasing pore size in the reservoir, fluid tends to behave more like a dry gas with the two-phase region shrinking therefore condensate drop-out and near wellbore permeability impairment is reduced. Considering effect of confinement did not greatly affect gas production but the liquid production increased significantly. After 15 years of production, Gas and condensate viscosities under confinement decrease 3-16% and 10-50% respectively. In general, phase behavior effect has a positive contribution to production while considering permeability variation with pore size has a negative impact on production. Connectivity type between different pore sizes has a pronounced effect and determines which of these factors has more impact on production. Results indicated that the non-Darcy flow is absent in the early stages of production where the pressure is significantly high. But as the reservoir pressure falls below 2000 psia, slip and transition flow occurs and results in an increase in apparent permeability and up to 5% in production.

The results of this study can contribute significantly to our understanding of gas condensation and transport in shale formations thereby enabling improved field planning, well placement, completions design and facilities management.

INTRODUCTION
In the past decade, there has been a rapid growth in production from unconventional condensate and gas resources. Due to the importance of these low permeability reservoirs in condensate and gas production, an extensive research has been conducted on these types of resources. Modeling studies on unconventional resources indicate applying physics of fluid and flow behavior in conventional reservoirs underestimate production from unconventional resources (Javadpour 2009; Swami 2012). Therefore in simulation studies in order to match production data, core derived matrix permeability and/or Stimulated Reservoir Volume (SRV) are increased (Swami 2012).

It has been observed that pore sizes of unconventional resources are in the range of 1-200 nm (Cipolla et al. 2009). Different previous studies show that the thermophysical properties of fluids under confinement deviate from their bulk value (Gelb 1999). In such very small pores the effect of interaction between pore walls and molecules become significant. Fluid properties such as critical properties, phase behavior, solubility, and viscosity change dramatically under confinement effects (Akkutlu and Rahmani 2013; Devegowda et al. 2012; Ma et al. 2013; Jin et al. 2013; Sanaei et al. 2014a). Considering these changes in fluid properties affects our production forecast analysis.

Different studies utilizing molecular simulation have investigated the effect of confinement on critical properties. Jiang et al. (2005) have studied the coexistence of n-alkanes on single-walled carbon nanotube bundle using the Monte Carlo simulation and observed a drop in critical temperature due to confinement (Jiang et al. 2005). Zaragoicoechea
and Kuz (2004) and Hamada et al. (2007) studied alteration of phase behavior and thermodynamic properties of Lennard-Jones (LJ) particles under confinement and demonstrated the deviation of these properties from bulk value under confinement (Zarragoicoechea and Kuz 2004; Hamada et al. 2007). Travalloni et al. (2010) investigated dependency of confined fluid critical properties on the pore size due to molecule-molecule and molecule-wall interactions (Travalloni et al. 2010). They showed that typically when pore to molecule size ratio is less than 20, confinement effects become significant. Singh et al. (2009) studied the effect of pore proximity on phase behavior for methane, n-butane and n-octane in the presence of mica or graphite solid surfaces. They reported critical properties shift due to the pore proximity effect for these components (Singh et al., 2009). Recent studies tried to evaluate the effect of pore proximity on production from unconventional resources (Devegowda et al. 2012; Akkutlu and Rahmani 2013; Alharthy et al. 2013; Sanaei et al. 2014a).

Transport and flow under nano confinement deviate from Darcy type flow. When gas flows in small pores at relatively low pressures, gas molecules slip on the surface of the pore. This phenomenon called gas slippage which was first introduced by Maxwell (1867) and causes an increase in effective permeability of gases (Klinkenberg 1941). Different studies have been done to evaluate the effect of slippage on effective permeability of gases.

In commercial simulators Darcy flow model is used to model tight and shale gas reservoirs. In this study effect of slip and transition flows are considered into the commercial simulator to evaluate the non-Darcy flow impact on production. This study focuses on modeling actual reservoir situations of mixed pore sizes. First, phase behavior of an Eagle Ford gas condensate sample is calculated based on the developed correlation for phase behavior shift under confinement. Second, a synthetic reservoir with a gas condensate fluid is considered. Then, two confined and unconfined cases are modeled and effects of phase behavior and transport properties change due to pore proximity on production are evaluated. Then the effect of non-Darcy flow on production from the developed shale gas reservoir is evaluated using a second order Klinkenberg’s equation. Pore size distribution of one shale sample is applied to the reservoir model. Different PVT and permeability regions are considered for each specific pore size region. Random and series connectivities between pores were considered and the results are compared. Thus, the numerical simulation honors the interrelation between transport (permeability) and PVT (altered fluid properties).

1 Pore proximity effect on phase behavior

Singh et al. (2009) reported critical properties shift due to the pore proximity effect for methane, n-butane and n-octane. Ma et al. (2013) and Jin et al. (2013) developed a series of correlation to take into account the effect of confinement on hydrocarbon critical properties based on Singh (2009) study. These correlations are used to predict critical properties change due to confinement effect.

1.1 Pore proximity effects on two-phase envelope

In this section, the effect of confinement on phase behavior of the Eagle Ford sample fluid mixture (Sanaei et al. 2014b) is investigated. In order to see the pore proximity effect on two phase diagram, first, critical pressure and temperature shift for each component of fluid mixture are calculated. Second, these updated critical properties are used in commercial PVT package software and modified phase envelope is calculated using the Peng-Robinson EOS.

Figure 1 indicates different phase envelopes for 5 nm, 10 nm, 15 nm, 30 nm pore sizes and bulk state. As the pore size decreases, the phase envelope shrinks, critical pressure and temperature drop and the critical point shifts to the left. The fluid behaves more like a dry gas as the pore size decreases. Additionally, by decreasing the pore size dew point pressure decreases between 5% to 24%. From this figure it can also be concluded that at a constant pressure and temperature significant decrease in liquid dropout is expected considering confinement. This result is very important since this indicates that less condensate drop out is expected for a reservoir with smaller pore sizes.

2 Non Darcy flow in shale nanopores

Klinkenberg (1941) first introduced the effect of gas slippage on permeability of gas flowing inside a very small pore. He proposed a linear correlation for correction of apparent gas permeability as below:

\[
k_a = k_i \left(1 + \frac{b_k}{P}\right)
\]

(1)

Where \(k_i\) is the apparent permeability of gas and \(k_o\) is intrinsic permeability of the porous media, \(p\) is the average pore pressure and \(b_k\) is the Klinkenberg’s slippage factor which is defined as below (Klinkenberg 1941):

\[
b_k = \frac{4c\lambda}{P} n
\]

(2)

In this equation \(c\) is a constant and close to unity. \(\lambda\) is molecular mean free path and \(r\) is the pore-throat radius. Many authors have tried to develop correlations for prediction of apparent permeability by changing slippage...
factor. These equations are known as Klinkenberg’s first-order equation. 

Knudsen number is used to classify different flow regimes and is defined as below:

\[ K_n = \frac{\lambda}{d} \]  

(3)

In which \( \lambda \) is molecular mean free path (nm) and \( d \) is pore diameter (nm). Javadpour (2007) defined \( \lambda \) for real gases as below:

\[ \lambda = \frac{k_B T}{\sqrt{2 \pi \delta^3} P} \]  

(4)

Where: \( k_B \) is the Boltzmann constant (1.3805x10^{-23} J/K), \( T \) is temperature (K), \( P \) is pressure (Pa) and \( \delta \) is the collision diameter of the gas molecule. When Knudsen number increases and flow becomes a transition flow, first-order equations cannot be used. Tang et al. (2005), suggested a second order equation for gas permeability correction as below (Tang et al. 2005):

\[ k_a = k_c \left(1 + \frac{A}{P} + \frac{B}{P^2}\right) \]  

(5)

Different researchers developed equations to predict apparent gas permeability in transition flow. Figure 2 indicates a summary of the developed models and the Knudsen range of their applicability (Ziarani and Aguilera 2012; Tang et al. 2005; Agrawal 2011).

![Flow regimes in terms of Knudsen number](image)

Figure 2: Flow regimes in terms of Knudsen number

In Figure 3, \( k_a/k_c \) for different Klinkenberg’s second-order equations is shown. It can be seen that apparent permeability is equal to intrinsic permeability at high pressures but as the pressure falls below 2000 psia, apparent permeability starts to increase. At this pressure flow becomes slip flow and as the pressure drops below 800 psia, Knudsen number goes beyond 0.1 and transition flow occurs.

![Figure 3: k_a/k_c as a function of pressure for different models (r_pore=15 nm)](image)

Figure 3: \( k_a/k_c \) as a function of pressure for different models (\( r_{pore} = 15 \) nm)

Fathi et al. (2012) used Lattice-Boltzmann simulation of steady-state gas flow in nano-scale capillaries and indicated that apparent permeability of flowing gases is much higher than those predicted by Klinkenberg theory. They explained this phenomenon due to neglecting inelastic collision of molecules with solid interface. This model is as below:

\[ k_a = k_c \left(1 + \left(\frac{b}{P}\right) \left(\frac{L_{KE}}{\lambda}\right)\right) \]  

(6)

In this equation \( L_{KE} \) is the length scale associated with kinetic energy of bouncing molecules. This model is validated by running experimental studies on gas flow through nanopore shale samples (Fathi et al. 2012). Figure 4 indicates \( k_a/k_c \) for different pore sizes for a pressure range of 0-3000 psia using Fathi et al. (2012) model. It is seen as the pore size gets smaller and pressure decreases apparent permeability increases. In this study this model is used to assess effect of non-Darcy flow on production.

![Figure 4: k_a/k_c as a function of pressure for different pore sizes](image)

Figure 4: \( k_a/k_c \) as a function of pressure for different pore sizes

3 Reservoir simulation model

The model is representative of a 1-stage hydraulic fracturing and the reservoir is 1325 ft. long x 525 ft. wide x 60 ft. thick. Fracture has a half-length of 250 ft. with a conductivity of 4 md-ft and centered in the model. Matrix has permeability and porosity of 149 nD and 9.8%, respectively. The grids are logarithmically
distributed in vicinity of the fracture. The entire reservoir is initialized to 5000 psia and the well produces for 30 years at a minimum bottom-hole pressure constraint of 1000 psia and is subject to a maximum rate constraint of 420 Mscf per day. The reservoir is considered homogeneous and gravitational and anisotropy effects are not taken into account. The horizontal well is drilled in the center of the reservoir. Reservoir fluid is considered an Eagle Ford gas condensate sample. Matrix permeability and porosity of this reservoir are used from results of core plug permeability and helium porosity measurements on one of the Eagle Ford shale samples (Sanaei et al. 2014b).

4 Effect of confinement on production
In this section, the results of two cases are discussed. No pore size distribution is considered here in either cases. Both cases have the same reservoir properties. The only difference between the two cases is that in the confined case critical temperature and critical pressure of each component have been changed for an average pore size of 15 nm for the whole matrix.

The results show that the viscosity of condensate and gas drops considerably under confinement which causes the fluid to flow easier. This drop is more remarkable for condensate viscosity. For instance, after 15 years of production, gas and condensate viscosities under confinement decrease 3-16% and 10-50%, respectively. As the reservoir depletes, more condensate drop-out is expected. The results indicate that condensate front in unconfined case is 20-40 ft. ahead of condensate front in confined case. After 15 years of production, condensate saturation around fracture is up to 7% less under confinement effects. Additionally an increase in in-situ light component (CH₄) and a decrease in intermediate and heavy components under confinement is seen. It can be concluded that in the confined case heavier components are producing and less condensate drop-out is expected.

After 30 years of production, confinement did not change gas production considerably, but cumulative condensate production increased approximately 35% under confinement. This dramatic increase in condensate production is due to the decrease in condensate saturation around fracture and decrease in condensate viscosity, as discussed before.

5 Pore size distribution and connectivity consideration
Based on MICP experiments and pore-throat size distribution, the pore volume of the reservoir is divided into five regions: bulk (pore sizes more than 50nm (10% PV)), 20-50nm (12% of PV), 12-20nm (29% of PV), 7-12nm (39% of PV), and less than 7nm (10% of PV). Various PVT regions are defined based on different pore sizes and their distribution inside the reservoir. Three models are considered based on different connectivity realizations between pores. These connectivity realizations are:

Model 1: Pore sizes from smallest to largest connected to the fracture in series.
Model 2: Pore sizes from largest to smallest connected to the fracture in series.
Model 3: Completely random distribution.
Permeability of each region is estimated using the correlation developed by Sanaei et al. (2014b). Then, critical properties of each component is calculated using developed correlation, modified properties inputted into a commercial simulator, and new phase behavior model for each region is calculated and used into a compositional simulator. A schematic view of these three models are given in Figure 16 by Sanaei et al. (2014b).

In all simulations through this section, four models are discussed and compared. The first three are the ones with different connectivities, and in Model 4, no PVT change effect is considered.

5.1 Multiple PVT regions
Specific PVT properties as shown in Figure 1 are assigned to each region and results for different models are compared. Figures 5 and 6 indicate the cumulative condensate and gas after 30 years of production from the four considered models, respectively. From these figures, it can be seen that considering phase behavior modification increased cumulative gas production 11-27% based on connectivity type. Condensate production in models 1, 2, and 3 increased at least 40% compare to model 4 due to considering confinement effect on phase behavior. In Figure 5, model 1 demonstrates the highest liquid production; since smaller pore sizes which have less condensate dropout are closer to fracture. In this figure, models 2 and 3 have almost the same amount of liquid production. Therefore, considering different connectivities can affect liquid production by 30%.

5.2 Multiple PVT and permeability regions
In this case in addition to considering PVT change, specific permeability is assigned to each region. So, each region has its own permeability and PVT properties. It is seen that both condensate and gas production in model 2 are more than other models. Since in this model bigger pore sizes with higher permeability are closer to the fracture. Models 1 and 3 have less gas production when both effects are considered comparing to model 4. Thus, it can be concluded that effect of permeability variation along with PVT effect have negative effect on gas production in these two models. In Figures 5 and 6, it can be seen that considering both effects have positive effect on liquid production for all models except model 1 which permeability variation effect dominates phase behavior change effect.
Effect of non-Darcy flow on production

The impact of non-Darcy flow is evaluated on the production from the described reservoir. Each pore size region has its own permeability dependency on pressure as shown in Figure 4. The results are summarized in Figure 7; considering the non-Darcy flow increases the cumulative gas production by 5% and 2% for models 1 and 3 respectively. On the other hand, the cumulative gas production for model 2 does not change. In Model 2 smaller pore sizes in which the non-Darcy effect are dominant are far from the fracture. Considering non-Darcy did not affect condensate production. It is worth notifying that the non-Darcy flow is absent in the early stages of production where the pressure is significantly high (above 2000 psia). As a consequence of pressure depletion due to production, the Knudsen number increases. This results in slip and transition flow followed by increase in apparent permeability.

CONCLUSIONS

From results of this study, we can draw the following final conclusions:

- Two-phase envelope shrinks due to decrease in pore size and fluid starts to behave more like a dry gas.
- Condensate and gas viscosity decrease under confinement.
- A significant decrease in condensate drop-out and decrease in condensate viscosity result in a dramatic increase in liquid production under confinement.
- There may be at most 200% difference in condensate production prediction considering different connectivity types, when both effect of permeability and PVT change due to pore size distribution are considered.
- Non-Darcy flow does not have significant impact on production at high pressures.

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