Pressure Dependent Gas Flow in Tight Porous Media

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November 26, 2022

Abstract

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Key Points:

- Gas pressure diffusivity is a better measure of flow efficiency than gas permeability in the porous media.
- Pressure-dependent permeability is successfully employed in history matching pulse-decay experiments for the first time.

Abstract

Because of the gas compressive storage effect, permeability as a critical parameter describing the flow efficiency for liquid might not apply to gas, but gas pressure diffusivity that takes into account of gas compressive effect might do. In this study, pulse-decay experiments were performed on one shale core under different pore pressures with different pressure pulse magnitudes. A novel approach was put forward to determining the intrinsic permeability and gas slippage factor through a single pulse-decay experiment, which is significantly more efficient than the conventional method that requires multiple operations. We verify that gas pressure diffusivity instead of the permeability is the appropriate measure of the efficiency of gas flow, given the fact that the ratio of pulse size over diffusivity is roughly proportional to the experiment duration. We obtain consistent results using different empirical models to capture the intrinsic permeability, gas slippage factor, and pressure-dependent apparent gas permeability simultaneously.

Plain Language Summary

There are still some mysteries about the flow of gas in porous media. Permeability has long been used to measure the efficiency of fluid flow in porous media. Because, according to common sense, under the same pressure difference and travel distance, the higher the permeability, the shorter the flow time of the fluid. However, we find that for gases, the trend is the opposite, that is, higher permeability will cause longer flow time. The estimation shows that the gas pressure diffusivity can better represent the gas flow efficiency because of gas compressive storage effect. In addition, we invent a new method to match pressure curves by pressure-dependent permeability in the transient way of measuring permeability of tight porous media, which can quickly obtain intrinsic permeability and gas slippage-related parameters through one experiment instead of multiple experiments.

1 Introduction

Transient gas transport (refers to pulse-decay in this article that pressure decreases in the upstream and increases in the downstream) tests have been applied to investigate the flow properties of tight rocks decades ago (Brace et al., 1968). Many studies have advanced the developments of interpretation solutions of the transient process over the years; among them, there are two important milestones (Sander el al. 2017). One is by Hsieh et al. (1988) that the restrictive analytical solution was provided, including the compressive storage effect, which is significant for highly compressible gas. The other one is by Cui et al. (2009) that adsorption was taken into account, providing the theoretical foundation and important tool to analyze adsorptive gas flow processes in porous media like organic-rich shale gas reservoirs and coal bed methane (CBM). The solutions by Hsieh et al. (1988) and Cui et al. (2009) are analytical. However, the pressure curves could also be analyzed numerically by history matching. Ning (1992) developed an in-house numerical model based on the finite-difference method that was able to estimate the permeability of both intact and fractured core samples. Alnoaimi (2016) provided a model based on the finite-volume method that was able to study adsorptive gas like carbon dioxide.

In recent years, there have been quite a few studies that investigated the non-darcy behaviors of the gas flow in micro-porous rocks and proposed different formulas to account for the diffusion-dominated effects. For instance, Javadpour et al. (2009) provided a formula for describing the ratio without *Kn*:

$$\frac{k_a}{k_\infty} = \frac{2\mu M}{3\times10^3 RT\rho^2}\left(\frac{8RT}{\pi M}\right)^{0.5}\frac{8}{r} + \left[1 + \left(\frac{8RT}{\pi M}\right)^{0.5}\frac{\mu}{pr}\left(\frac{2}{\gamma} - 1\right)\right]\frac{1}{\rho} \qquad (1)$$

where ρ is density, μ is viscosity, M is molecular weight, R is gas constant, T is temperature, r is pore size, p is pressure, and γ is the "momentum accommodation coefficient" that depends on flow conditions, gas type, and surface roughness.

However, some aspects remain unexploited in terms of the fundamentals of gas transport in tight porous media, and interpretations of pulse-decay experiments. Permeability has been used to describe the level of fluid flow easiness in porous media, i.e., the higher the permeability, the shorter of the fluid propagation time at a given distance. However, Jones (1997) found that in the pulse-decay experiment, "Measurement time is roughly inversely proportional to mean pore pressure", which is contrary to the common belief that gas permeability is higher under lower pore pressure due to the gas slippage effect. Therefore, a comprehensive study is needed to justify permeability's function in evaluating gas flow efficiency.

In terms of analyzing the diffusion effect, a common practice is to perform a series of experiments under a range of pressures and derive the relationship between gas permeability and reciprocal of pore pressure. By analyzing this relationship, two factors, namely the intrinsic permeability and gas slippage factor, could be estimated. Intrinsic permeability, which could be approximated as liquid permeability, is the inherent property of the porous media independent of flow conditions. Actually, during one pulse-decay experiment, a range of pressures will be involved - pressure decreases at the upstream and increases at the downstream. This feature could be utilized by using pressure-dependent permeability in the numerical model so that those two factors could be obtained by performing a single experiment by history matching, serving as an efficient tool for investigating the non-Darcy component in the micro-porous media, which, to the best of our knowledge, has not been attempted by previous studies.

In a pulse-decay experimental set-up, a core sample is connected to upstream and downstream reservoirs. Initially, the core sample and the downstream reservoir are under the same low pressure; the upstream reservoir is under high pressure. The pressure difference between the upstream and downstream is termed as pulse size, which could be quantified with absolute values or percentages of the pore pressure. Walder and Nur (1986) suggested using pulse size as small as possible in the pulse-decay experiments due to the "non-linear pore pressure diffusion". However, there have been no comprehensive and quantitative studies regarding the variation of determined permeability with pulse sizes, to the best of our knowledge.

In sum, the objectives of this study are: (1) investigate the early-time pressure response under different pressure and pressure gradient; (2) evaluate the measure of flow propagation efficiency by permeability and pressure diffusivity in tight porous media; (3) put forward a variable-permeability history matching approach to obtain parameters of intrinsic flow capacity and diffusion simultaneously from a single pulse-decay experiment.

2 Background of the Pulse-decay Experiment and Gas Flow in Porous Media

Figure 1a shows a simplified schematic of the pulse-decay experimental set-up. The upstream reservoir is composed of two parts: the part between valve V_1 and V_2 is the first part upstream reservoir, U_1, and the isolated void volume between valve V_2 and the inlet of the core, U_2. Initially, high-pressure gas is stored in U_1. Low-pressure gas is present in U_2, the core, and the downstream, D.

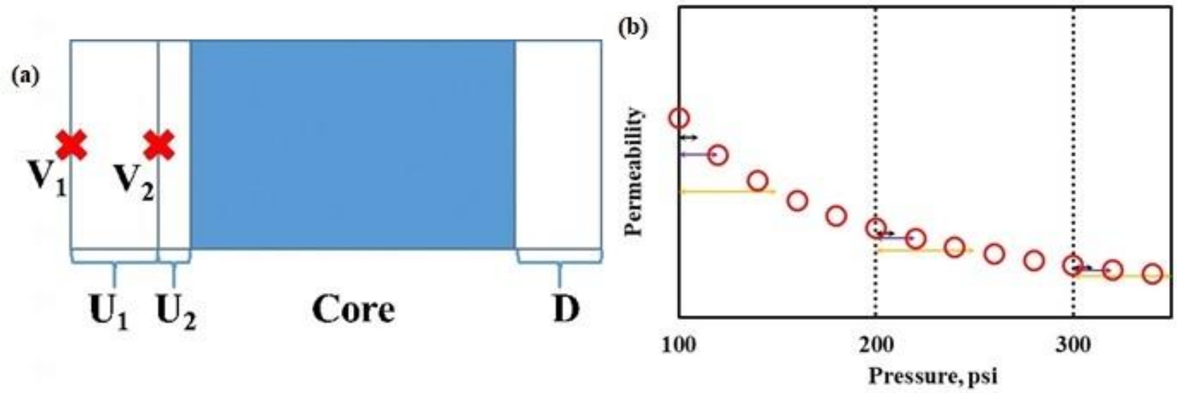

Figure 1. (a) Simplified schematic of the pulse-decay experimental set-up, and (b) sketch of gas permeability with pressure.

By using density as the primary parameter, the equation governing one-dimensional fluid flow in the porous media is described below (Cui et al., 2009):

$$\frac{\partial\rho}{\partial t}=\frac{1}{\emptyset}\frac{\partial\rho}{\partial x}\left(\frac{\rho k}{\mu}\frac{\partial p}{\partial x}\right) \qquad (2)$$

where t is time, ϕ is porosity, k is permeability. The flow efficiency of liquid could be quantified sufficiently by a constant permeability k, which means that if permeability doubles, the time for liquid travel through the porous media should be halved under the same differential pressure. In contrast, the flow process of gas in porous media is different from liquid due to high gas compressibility. The resulting gas density changes in the system during and after gas flow-through contributes to the compressive storage of the test system, which is negligible for liquid but significant for gas. Therefore, permeability's quantifying flow efficiency for liquid does not necessarily apply for gas. Equation 2 could be converted to equation 3 with pressure as the primary parameter as follow (Cui et al., 2009)

$$\frac{\partial p}{\partial t}=\frac{k}{\emptyset\mu c_g}\frac{\partial}{\partial x}\left(\frac{\partial p}{\partial x}\right) \qquad (3)$$

where c_g is gas compressibility. Equation 3 is in the same fashion as Fick's law that gas diffusivity could be defined as (Cui et al., 2009)

$$K=\frac{k}{\emptyset\mu c_g} \qquad (4)$$

Gas pressure diffusivity, K, instead of the single parameter, k, might be able to represent better flow efficiency of gas transport in the porous media, which needs to be validated experimentally. This kind of proof of concept research is not important for conventional reservoirs as gas propagation through such porous media is very fast, but very important for unconventional shale reservoirs due to their ultra-tight nature that gas propagation time will be prolonged.

Gas permeability is related to pore pressure. Equation 5 is the original Klinkenberg equation (Klinkenberg, 1941), in which b_{slip} is termed as the slippage factor. Gas slippage refers to the phenomenon of gas molecules slides at the pore surface when the non-slip boundary condition is not valid under low pressure. Apparent gas permeability is higher than the intrinsic permeability, and the contribution of gas slippage to the permeability could be quantified by the ratio of b_{slip} to p.

$$k = k_\infty(1 + \frac{b_{slip}}{p}) \qquad (5)$$

Figure 1b shows a sketch of a typical relationship between gas permeability and pressure. Pressure differentials of 10, 20, and 50 psi with the initial downstream pressures of 100, 200, and 300 psi for the pulse-decay experiments are represented by the arrowed lines of different colors. The low-pressure and high-pressure ends of the arrows represent the initial downstream and upstream pressures, respectively. As highlighted in Figure 1b, theoretically, the estimated permeability will decrease with larger pressure differentials even with the same initial downstream pressure. But the level of variation is expected to decrease as the initial downstream pressure increases.

The original Klinkenberg's equation (equation 5) does not reveal that b_{slip} depends on the gas type or petrophysical properties of the rock. Several researchers have proposed empirical models to relate b_{slip} intrinsic or absolute permeability and porosity of the rock. Heid et al. (1950) only included the intrinsic permeability in the expression of the slippage factor:

$$b_{slip} = 11.42(k_\infty)^{-0.39} \qquad (6)$$

Jones and Owens (1980) performed permeability measurement on more than 100 tight sands and correlated the slippage factor to absolute permeability as down by Heid et al. (1950), which resulted in a matched exponent of −0.33 (equation 7) different than the exponent of −0.39 in equation 6. The difference is most likely because equation 8 is more applicable to ideal slit flow channels (Jones and Owens, 1980).

$$b_{slip} = 12.64(k_\infty)^{-0.33} \qquad (7)$$

Sampath and Keighin (1982) studied 10 tight sandstone samples under different water saturation and confining pressures, and expanded the correlation further by including porosity:

$$b_{slip} = 13.85(\frac{k_\infty}{\phi})^{-0.53} \qquad (8)$$

For a given data set of permeability of specific rock samples, however, it is difficult to choose which of these models is the most applicable one because the fitting depends on rock properties and experimental conditions.

Furthermore, all the previous interpretations of the pulse-decay experiments assumed that permeability is a constant during the testing pressure range, which likely becomes over-simplified with large differential pressure as highlighted in Figure 1b. In this study, we attempt to determine the pressure-dependent permeability relationship and the associated parameters as required in the empirical models, such as the intrinsic permeability and slippage factor with a single pulse-decay experiment.

3 Experiment Settings and Pressure Dependent Gas Permeability History Matching

An unfractured Barnett shale core was used to perform the pulse-decay test. The net confining pressure, which is the difference between the overburden pressure and the pore pressure (average of the upstream and downstream pressure), was set as 2000 psi in all the experiments, i.e., the total overburden pressure was adjusted for different operations. The core sample has a diameter of 1.5 inches and a length of 3 inches. After the core was loaded into the core holder of a pulse-decay test apparatus, vacuuming was applied to the system; helium was flowed into the test system to reach a pressure of ~ 100 psi within core pore space and the upstream and down-stream reservoirs (Figure 1a). To conduct a pulse-decay test, the upstream gas pressure was increased instantaneously to create a ~10 psi pressure differential, which led to a decreasing pressure in the upstream and a build-up pressure in the downstream. After pressure across the sample reached equilibrium, i.e., the differential pressure approached zero, the pore pressure was elevated to ~200 psi, and the upstream reservoir was further pressurized again with ~10 psi pressure differential to start another test. The same procedure was followed to perform a pulse-decay test with an initial downstream pressure a ~300 psi. Two more series of tests were conducted as described above but with larger pressure differentials of ~20 and ~50 psi respectively. Therefore, 9 experiments were completed in total. The experiment duration of each test was determined as the time required for the pressure difference between the upstream and downstream to become less than 0.1 psi.

IMEX (IMEX, 2018), a black oil simulator, was used to numerically model the pressure pulse-decay process and CMOST (CMOST, 2018), the uncertainty and optimization tool in CMG software package, was used to obtain flow parameters including porosity, apparent gas permeability, intrinsic permeability, and slippage factor by history matching.

History matching-based investigations were extensively performed in this study. First, matchings were performed for the 9 experiments with a constant permeability during each experiment. Second, for matchings with variable-permeability, permeability was expressed as a function of pore pressure and porosity; to this end, a table of pore pressure vs. permeability with a fixed pressure increment of 1 psi was input into the file in CMOST. Table S1 in the **Supporting Information** shows an example using Sampath and Keighin's (1982) model to match the experimental data with pore pressure of ~100 psi and ~10 psi pulse size. Pressures from 113 to 124 psi cover the whole range encountered in the experiment.

Models proposed by Heid et al. (1950), Jones and Owens (1980), Sampath and Keighin (1982) were all applied for the 9 experiments. Hence, 27 variable-permeability history matchings were performed along with the 9 constant-permeability history matchings. The history matching processes, including the base cases, numerical experiments, and optimal solution, are provided in Figure S1 to S9 of **Supporting Information**. Consistent results were obtained for all three models, and thus, here, only the detailed results from Sampath and Keighin (1982) will be presented and discussed next.

4 Results and Discussions

4.1 Gas Permeability and Pressure Diffusivity vs. Time Duration

Figure 2 shows experimental data along with the constant-permeability history matched pressure curves. The criterion of the history matching is that the matching error is below 0.2% with the experimental data. Porosity is best-fitted to be 10% on average, with a negligible deviation of 0.3%.

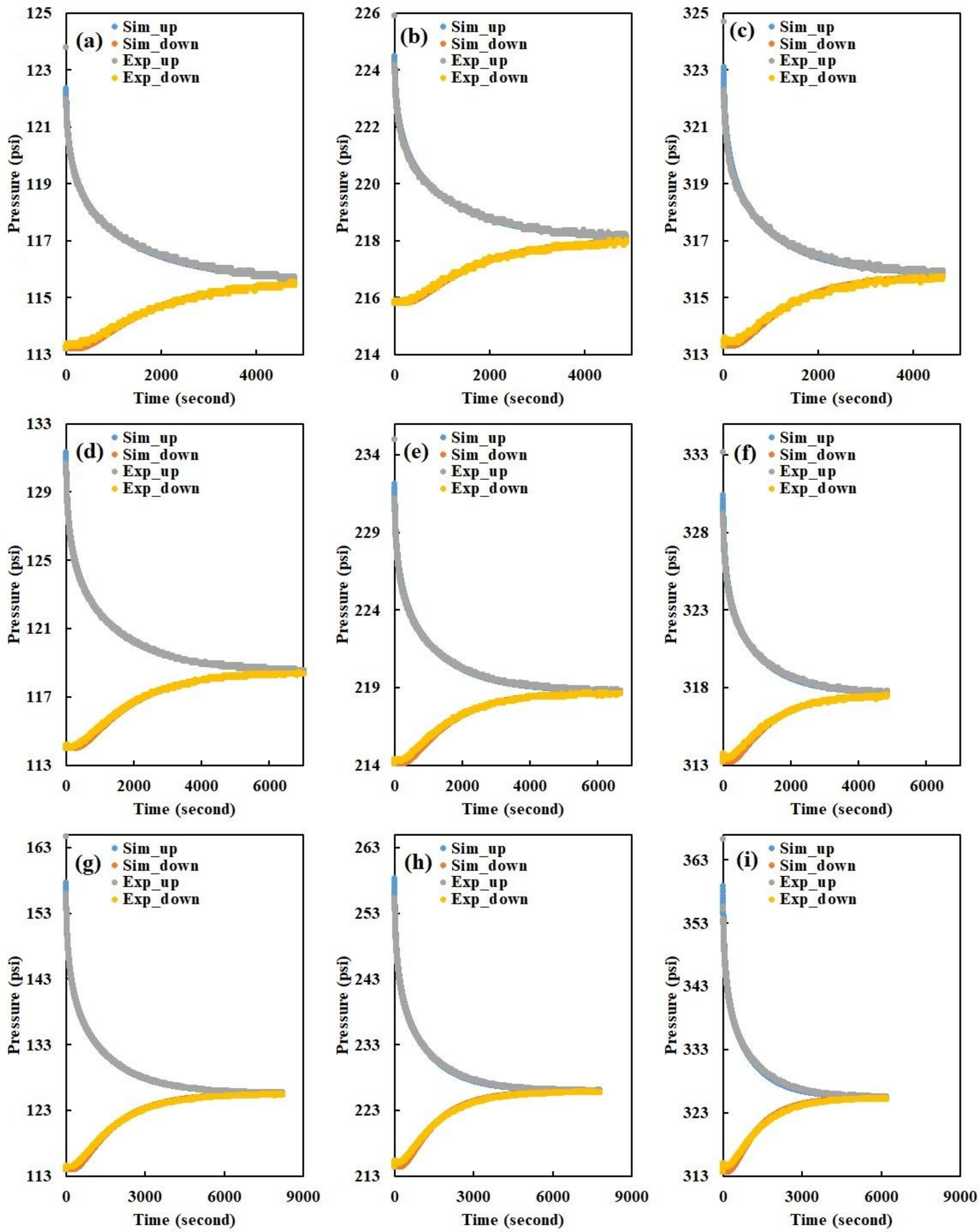

Figure 2. 9 sets of pressure profiles, including experimental data and simulation results. The simulation results are based on constant-permeability history matchings. (a) pore pressure of ~100 psi with pulse size of ~10 psi, (b) pore pressure of ~100 psi with pulse size of ~20 psi, (c) pore pressure of ~100 psi with pulse size of ~50 psi, (d) pore pressure of ~200 psi with pulse size

of ~10 psi, (e) pore pressure of ~200 psi with pulse size of ~20 psi, (f) pore pressure of ~200 psi with pulse size of ~50 psi, (g) pore pressure of ~300 psi with pulse size of ~10 psi, (h) pore pressure of ~300 psi with pulse size of ~20 psi, and (i) pore pressure of ~300 psi with pulse size of ~50 psi.

Figure 3a summarizes the fitted permeability values from all the pulse-decay experiments with constant-permeably history matching. Overall, the estimated permeability is lower under higher pressure due to the gas slippage effect. Pulse size affects the determined permeability when the gas pressure is ~100 psi: the estimated permeability is higher with a smaller pulse size, validating the previous discussions highlighted in Figure 2. However, when gas pressures are above 200 psi, the pulse size up to 50 psi has a negligible effect on matched permeability.

Figure 3b summarizes the experiment durations of all the tests. Similar to the permeability, the experiment duration decreases with increasing pressure, which was also observed in Jones's study (1997). Figure 3c shows the ratio between the pulse size and permeability to compare with Figure 3b. Trends of plots in Figure 3b and Figure 3c are the opposite.

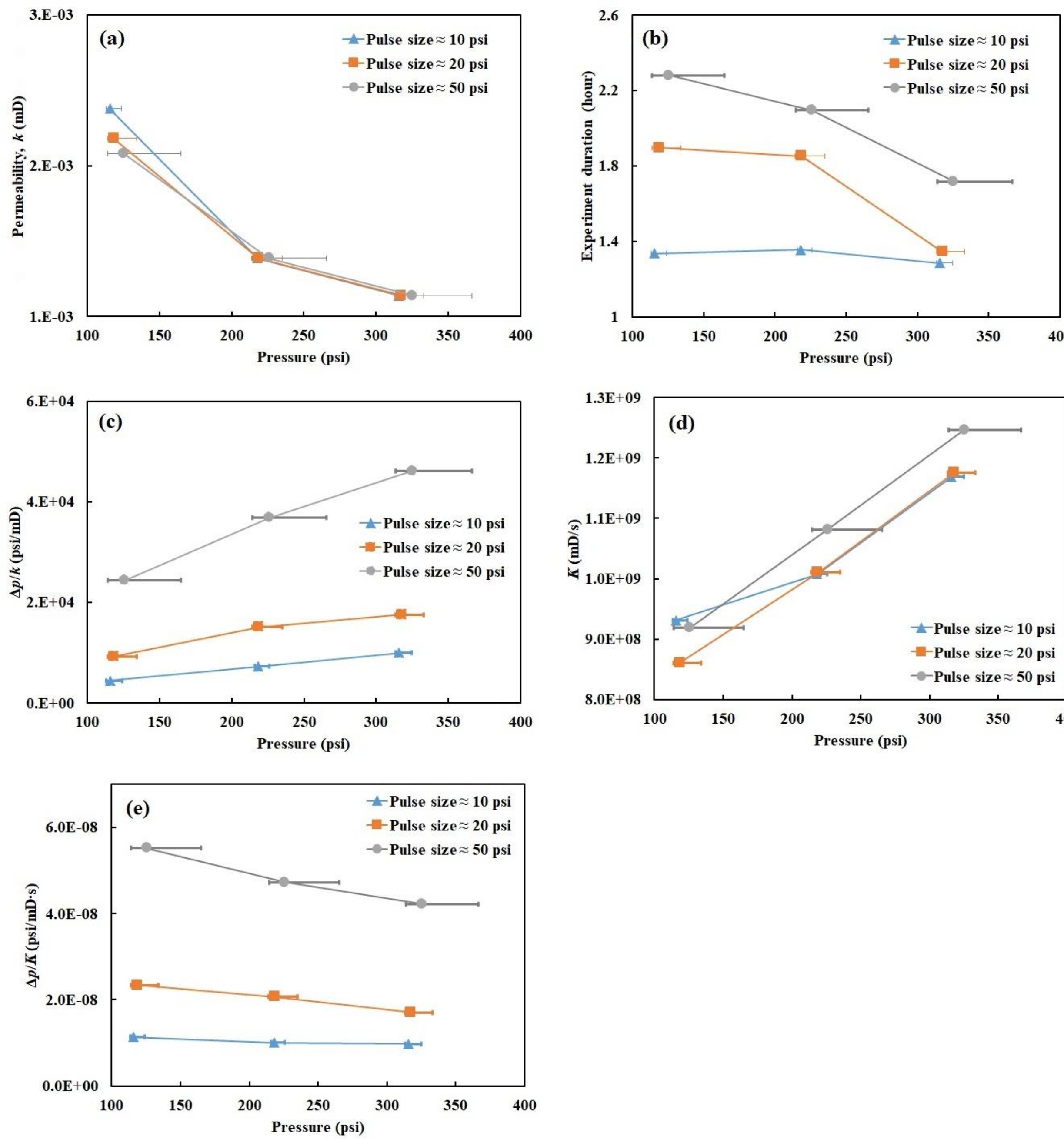

Figure 3. Results using the constant-permeability history matching approach: (a) Permeability, k, determined with history matching, (b) experiment durations, (c) the ratio between pressure differential and permeability as functions of pore pressures for each test, (d) gas pressure diffusivity K, and (e) the ratio between pressure differential and gas pressure diffusivity as functions of pore pressures for each test determined using the constant permeability matching approach. The central data points represent equilibrium pressures. The lower and upper bounds of the data points represent the initial downstream and upstream pressures, respectively.

Figure 3d shows the results of gas pressure diffusivity calculated based on equation 4. Gas compressibility is estimated based on the procedures proposed by Abou-Kassem et al. (1990). Diffusivity values are consistent for the pulse sizes of ~10 psi and ~20 psi except for the point with the pressure of ~100 psi and the pulse size of ~10 psi when gas diffusion becomes predominant. Gas diffusivity shows an opposite trend with pressure as compared to that of permeability. As expected, the trend of the ratio between pulse size and diffusivity (Figure 3e) is roughly consistent with the experiment duration (Figure 4b), suggesting that gas pressure diffusivity is a more appropriate measure of evaluating flow propagation rate in the porous media than gas permeability.

4.2 Pressure Dependent Permeability History Matching

Figure 4 summarizes the results of history matchings using the variable-permeability approach based on the empirical extended Klinkenberg models by Sampath and Keighin (1982). Figure 4a shows that the intrinsic permeabilities exhibit a decreasing trend as the pore pressure decreases. Florence et al. (2007) also noticed this behavior: if we estaimate the associated intrinsic permeability by linear regression of every three adjacent points based on equation 5. A smaller 1/*p*, which is equivalent to higher pore pressure, leads to a lower estimation of the intrinsic permeability. Florence et al. (2007) explained that the phenomenon is caused by the increasing inertia effect as the pressure increases.

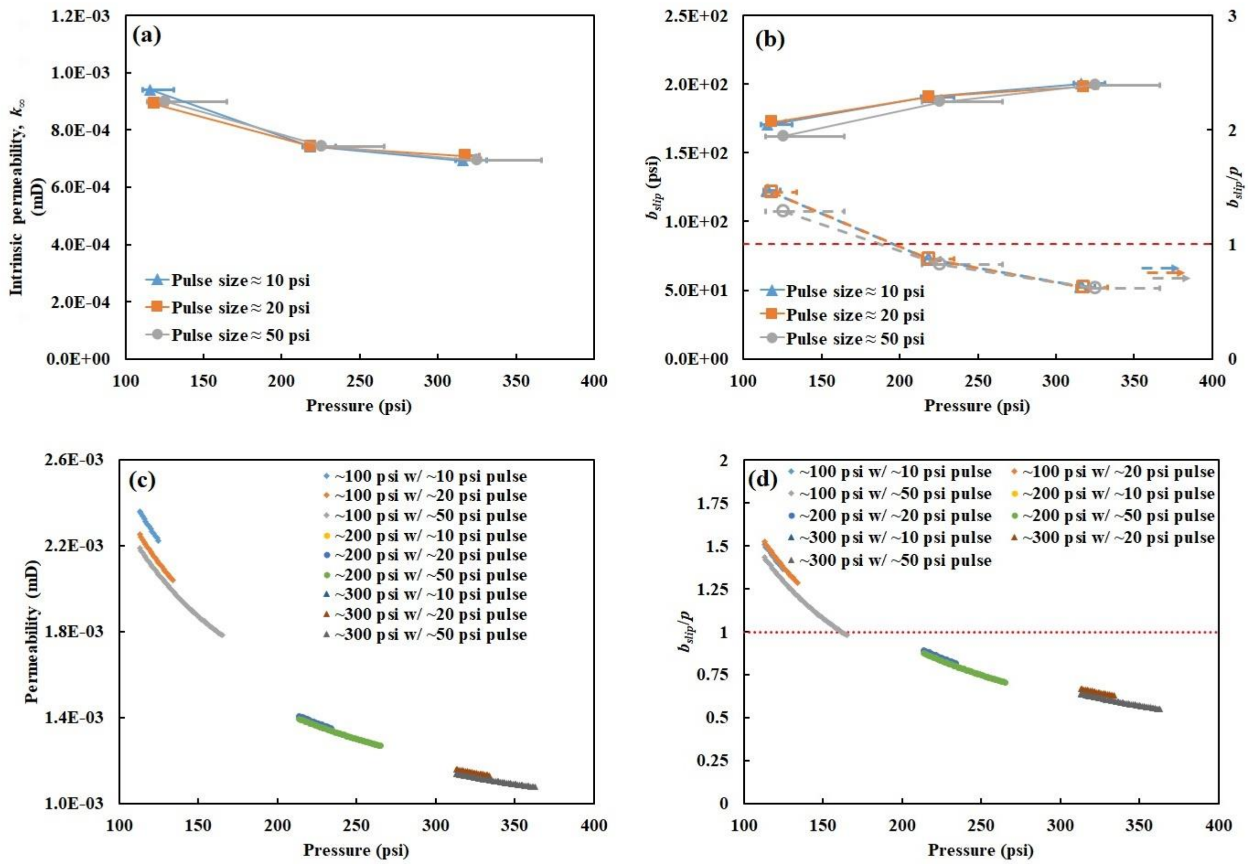

Figure 4. (a) Intrinsic Permeability, k_∞, and (b) b_{slip} and b_{slip}/p, the pressure is the equilibrium pressure. (c) Pressure-dependent permeability and (d) b_{slip}/p based on variable-permeability history matching using Sampath and Keighin's (1982) model.

Similar to the constant-permeability matching results, the pulse size has a negligible impact on the ~200 psi and~300 psi matching results, and the difference between ~200 psi and ~300 psi becomes smaller compared with that between ~100 psi and ~200 psi (Figure 4a). These phenomena could also be explained by the smaller relative change in fluid properties under higher pressures. Intrinsic permeability matched from the experiment with ~10 psi pulse size is remarkably higher than those with ~20 psi and ~50 psi pulse sizes under the pore pressure of ~100 psi for all three empirical models (equations 6 to 8) although only the results for the Sampath and Keighin model is shown here.

The determined gas slippage impact factor is b_{slip}, increases with pore pressures (Figure 4b), but it does not imply that the diffusive flux is more important under a higher pore pressure. b_{slip}/p, as illustrated in equation 5, is able to quantify the relative magnitude of the diffusion flux to the Darcy flux in the porous media. For example, b_{slip}/p being equal to unity suggests that the impact of gas slippage is equal to the intrinsic flow capacity of the porous media. The fact that b_{slip}/p reduces with pore pressure reveals that the diffusion component is more important than the intrinsic flow capacity under lower pressure. Figure 4d shows that gas slippage is more important than the intrinsic flow capacity below 200 psi because b_{slip}/p is smaller than one.

Obtaining dynamic permeability as a function of pore pressure is the primary advantage of the variable-permeability history matching, as shown in Figure 4c. The determined gas permeability decreases significantly from ~2.2E-3 mD to ~1.1E-3 mD as pressure increases from ~100 psi to ~300 psi. Similar to intrinsic permeability and the gas slippage factor shown in Figures 4a and 4b, the impact of pulse size is small when the pore pressures are ~200 psi and ~300 psi but remarkable for ~100 psi. This can be attributed to the more dynamically changing permeability under a lower pore pressure. In addition, a larger pulse size has an additional advantage that a wider range of dynamic permeability could be obtained from a single test (Figure 4c and 4d).

4.3 Limitation of the Proposed Pressure-dependent Permeability History Matching

It should be mentioned that the method we propose is workable when parameters in the empirical equation are correlated to each other, like equations 6 to 8. In the models by Sampath and Keighin (1982), Jones and Owens (1980), and Heid et al. (1950), b_{slip} and intrinsic permeability/porosity in the empirical equation are linked; history matching based on these models generate meaningful results. If one tries to apply more complex parameters, like the “momentum accommodation coefficient” and pore size effects in equation 1 by Javadpour et al. (2009), valid inherent relationships between them should be established first.

5 Conclusions

In this work, we systematically tackle several fundamental issues of gas transport in the porous media and routine pulse-decay permeability interpretations. The results show that the selection of pressure pulse size and pore pressure during one pulse-decay experiment affect the determined permeability value in certain scenarios. Our proposed variable-permeability, instead of a constant-permeability approach, can significantly improve the interpretation of the pulse-decay experiment data.

Permeability, k, is shown not a valid measure of evaluating the flow efficiency of gas in the porous media because of the gas compressive storage effect. Gas pressure diffusivity, K, including the factor of gas compressibility, is proved experimentally as a more suitable parameter describing gas flow efficiency.

Based on constant-permeability modeling of the pulse-decay experiments, pulse size selection (~10 to ~ 50 psi) influences permeability estimations for low-pressure experiments but not high-pressure experiments; the transition point is between ~100 and ~200 psi in our study. For low-pressure experiments, a smaller pressure pulse leads to a higher permeability estimation, which is closer to the in situ permeability for the initial core pressure. The transition pressure in this study may be only valid for this sample as it has relatively high permeability in the category of "tight cores"; for lower permeability samples, this transition pressure is expected to be higher.

Based on the variable-permeability modeling of the pulse-decay experiments, plots of pressure-dependent permeability with pressure, intrinsic permeability, and slippage factor, all could be determined from one pulse-decay test, saving the time of running multiple experiments as done in routine core analysis. This method is demonstrated to be effective and convenient, using extended empirical models based on the Klinkenberg equation.

Acknowledgments

The authors declare no competing interests. This article aims at deepening readers' understanding of low-pressure gas transport in the porous media and advancing interpretation methods of measuring ultra-low permeability. All data in this article are available at https://kuscholarworks.ku.edu/. Bao Jia is grateful to Dr. Paul Hsieh at the United States Geological Survey for his instructions on the analytical solution of obtaining permeability in the transient pressure transmission test.

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