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Paper Title: **Non-Darcy Flow in Tight Reservoirs**

ABDELAZIZ KHLAIFAT^{1,*}, HANI QUTOB¹ and HAMID ARASTOPOUR²

¹Weatherford Oil Tool Middle East Ltd., Dubai, UAE

²Department of Chemical and Biological Eng., Illinois Institute of Technology, Chicago, USA

*Corresponding Author: abdelaziz.khlaifat@me.weatherford.com

ABSTRACT

The future of the energy sector in the coming years is expected to be significantly affected by unconventional gas resources. Most of the fundamental studies of flow in porous media are focused on the influence of the microscopic geometric structure on the macroscopic parameters. In order to address this question for flow through tight porous medium a series of single phase gas flow experiments were conducted. The considered porous medium sample was slot-pore type tight sand from the Travis Peak Formation with permeability in microdarcy range and porosity of 7%. Nitrogen and helium were the used gases. Single-phase experiments were conducted at different pressure drops and overburden pressures. They showed that the sample used is very sensitive to overburden pressure. Pore size distribution measurements, by mercury intrusion porosimetry and sorption isotherm, showed the existence of a wide range of pore size (from 0.4 to 400 nm) distribution. Moreover, the single phase gas flow through the sample particularly at low pressure is of Knudsen diffusion type. Thus, the gas molecules may slip at the wall of the capillary and the Klinkenberg formulation may be the approach to describe the deviation from Darcy's law.

KEYWORDS: Tight Reservoir; Non-Darcy Flow; Pore Size Distribution; Slip Phenomenon; Knudsen Diffusion.

Introduction

Deviation from Darcy's law have been observed in the case of single phase gas flow experiments as was discussed by Khlaifat [1]. As long as the pore structure of porous media is exceedingly complex and for the most part unknown, the main challenge we face is that how can we take all parts of the non-Darcy equation into account and provide a reasonable explanation about the occurrence of its deviation from Darcy's flow. In order to address this deviation, first a comparison between single gas phase experiments of two different gases (Nitrogen N₂ and Helium He) at the same operating conditions was carried out. Then, the results of pore size distribution using both mercury injection and nitrogen adsorption methods will be discussed. After that, the mean free path of gas (N₂, and He) molecules and the existence of different modes of diffusion through porous media will be discussed. Then, an analysis for diffusivity equations will be made in the last section of the manuscript.

Single Phase Gas Flow Experiment Using Two Different Gases

Figure 1 shows a comparison between steady state gas flow rate experiments through fractured porous media with 0.0 mm aperture for both nitrogen and helium gases. From this figure, one can see that the gas flow rate for both gases versus pressure drop has the same trend (non-linear behavior). Also, as the pressure drop for a gas increased, a slow increment in the gas flow rate becomes apparent. At high pressure drops the increase in gas flow rate becomes significant. A rapid rise in the curve for helium occurs because of its lower density (0.1769 kg/m³) compared to the density of nitrogen (1.2507 kg/m³). From this observation we conclude that the use of less dense gas will deviate further from Darcy's law and the opposite is correct.

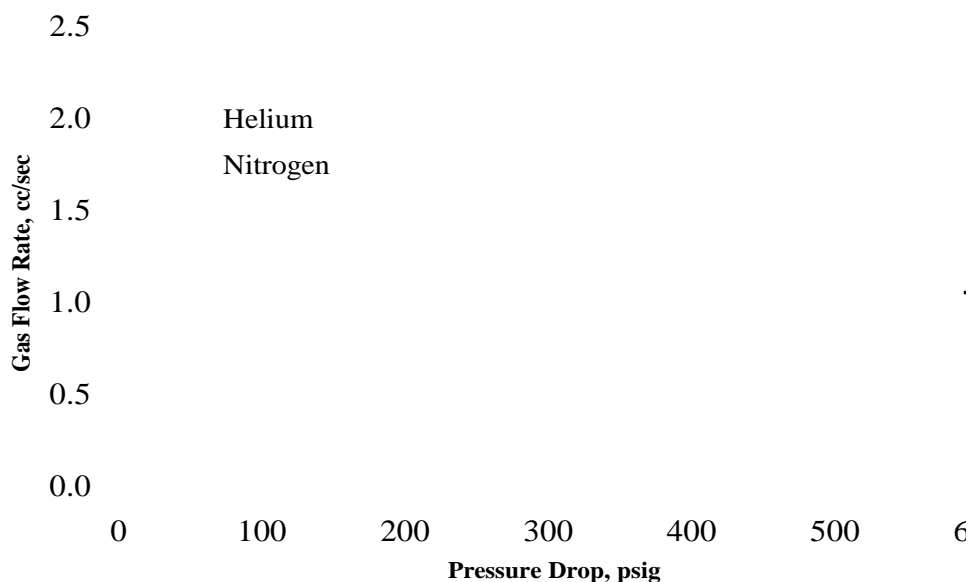


Figure 1. Comparison Between Experimental Data of Steady State Gas Flow Through Fractured SFE2-8707-Plug No. 2

Pore Size and Pore Size Distribution Measurements

Mercury Porosimetry: Mercury intrusion porosimetry has a very extensive literature (see, for example, Modry et al. [2]). Performing mercury porosimetry measurement on the low permeability porous media enables us to plot the percent volume intruded (which was calculated as a ratio between the incremental volume and the total intrusion volume) versus the pore diameter. This plot gives the most convenient form of data presentation illustrated by Figure 2.

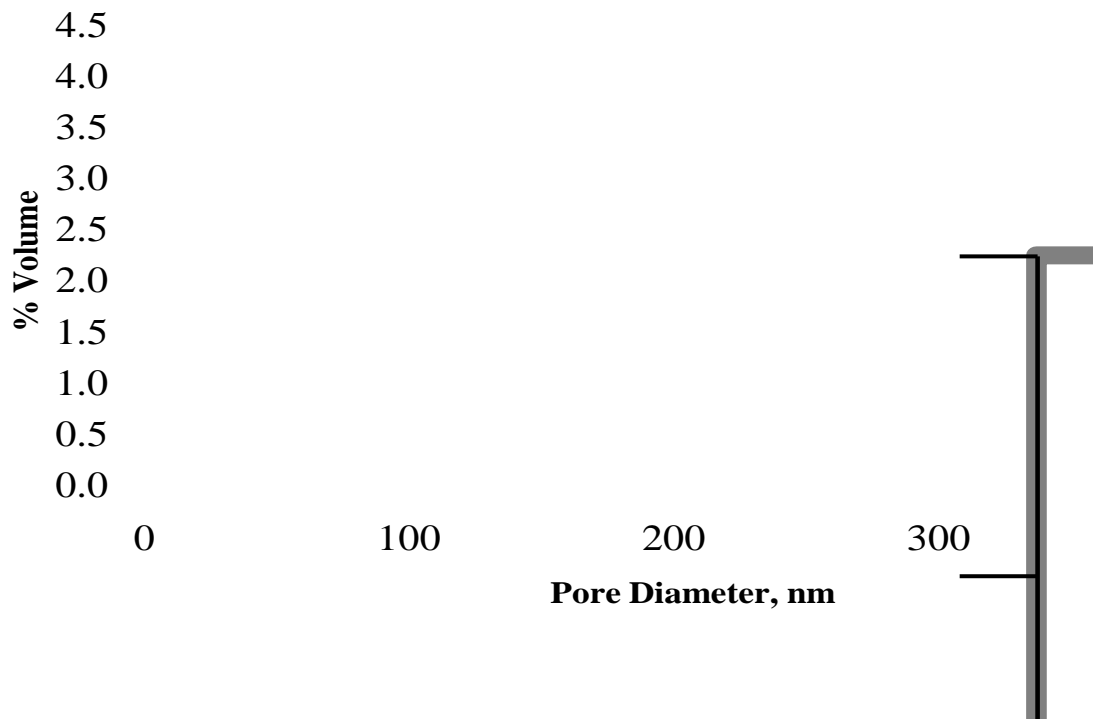


Figure 2. Pore Size Distribution for SFE2-8707-Plug No.2

From Figure 2 we can see that we have very wide pore size distribution. All of the pores exist with a diameter less than 400 nm. It is also clear that the pores which have a diameter from about 100 to 300 nm can be classified as large pores, while the pores with a diameter less than 100 nm as small pores. In order to have a clear picture about small pores distribution, we have performed the adsorption BJH pore size distribution measurement.

Sorption Isotherms. Gas sorption is the most widely used and accurate method for total surface area measurements and pore size distribution within the approximate range of 0.4 to 200 nm diameter. This method provides very high resolution data and has very wide applicability. The method used is based on BJH (Barrett, Joyner, and Halenda) method which involves the area of pore walls, and uses the Kelvin equation to correlate the relative pressure of nitrogen in equilibrium with the porous solid, to the size of the pores where capillary condensation takes place. A detailed theoretical study of this and other aspects of gas sorption may be found in Sing

et al. [3]. Figure 3 shows the pore size distribution using BJH method for low permeability SFE2-8707-Plug No. 2 porous medium sample. From this figure we can see also that we have a wide range distribution for small pores. The comparison between the data associated with figures 2 and 3 shows that both mercury injection and gas sorption isotherm methods detect very close pore surface area per each gram of the sample. Pore size distribution using BJH method provided more detailed information about small pores which could not be detected by mercury injection technique. So these two distribution integrate each other to show the existence of very wide range pore size distribution for SFE2-8707-Plug No. 2 porous medium sample.

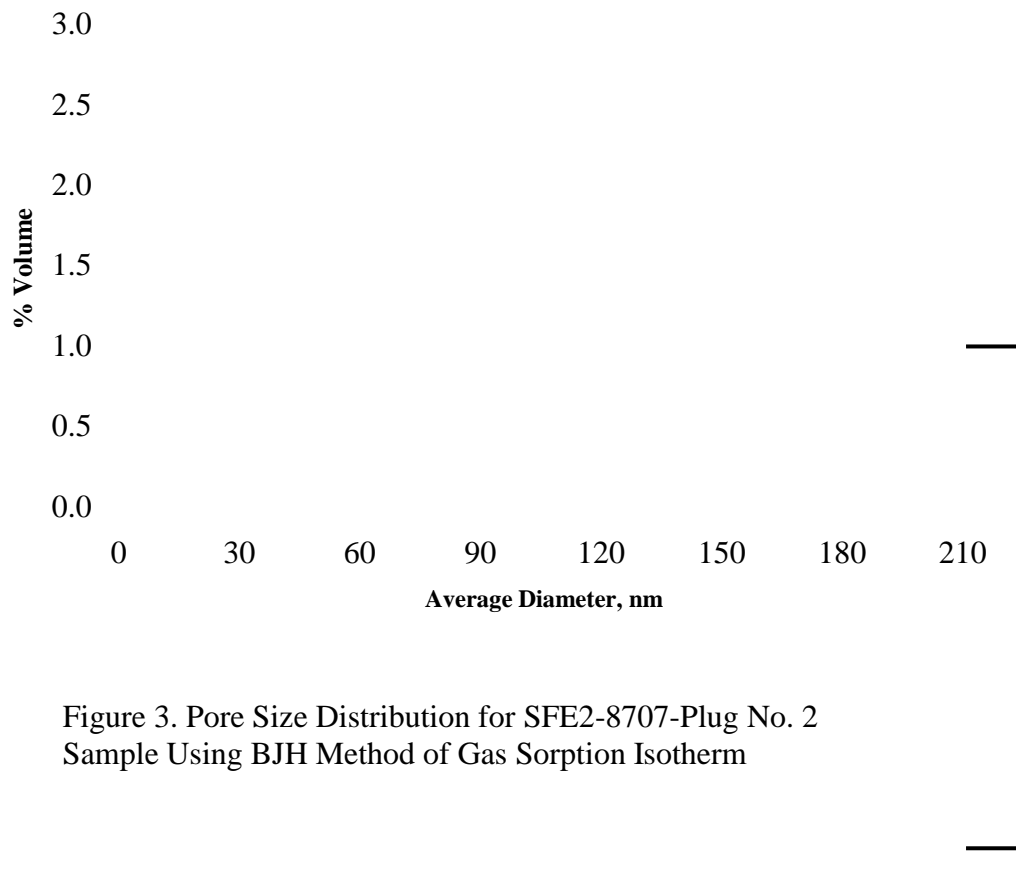


Figure 3. Pore Size Distribution for SFE2-8707-Plug No. 2 Sample Using BJH Method of Gas Sorption Isotherm

Diffusion of Gas through Porous Media

Flow of gases through porous media is treated in the literature mostly with pore diffusion. Since the pore size distribution discussed above showed that pores of SFE2-8707-Plug No. 2 low permeability sample are often small, the diffusion of gases may depend upon the diameter of the pores. Flow of gases in porous media has certain special characteristics that distinguish it from flow of liquids and this might be the reason behind its flow deviation from Darcy's law.

In order to have a better understanding about diffusion of gases through porous media, we have to find the necessary and sufficient conditions required for the existence of each kind of diffusion. The first of these conditions is called the mean free path λ . Mean free path usually defined as a function gas physical parameters, Geankoplis [4]. The calculations showed that low pressures give large values of mean free path for a single gas, and the mean free path is higher for helium than nitrogen at the same pressure, this is caused by its lower molecular weight and higher viscosity compared to nitrogen.

Now, we shall consider what happens to the basic mechanism of diffusion in gases as the relative value of the first condition (mean free path) compared to the second condition (pore diameter) varies. This ratio is usually called Knudsen number and defined as: $N_{Kn} = \lambda/2\bar{r}$, where \bar{r} is average pore radius in m ($\bar{r} = d/2$, where d is the diameter of the pore in m). The analysis was performed by considering the following three limiting cases:

1. The mean free path (λ) is large compared to the pore diameter (d); Under this circumstance only collisions between gas molecules and the walls of the capillary are important. This type is called "molecular streaming" or Knudsen diffusion (flow). As the mean free paths of gas molecules are, at room temperature and pressure, roughly in the range 10 to 100 nm, flow in pores under 100 Å (angstrom) diameter is usually the Knudsen type Dullien [5]. So for Knudsen diffusion, Knudsen number is bigger than ten ($N_{Kn} \geq 10$).
2. The mean free path (λ) is small compared to the pore diameter (d); In this case molecule-molecule collisions predominate and molecule-wall collisions are few. Ordinary molecular of Fickian diffusion holds Dullien [5]. Knudsen number for such kind of diffusion should be less than one percent ($N_{Kn} \leq 0.01$).
3. The mean free path (λ) and pore diameter (d) are intermediate in size between the two limits given for Knudsen and molecular diffusion. This kind of diffusion called transition-region diffusion of gases, where molecule-molecule and molecule-wall collisions are important in diffusion. For this case Knudsen number is $0.01 < N_{Kn} < 10$.

In the last limiting case Knudsen number can have a value equal to one which means that the mean free path of the gas molecules is of comparable magnitude as the pore size. It is known from fluid mechanics, Bird et al. [6], that when the diameter of capillary tube approaches the mean free path of the molecules, gas flows through it more rapidly than would be predicted by Poiseuille's law. The same should be true for flow of gas at low pressure through porous media Dullien [5], Greenkorn [7]; the flow is faster than would be predicted by Darcy's law. Contrary to laminar flow theory (on which Darcy's law is based, where assume zero fluid velocity at the

solid wall with shear taking place in the fluid), here there is no intimate contact of the fluid molecules with the solid wall and the velocity at the solid-fluid interface has a finite value, not necessarily zero. Thus, whenever the mean free path of the gas molecules approaches the dimensions of pore diameter, the individual gas molecules are in motion at the interface and contribute an additional flux. This phenomenon is called slip phenomenon, or Klinkenberg effect (or slip flow).

From the context of the above reasoning one might become confused and say that based on what stated above the second limiting case ($N_{Kn} \leq 0.01$) is of slip flow type. This is not true, because of the fact that when the mean free path is much smaller than pore diameter, the slip velocity becomes negligibly small. As in liquids the mean free path of molecules is of the order of the molecular diameter, so the no-slip condition always applies in liquid flow. This means that when $\lambda \ll d$ Darcy's law is becoming valid for gas phase as well.

It was investigated further whether the observed deviations from Darcy's law were caused by slip flow or not. As long as we measured the gas flow rate at the exit from the core holder where the pressure was atmospheric, we assume that at the exit all kinds of pore diameters exist. So using the calculated mean free path values at atmospheric pressure for both nitrogen and helium, we calculated Knudsen number for the whole range of pore diameters discussed above. Different plots of pore diameter versus Knudsen number were generated. Based on these plots, the three types of diffusions (viscous, Knudsen, and transition regime) were discussed.

Conclusions

Two kinds of diffusion (Knudsen diffusion and transition region diffusion) for the case of single phase gas flow through low permeability porous media exist. A simplified justification in terms of fundamental equations governing the flow for both kinds of diffusion was provided. The combined pore size distribution information using both mercury injection and sorption isotherm techniques showed the existence of a very wide range of distribution in pore size (from 0.4 to 400 nm) for the SFE2-8707-Plug No. 2 porous medium sample taken from Travis Peak formation. Flow through SFE2-8707-Plug No. 2 sample showed that the flow, particularly at low pressures, is Knudsen diffusion type. Thus, the gas molecules may slip at the wall of capillary and the Klinkenberg formulation may be appropriate to describe the deviation from Darcy's law in single-phase gas experiments at lower pressure.

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