



## Slippage in shale based on acyclic pore model

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### ABSTRACT

A significant fraction of the pore-throat size in the matrix of a shale formation is smaller than 100 nm. Nanofluidics, a field that deals with the transport properties of sub-100-nm conduits, indicates that the fluid flow is enhanced for this range of pore-throat size. However, it is unclear how the slippage at the pore scale (single conduit) controls the effective slippage at the core scale ( $\sim 1$  in.). The present study reviews the slippage models for the gas and liquid flows inside a single conduit based on the experimental and theoretical studies in the literature. It then investigates the effective enhancement in shale formations using an acyclic pore model, which represents the effective connectivity of the shale pore space at the core scale as it captures the mercury injection capillary pressure measurements (drainage). The effective slippage is presented in terms of governing parameters such as pore pressure and wettability. This study presents the effective pore-throat size, whose corresponding slippage is equal to the effective gas slippage at the core scale, for three shale samples. The numerical simulations indicate that the effective pore-throat size for the gas flow depends on the pore pressure. In addition, the measured permeability with liquid is higher than the nominal permeability, often referred to as the Hagen–Poiseuille model, with no slippage. The presented results have major implications for reservoir characterization based on standard petrophysical measurements.

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### 1. Introduction

Hydrocarbon production from conventional reservoirs was the primary focus of the oil and gas industry in the previous century. In the present century, however, industry attention has focused more on the hydrocarbon recovery from shale formations, which are characterized by organic-rich and high-clay content [1,2]. It is imperative to characterize the transport properties of shale formations to improve the energy recovery.

The main assumptions in the continuum models are usually invalid at the nano scale because the interactions between the fluid molecules are less important than the interactions with the porous wall. Thus, it is inaccurate to use transport properties that are characterized at ambient conditions (without nano-size confinements) for fluid flow in nano-size conduits. Nanofluidics—the study of the fluid flow in channels whose characteristic sizes are below 100 nm—has helped us to better understand the transport properties of shale formations, whose pore space has nano-size conduits.

Researchers have used different methods (experimental and non-experimental) to determine the transport properties of a single conduit whose characteristic size is smaller than 100 nm.

Slippage, which is an indicator of the fluid velocity at the boundary, is one of those properties. Slippage, which can be related to larger scales, is a pore-scale phenomenon, as it is concerned with the flow inside a single a conduit. Slippage is often represented with the slip length, which is an extrapolated distance (imaginary) away from the boundary at which the fluid velocity is zero; extensive reviews on slip-length calculation can be found in the literature [3,4].

Researchers have performed different experiments to determine the slip length in nano-size conduits. Whitby et al. [5] determined that the slip length of a 44-nm channel (a nanopipe) was 113–177 nm by conducting a fluid-flow experiment. Similar investigations have been undertaken by other researchers to calculate the slip length for conduits of different sizes and with different fluids [6–9]. More recently, Javadpour et al. [10] showed that the atomic force microscope (AFM) could also be employed to obtain the slip length in organic pores. In another study, Zhy and Granick [11] used an oscillating surface force apparatus to estimate the slip lengths of 20–100 nm slits.

Researchers have conducted numerical simulations to determine the slip length. The main approaches are the direct simulation Monte Carlo, the lattice Boltzmann, and molecular dynamics [12]. Thomas and McGaughey [13] used non-equilibrium molecular dynamics to calculate the slip length in carbon nanotubes (CNTs). Their study showed that the slip length decreased from

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105 to 30 nm when the diameter increased from 1.6 to 4.9 nm, and it was negligible for wider tubes. In addition, Falk et al. [14] computed the slip length for 0.8–7 nm CNTs. Other researchers have performed similar numerical simulations to calculate the slip lengths for channels with different diameters and with different fluids [15–17], and those results will be used in the present study.

Researchers have studied the transport properties in individual conduits whose properties mimic shale formations [18]. Sun et al. [19] used a three-dimensional model based on scanning electron microscopy (SEM) images to compute the intrinsic permeability, the porosity, and the tortuosity. Sun et al. [20] further analyzed the apparent permeability of organic and inorganic pores. Wu et al. [21] adopted a molecular dynamics simulation to calculate the methane adsorption and displacement in carbon nanochannels. They discovered that the Van der Waals forces were the main reason for the significant storage in slit pores, which was consistent with a previous investigation [22].

The effects of the pore geometry and size on the adsorption were also investigated. Song et al. [23] showed that the excess adsorption density increased when the pore size decreased. Further, the maximum excess adsorption was the largest in the triangle pore shape, followed by the slit, the circle, and the square. The pore-throat size has also been shown to have an effect on the adsorption-desorption hysteresis [24,25].

Wang et al. [26] and Song et al. [27] investigated the impact of surface diffusion for gas flow in nanopores. They demonstrated that, for formations with a large fraction of mesopores and micropores, surface diffusion dominates the late stage of gas production, a finding corroborated by other investigations [28,29]. Klinkenberg [30] suggested expressing the gas flow in the porous medium using the effective permeability by accounting for the existing flow mechanisms, which are the diffusive flow and the viscous flow [31]. The former includes Knudsen diffusion, surface diffusion, and molecular diffusion [32,33], though surface diffusion is negligible when the characteristic pore size is larger than 2 nm [20,34].

Li et al. [35] modified the continuum models to account for the gas slippage, which is enhanced with the increase in the Knudsen number ( $Kn$ ). Singh et al. [36] also proposed a dynamic permeability model that accounts for the Darcy and Knudsen flows. Further, Singh and Javadpour [37] used the Langmuir sorption data to determine the slip coefficient for gas flow and defined an apparent permeability model. In addition, Song et al. [38] suggested a unified apparent permeability model that takes into account the viscous flow, the Knudsen diffusion, the surface diffusion, and the adsorption.

A knowledge of nanofluidics allows us to gain a better understanding of the transport properties in nano-size conduits (pore-scale), but we need to upscale them to core-scale ( $\sim 1$  in.) properties to make them applicable to petroleum engineering. The upscaling can be done using the pore-scale modeling approach, which enables us to predict different transport properties, such as permeability [35,39] based on the pore-scale processes. Purcell [40] proposed the first pore model by assuming that the pore space could be represented as a bundle of tubes. Fatt [41] improved his model by accounting for the interconnectivity when he supposed that the regular lattice could capture the void space. Subsequently, Bryant et al. [42] derived a method of extracting the network model from a granular packing [43], which is realistic for unconsolidated sandstones. More recently, Sakhaee-Pour and Bryant [44] have shown that the tree-like pore model, which is an acyclic model, can capture the effective connectivity of the pore space in a shale formation, as it can simulate the mercury injection capillary pressure measurements. The particular acyclic pore model has applications in characterizing the transport properties of shale

formations such as viscosity [45] and nitrogen adsorption and desorption [25].

In the present study, we first review the slippage models for the fluid (gas and liquid) flow inside a single conduit. We then relate the slippage inside a single conduit to the effective permeability at the core scale. The core-scale properties are predicted using an acyclic pore model [44], which is physically representative of the pore connectivity at the core scale. We account for the pore pressure and wettability, and discuss the results.

## 2. Slippage in a single conduit

Numerous studies have examined the liquid and gas slippage inside a single conduit. We present a general relation to discuss the slippage as follows:

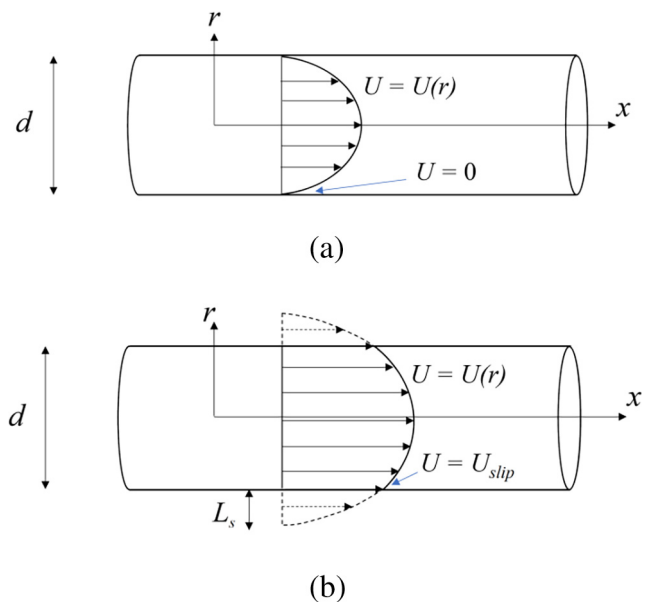
$$e(\text{fraction}) = \frac{k_{\text{fluid}}}{k_{\text{nominal}}} - 1 = \begin{cases} e_g(d, p, T, \varepsilon) \\ e_l(d, \text{wettability}) \end{cases} \quad (1)$$

where  $e$  is the flow enhancement,  $d$  is the conduit size,  $p$  is the pore pressure,  $T$  is the Temperature,  $\varepsilon$  is representative of gas composition, and  $k_{\text{fluid}}$  is the effective fluid permeability that is equal to the single-phase gas permeability ( $k_g$ ) or single-phase liquid permeability ( $k_l$ ).  $k_{\text{nominal}}$  is a nominal permeability, which is based on the Hagen–Poiseuille relation [46] with no-slip conditions, as follows:

$$k_{\text{nominal}} = \frac{d^2}{32} \quad (2)$$

The fluid velocity does not become equal to zero at the boundary (wall) when there is slippage (Fig. 1b), in contrast to no-slip boundary conditions (Fig. 1a). The slippage at the boundary is usually quantified using the slip length, which is the extrapolated distance at which the tangential velocity vanishes ( $L_s$  in Fig. 1b). In a circular tube, the slip length is related to the liquid enhancement as follows [5]:

$$e = 1 + \frac{8L_s}{d} \quad (3)$$



**Fig. 1.** (a) Schematic of a fluid velocity profile ( $U = U(r)$ ) with no-slip boundary conditions (b) The fluid velocity does not vanish at the boundary, which is denoted by  $U_{\text{slip}}$ , when there is slippage, and its extrapolation becomes equal to zero at the distance  $L_s$ , referred to as the slip length (Eq. (3)), away from the interface.

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