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Microscopic choked flow for a highly compressible gas in porous media

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ABSTRACT

Choked flow can impact the gas flow rate from a high-pressure gas well with a vertical fracture of finite conductivity and the development of tensile stress near the wellbore. Traditionally, the choking condition of the flow of a highly compressible gas in porous media is obtained by considering the porous media to be a homogeneous porous medium at the macroscopic scale. In reality, when the average existing pressure of the porous medium decreases, if the compressible gas flow is choked in only one microscopic basic structural unit, the gas flow is choked in the macroscopic porous medium. In this paper, the choking condition of a compressible gas flow in a basic structural unit is studied. It is shown that for the given inlet pressure and temperature, the choked flow occurs first in the basic structural unit with a constant cross-section and with lower porosity and shorter flow distance. If the roughness of the basic structural unit is more complicated or its flow distance is shorter, this basic structural unit requires a lower pressure drop when the gas flow is choked. Whether the basic structural unit is a pipe with finite wall thickness or a single pore, the choking condition first occurs in the position with the smallest porosity or permeability near the exit. It is found that for microscopic choked flow, the outlet-to-inlet pressure under conditions of varying friction is substantially lower than that under the effect of constant friction.

1. Introduction

The Darcy–Forchheimer equation is given by the appropriate square velocity modification to Darcy's law (Joseph et al., 1982). This modification has been discussed in detail for nearly incompressible flows by Du Plessis and Masliyah (1988), Du Plessis (1994), Hayes et al. (1995), Skjetne and Auriault (1999), Handren et al. (2001), Wang (2012), Wang et al. (2014), and Ai et al. (2015). For compressible flows, the Darcy–Forchheimer equation with an acceleration term is adequate. It is noted that choked flow will occur in the Darcy–Forchheimer equation with an acceleration term (Shreeve, 1968; Emanuel and Jones, 1968; Meyer and Smith, 1985; Nield, 1994; Kodres, 1994; Levy et al., 1995; De Ville, 1996; Ciarletta and Straughan, 2006; Straughan, 2008; Jin et al., 2012a, 2012b; Jiang et al., 2015a, 2015b, 2015c). In these cited works, choked flow is simulated by the averaged Darcy–Forchheimer equation with an acceleration term at the macroscopic scale. In previous studies on choked flows at a macroscopic scale, the choking condition can reduce the gas flow rate in a high-pressure gas well with a finite conductivity vertical fracture (Jiang et al., 2015c) and increase the risk of tensile failure near the wellbore (Jin et al., 2011). However, it matters that the macroscopic choked flow and the microscopic choked flow have minute differences when the gas flows through nonhomogeneous porous media, i.e., the microscopic choking condition is different from the macroscopic choking condition. Therefore, it is important to understand what the choking condition is and its influence rule induced by the geometric shape parameters of the basic structural unit at a microscopic scale.

Recently, Yuan (2013) and Yuan and Chen (2016) studied the choked gas flow at the pore scale. Macroscopic choked flow can occur when flow in just one pore is choked. It is noted that this research finding was obtained under the effect of constant friction. However, the friction factor cannot be a constant, and it will change with varying gas velocity. The friction factor has a significant effect on the outlet pressure in macroscopic choked flows (Jiang et al.,

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2015a, 2015b). In this paper, we investigate the relation between the critical condition in which the flow is choked in macroscopic porous media and the microscopic basic structural unit under varying friction, where the microscopic basic structural unit is a pipe with finite wall thickness. We prove that when gas flows through a homogeneous porous medium, the critical conditions of choked flow in a macroscopic porous medium and a microscopic basic structural unit are similar, but they are different when the gas flows through a nonhomogeneous porous medium. To elucidate the critical condition at which the flow becomes choked, the geometrically simpler linear adiabatic flow is studied. We explore how the length, the inner radius and the spatial periods of the basic structural unit affect the choking condition. Finally, it is shown that for the same inlet pressure, the outlet pressure under conditions of varying friction is substantially smaller than it is under the constant friction at the choking condition.

2. Description of porous medium flow

It is assumed that the void space is an axisymmetric pore throat whose geometrical feature is a circular tube, and the axis of the pore throat is parallel to the X-axis (see Fig. 1). If the geometric shape of all pore throats in a porous medium is the same, the basic structural unit which is a pipe with finite wall thickness can be used to represent the porous medium (see Fig. 2). The inner radius and the outer radius of the basic structural unit are r and R, respectively. A similar model has been utilized by several authors (Van Golf-Racht, 1982; Coulaud et al., 1988; Ma and Ruth, 1993; Chukwudozie et al., 2012). The gas flow is the geometrically simpler linear adiabatic flow. We will employ the ideal gas equation due to its simplicity:

$$p^{*} = \rho R^{*} T \tag{1}$$

where R^{*} is the gas constant; and p^{*}, ρ and T are the pressure, density and temperature of the gas, respectively.

The porosity of the basic structural unit $\phi = \left(\frac{r}{R}\right)^2$ (2)

Van Golf-Racht (1982) derived the permeability of a hydrodynamic unit based on the classic Darcy definition. Similarly we can derive the permeability of the basic structural unit using the same method.

The flow rate of the basic structural unit is like that of a cylindrical capillary,

$$Q = \frac{\pi r^4}{8\mu}\frac{\Delta p}{\Delta L} \tag{3}$$

where $\frac{\Delta p}{\Delta L}$ is the pressure gradient in the flow direction, and μ is the gas viscosity.

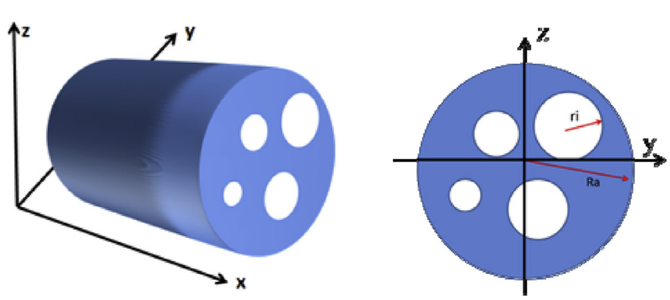

Fig. 1. Schematic diagram of porous media.

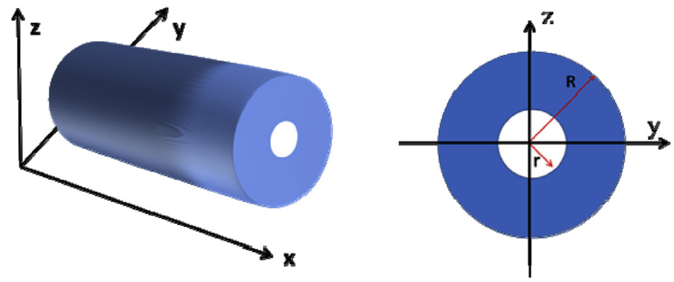

Fig. 2. Schematic diagram of the basic structural unit.

The flow rate of the basic structural unit based on the definition of Darcy is

$$Q = \pi R^2 \frac{\kappa}{\mu}\frac{\Delta p}{\Delta L} \tag{4}$$

where κ is the permeability of the basic structural unit.

If Equation (3) and Equation (4) are compared, the following expression will be obtained,

$$\kappa = \frac{r^4}{8R^2} = \frac{1}{8} r^2 \phi \tag{5}$$

3. The relation of choked flow in a porous medium and the basic structural unit

The gas flow becomes choked when the average pressure gradient ($\frac{dp_{average}}{dx}$) of the porous medium tends to infinite (Jin et al., 2012a). There is a difference between the average pressure gradient of the porous medium and the pressure gradient of the basic structural unit. We investigate the reasons for this below.

3.1. Choked flow in a homogeneous porous medium

A homogeneous porous medium is one with same inner radius of all its basic structural units in this paper. To simplify the analysis, we assume that the number of basic structural units constituting the homogeneous porous medium is N. The radii of the basic structural unit and the porous medium are R and Ra, respectively. It is obvious that$R = \frac{R_a}{\sqrt{N}}$. The pressures$p$ and $p_{average}$ are the average pressures of the basic structural unit and homogeneous porous medium, respectively. The average pressure gradient across the homogeneous porous medium is:

$$\frac{dp_{average}}{dx} = \frac{d\frac{N\pi R^2}{\pi R_a^2}}{dx} = \frac{dp}{dx} \tag{6}$$

Because the average pressure gradient of the basic structural unit in the flow direction increases unbound ($\frac{dp}{dx} \rightarrow -\infty$), the average pressure gradient of a homogeneous porous medium in the flow direction becomes unbound ($\frac{dp_{average}}{dx} \rightarrow -\infty$). Namely, there is no difference between the macroscopic choked flow in the porous medium and the microscopic choked flow in the basic structural unit.

3.2. Choked flow in nonhomogeneous porous media

A nonhomogeneous porous medium in this paper is one with several inner radius ranges of the basic structural unit. In the same