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Mechanism of fluid production from the nanopores of shale

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ABSTRACT

Fluid production from the nanopores of shale is elucidated by an analytical solution of the linearized compressible Navier-Stokes equations with no-slip condition for the pore-scale drainage flow from a small capillary in a matrix block to the surrounding fractures. The pore-scale drainage flow is driven by the volumetric expansion of the compressed fluid and it is always unsteady. It is shown that fluid is produced by the decay of a standing acoustic wave and the no-slip flow has a period-averaged mass flow rate (drainage rate) proportional to the square of the capillary radius which is two orders of magnitude higher than that from the Poiseuille's law. The drainage speed is found proportional to fluid's kinematic viscosity but independent of the capillary radius, allowing the fluid to escape to the fracture with a finite speed regardless how small the capillary is. This result represents a fundamental departure from the classical Poiseuille flow theory and it provides a unified mechanism on how shale fluid is produced.

1. Introduction

In recent years, oil and gas production from shale has dramatically changed the energy landscape of the world. Compared to conventional sandstone and limestone reservoirs, a large percentage of the pores in shale are very small, with diameters in the 10–100 nm range [1–3]. These nano-size pores result in extremely low permeability for the shale matrix, typically in the range of 0.1 microdarcy to a few nanodarcy ($1\ \mathrm{nd} \approx 10^{-21}\mathrm{m}^2$) versus the minidarcy ($1\ \mathrm{md} \approx 10^{-15}\mathrm{m}^2$) range for conventional reservoirs. Recent success in commercial shale production is driven by the technological advances in horizontal well drilling and multistage hydraulic fracturing. A horizontal well exposes the wellbore to a large formation volume while multistage hydraulic fracturing creates a highly interconnected fracture network that breaks the shale formation into small blocks of meter size. Such a small block size significantly reduces the distance fluid has to travel from the matrix block where it is stored to the high conductivity fracture network where it can move with a much greater speed to the wellbore.

Even after hydraulic fracturing, fluid still has to first travel from the ultra-tight nanopores of a matrix block to the surrounding fractures before it can move to the wellbore. Darcy's law [9] predicts that it takes methane over 70 years to migrate just one meter for 100-nanodarcy permeability and a large pressure gradient of 2 kPa per meter. Shale oil production is even more unimaginable due to oil's high viscosity. Reconciling such a dire prediction with the reality of booming shale production has been a huge challenge for the scientific community [4–8]. Recent studies have been focused on gas transport through nano-scale capillaries and these studies are essentially modifications to the Poiseuille's law and Darcy's law. The popular slip theory believes that gas slips in nano-size capillaries and the slippage enhances flow rate [4–5,10–17]. This theory, however, is based on rarefied gas dynamics and the kinetic theory for dilute gas [18–20]; but natural gas is a supercritical fluid with high density in typical shale reservoir conditions (21 MPa and above) [21]. The commonly used classification of slip flow regime for Knudsen number in the range $0.001 < Kn < 0.1$ can be misleading, since slip is *inferred* from measured mass flow rate being higher than that given by Poiseuille flow [11]. As shown by the work reported here and elsewhere [22], compressible Navier-Stokes eqns. can admit solutions with a no-slip velocity but a slip-like mass flow rate higher than that given by Poiseuille flow. Slip may occur for gas in extremely small capillaries less than 10 nm in diameter when the pressure is below 10 MPa [4]. These extremely small pores, however, are associated with the organic matters that store gas in adsorbed phase; and compared to the dominant larger inorganic pores, they hold very little free-gas which is the gas produced in the first year or two. Desorption is a much slower process and there is no evidence suggesting that adsorbed gas has been produced in the first year [7–8]. Furthermore, a recent study shows that these extremely small organic nanopores actually trap oil and gas molecules instead of allowing them to flow [23]. Together, high gas pressure, little free gas stored in the smallest pores and the trapping effect of the organic pores make wall slip highly questionable as the mechanism responsible for the observed high shale gas production rate. Additionally, no theory has been proposed to

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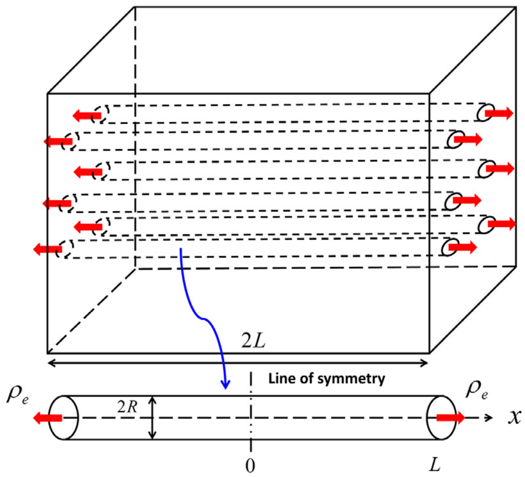

Fig. 1. Symmetric drainage from a capillary tube embedded in a shale matrix block surrounded by fractures. The capillary has an inner radius R and it penetrates through the entire block of length 2 L. The flow is symmetric about $x=0$.

explain why oil can also be produced abundantly from the ultra-tight shale matrix. So far, fluid production from shale has defied explanation from fluid dynamics theory [6].

The single most fundamental problem for shale production is the drainage flow from the meter-size matrix blocks to the surrounding fractures. Such a drainage flow is driven solely by the volumetric expansion of the compressed fluid stored in the nanopores. To explore a unified physical mechanism for both liquid and gas production, here we study the simplest of such a drainage flow at the pore-scale: the volume-expansion-driven drainage flow of a single phase compressible fluid from a small capillary tube embedded in a matrix block with its ends open to the surrounding fractures (Fig. 1). This drainage flow is always unsteady and we solve an initial-boundary-value-problem for this pore-scale drainage flow using the linearized compressible Navier-Stokes equations with no-slip condition without introducing any additional hypothesis. Analytical solution for the density and velocity are obtained explicitly and the mass flow-rate is computed using the analytical solution. The solution reveals a unified physical mechanism on how shale oil and gas are produced from the nanopores of shale.

2. Drainage flow from a capillary tube to the surrounding fractures

A straight capillary embedded in a typical shale matrix block has an inner radius R and length 2 L, with the two ends connected directly to the fractures on the sides of the block (Fig. 1). Pressure-depletion induced deformation of the shale matrix on the fluid production occurs on a time scale comparable to the production time scale of the reservoir. Therefore the shale matrix can be treated as rigid during the early production period. The fluid stored in the tube can be gas or liquid and it is initially at rest with a density ρ_i. The fluid is drained symmetrically from both ends of the tube upon lowering the density at the ends to ρ_e. Fluid in the fractures is maintained at the density ρ_e at all times thereafter. In practice, in order to maintain the mechanical integrity of the matrix block and the adjacent fractures, the exit density (or pressure) is lowered gradually by multiple small steps during production. In each step, the density perturbation can be considered as small and temperature variation is negligible (small Mach number). Since the capillary is small, and the Mach number is also small, nonlinear inertial effect can be neglected [24]. Gravitational effect is negligible. The continuity and the compressible Navier-Stokes equations [25] linearized around the new equilibrium state $(\rho, \mathbf{v})=(\rho_e, 0)$ become [24,26]

$$\frac{\partial \rho'}{\partial t} + \rho_e \nabla \cdot \mathbf{v}' = 0, \tag{1}$$

$$\rho_e \frac{\partial \mathbf{v}'}{\partial t} = -\nabla p' + \left(\mu_b + \frac{1}{3}\mu\right)\nabla(\nabla \cdot \mathbf{v}') + \mu \nabla^2 \mathbf{v}', \tag{2}$$

where the density perturbation $\rho' = \rho - \rho_e$; p' is the pressure perturbation; $\mathbf{v}'$ is the velocity perturbation which is assumed to be axisymmetric; μ, μ_b are the shear and bulk viscosities of the fluid, respectively. Eq. (2) is justified under acoustic scaling and low Mach number assumption. Because the bulk viscosity is proportional to the relaxation times for the internal modes, to consider the case of large bulk viscosity, the molecular relaxation time of the fluid must be allowed to be large, and there is the possibility that the flow may not be in equilibrium. To ensure that the Navier-Stokes equations are valid, we must require the flow to be near equilibrium, which can be characterized by the condition that the characteristic time for the flow being much larger than the characteristic molecular relaxation time. This requirement is referred to as the local thermodynamic equilibrium (LTE) by Graves & Argrow [35]. Using eqn. (30) in Cramer [37], the relaxation time for the vibrational modes for methane at temperature of 300 K and pressure of 1 MPa is about $10^{-7}s$; while the time scale for an acoustic wave in a one-meter block is about $10^{-3}s$. Thus, the local thermodynamic equilibrium condition is satisfied and the use of the Navier-Stokes equations for large bulk viscosity is justified.

Taking the divergence of Eq. (2), using $p'=c^2\rho'$ with c being the constant speed of sound and then eliminating velocity from Eqs. (1) and (2) results in a damped wave equation for the density perturbation

$$\frac{\partial^2 \rho'}{\partial t^2} = \left(c^2 + D_\rho \frac{\partial}{\partial t}\right)\nabla^2 \rho', \tag{3}$$

where the diffusion coefficient $D_\rho = (\mu_b + 4\ \mu/3)/\rho_e$ characterizes the diffusion of a small density disturbance. It must be emphasized that this damped wave equation for the density is exact as long as the linearized continuity and Navier-Stokes Eqs. (1) and (2) hold; and this fundamental equation is well known in the acoustic community (see eqn. (6.4.22), p282 in [24]; eqn. (12) in [27]). Eq. (3) includes the full viscous effect on the density change. At large times, the damped wave Eq. (3) reduces to a diffusion equation [27]. If bulk viscosity is set to zero, as in the Stokes hypothesis, then the density diffusion coefficient for the density disturbance is just the kinematic viscosity of the fluid.

A very important property for the drainage flow is that the only driving force is the volumetric expansion of the compressed fluid. The drainage flow considered is symmetric about $x=0$(Fig. 1). Integrating the continuity Eq. (1) over one-half of the tube gives the mass flow rate at the tube exit as

$$\dot{m}_e(t) = -\int_{Half-tube} \frac{\partial \rho'}{\partial t} dv, \tag{4}$$

where the symmetry line $x=0$ has been used. Eq. (4) gives the instantaneous mass flow rate at each end of the capillary tube; and it shows that the mass flow rate for the drainage flow is completely determined by the density distribution inside the capillary. Since the damped wave Eq. (3) is decoupled from the velocity field, the solution to the appropriate initial-boundary-value-problem for the density will allow us to evaluate the mass flow rate at the tube exit.

Because of the symmetry about $x=0$, only one-half of the tube needs to be considered. The end conditions and the initial conditions for the density perturbations are

$$x=0: \frac{\partial \rho'}{\partial x} = 0; x=L: \rho' = 0, \tag{5}$$