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An advanced analytical solution for pressure build-up during CO_2 injection into infinite saline aquifers: The role of compressibility

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ABSTRACT

Existing analytical or approximate solutions that are appropriate for describing the migration mechanics of CO_2 and the evolution of fluid pressure in reservoirs do not consider the high compressibility of CO_2, which reduces their calculation accuracy and application value. Therefore, this work first derives a new governing equation that represents the movement of complex fluids in reservoirs, based on the equation of continuity and the generalized Darcy's law. A more rigorous definition of the coefficient of compressibility of fluid is then presented, and a power function model (PFM) that characterizes the relationship between the physical properties of CO_2 and the pressure is derived. Meanwhile, to avoid the difficulty of determining the saturation of fluids, a method that directly assumes the average relative permeability of each fluid phase in different fluid domains is proposed, based on the theory of gradual change. An advanced analytical solution is obtained that includes both the partial miscibility and the compressibility of CO_2 and brine in evaluating the evolution of fluid pressure by integrating within different regions. Finally, two typical sample analyses are used to verify the reliability, improved nature and universality of this new analytical solution. Based on the physical characteristics and the results calculated for the examples, this work elaborates the concept and basis of partitioning for use in further work.

1. Introduction

Investigations into the theory of multiphase flow in porous media originated in the exploitation of oil and gas resources. It has been shown by many years of engineering practice that the actual flow that is present during the process of exploitation of oil fields under conditions of saturated vapor pressure or with injection of water is two-phase flow involving oil-gas or oil-water (Kong, 2010). Therefore, the theory of multiphase flow was established gradually beginning in the 1930s. In this area, the most classic analytical solution is the particular solution for two phase flow in one dimension that was solved by Buckley and Leverett (1942), according to the method of characteristics, assuming incompressible and immiscible flow and no capillary pressure. It has been verified by ample practical engineering applications (Blunt and King, 1991; Kong, 2010). The relevant fluids are mainly incompressible or slightly compressible oil, water, natural gas, etc. in the traditional exploitation of oil and gas. They are immiscible and the capillary pressure is also small, so that the assumptions of the above analytical solution are basically appropriate (Kong, 2010).

However, in the most recent twenty years, oil and gas resources have become increasingly depleted, and traditional oil and gas resources and exploitation patterns cannot meet the demand of human development for energy. Therefore, some scholars have proposed a new exploitation method that involves injecting gas (nitrogen) to enhance the recovery efficiency of oil and gas resources (Johns et al., 2002; Taber et al., 1997), and new underground resources of shale gas (Cooper et al., 2016; Golding et al., 2013), condensate gas (Li et al., 2012), etc., have been discovered. Moreover, the demand for CO_2 (the main greenhouse gas causing global warming) storage is becoming increasingly large because of the increasingly deteriorated environment (IPCC, 2005). Many investigations have suggested that CO_2 geological storage is the most effective method of sequestration (Bachu, 2000; Lal, 2008; Michael et al., 2010). Subsequently, the concept and method of exploiting underground resources of oil, gas, geothermal energy, etc. by injecting CO_2 and realizing CO_2 storage at the same time has obtained general support among scholars, considering the economic costs (Alvarado and Manrique, 2010; Damen et al., 2005; Gozalpour et al., 2005; Nagy and Olajossy, 2008; Poordad and Forutan, 2013; Pruess, 2006; Wojnarowski, 2012). Hence, the main fluids are CO_2-brine or CO_2-oil in this new kind of engineering. However, it is not known whether the traditional analytical solutions for multiphase flow are valid because of the particularity of CO_2. Consequently, the physical

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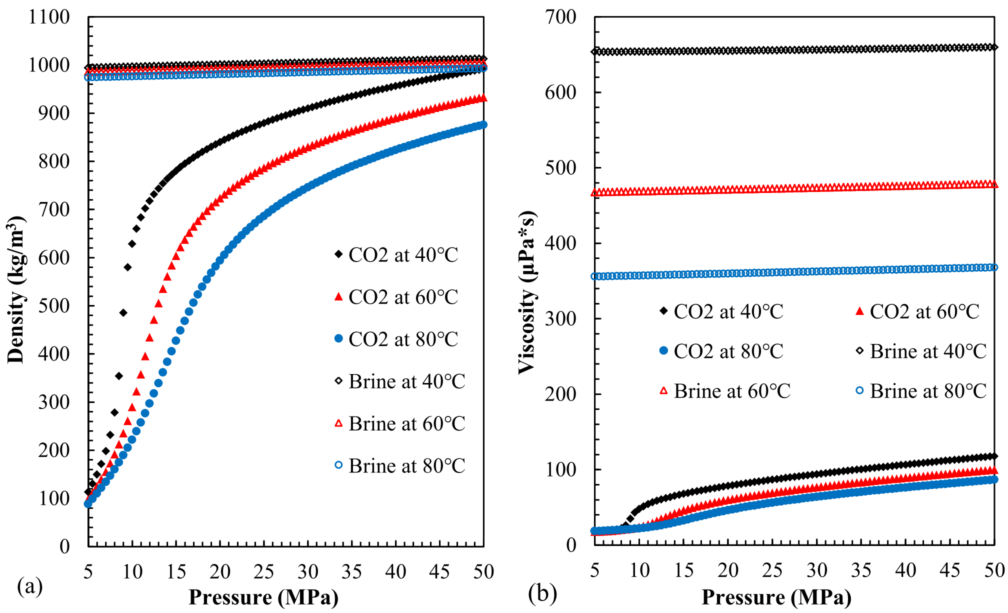

Fig. 1. State curves of the physical properties of CO_2 and brine as a function of pressure ((a): density; (b): viscosity). Data taken from the NIST (National Institute of Standards and Technology, USA) Chemistry WebBook (2016).

properties of CO_2 have been studied in many ways (Fenghour et al., 1998; Span and Wagner, 1996; Vesovic et al., 1990). The results show that the phase diagram of CO_2 is very special, compared with water and other gases. With changes in pressure and temperature, CO_2 can reach a supercritical state, in addition to the conventional three states of gas, liquid, and solid. When the pressure and temperature approach the critical point (7.38 MPa, 31.1 °C), the physical properties of CO_2 are very different (Span and Wagner, 1996). Fig. 1 shows the state curves of the physical properties of CO_2 and brine as a function of pressure ((a): density; (b): viscosity). It is clear that CO_2 has properties including high compressibility, low viscosity and low density compared with water. Therefore, the traditional assumption of an incompressible fluid described above is inappropriate. In addition, CO_2 is also partially miscible in brine (Dilmore et al., 2006; Lu et al., 2008).

Generally, to consider the complicated physical properties of CO_2, scholars prefer to apply numerical methods to explore the migration mechanics of CO_2 plumes and the evolution of fluid pressure in reservoirs (Pruess, 2005; Zyvoloski, 2007). However, the numerical method is very dependent on the availability of a high performance electronic computer, and problems often occur during the solution process. These problems include numerical oscillations, non-convergence and low efficiency. Therefore, sometimes the analytical method reflecting the physical essence of flow may be a better choice (Mathias et al., 2009; Mijic et al., 2014; Wu et al., 2016). In terms of analytical methods, many scholars have done considerable work in the area of CO_2 geological storage (Celia et al., 2015; Mijic et al., 2014). The work of Nordbotten and his research group (Nordbotten and Celia, 2006a,b; Nordbotten et al., 2005a,b) is most representative. They obtained a continuous function that represents the thickness of CO_2 plume based on the principle of energy minimization, and then proposed some semi-analytical solutions and approximate solutions. Subsequently, it was further developed by other scholars (Azizi and Cinar, 2013; Cihan et al., 2013; Mathias et al., 2009; Mathias et al., 2011a; Mathias et al., 2011b; Vilarrasa et al., 2013). Whereas, only the partial miscibility of CO_2 and brine is considered in the above work and it is limited to semi-analytical solutions or approximate solutions (Wu et al., 2016). More recently, Wu et al. (2016) developed an explicit integral solution by directly integrating the governing equation of fluid migration in the reservoir. The process of solution did not involve any numerical method, it is a pure analytical solution that considers the partial miscibility of CO_2 and brine. However, as to the compressibility of fluid, which has a great of impact on the evolution of fluid pressure in the reservoir for the high compressible fluid media, no breakthroughs at all exist in present analytical work. It should be noted that minority scholars (Mijic et al., 2014; Nordbotten and Celia, 2006b; Vilarrasa et al., 2010) presented some iterative algorithms for treating compressibility, although they are separated from the essence of the analytical method. The most pressing problem is that the variation in the density and viscosity of CO_2 under different pressures and temperatures is very considerable; however the appropriate function to characterize this complicated relationship has not yet been derived. Therefore, when considering the compressibility of fluid, the only applicable method to update the parameters of the fluid involves establishing a data base (Pruess, 2005; Zyvoloski, 2007), so that it transforms into a numerical solution method.

To solve the above problem regarding the compressibility of fluid, this work first describes the problem clearly and presents the basic assumptions applied in this article before presenting the following three innovative studies. In Section 3, we derive a new governing equation that describes the movement of complex fluids in reservoirs by combining the equation of continuity, including the compressibility of fluid, with the formulation of Darcy's law generalized to multiphase flows. In Section 4, we define a new coefficient of compressibility using the basic concept of compressibility. The power function model characterizing the relationship between the physical properties of CO_2 and pressure is then deduced. In Section 5, we apply the power function model to the above governing equation and obtain an advanced analytical solution, including the compressibility of fluid, for the evolution of fluid pressure in the reservoir by integrating within different regions. Finally, we analyze two typical examples to verify the reliability, improved nature and universality of this work by comparing the calculated results from this advanced analytical solution with the results of previous analytical solutions and simulated results from TOUGH2/ECO2N.

2. Problem description and basic assumptions

To express the problem clearly and conveniently, this work subsequently takes a two-phase flow involving CO_2-brine as an example to establish an analytical solution for fluid pressure evolution in the reservoir. The corresponding practical projects are mainly CO_2 geological storage and CO_2-enhanced geothermal systems. In these projects, CO_2 is generally injected into the target reservoirs through injection wells at a constant mass injection rate (Bai et al., 2017; Wu et al., 2017). As the reservoirs are completely saturated with brine in their natural state, the