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Transient, thermal wellbore flow of multispecies carbon dioxide mixtures with phase transition during geological storage

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ABSTRACT

A non-isothermal and unsteady wellbore flow model for multispecies mixtures is presented. The model uses a rigorous thermodynamic approach to describe the isothermal flash process for phase transitions, and contains both stability analyses and phase split calculations. For two-phase state flow, the thermodynamic restraint for the pertinent gas and liquid chemical potential of each species is strictly met. This process is fully coupled with the relevant flow equations. Two examples of applications of the model are presented: a practical field trial case study and a theoretical problem. In the first example, the simulations agree reasonably well with measurements from the field case study, demonstrating that the modelling approach can characterise the unsteady dynamic process observed. In the second example, we demonstrate that the model can handle multispecies carbon dioxide flow with complicated phase transition processes.

1. Introduction

Geological storage of carbon dioxide (CO_2) is an important greenhouse gas reduction strategy. Wells are used to inject CO_2 into geological reservoirs, which may be at depths of several thousand metres. The reservoirs are therefore under significant fluid pressure due to the weight of the fluid in the overlying geology. To overcome this, the CO_2 pressure at the bottom of the injection well must exceed the reservoir pressure. The CO_2 is therefore compressed at the surface and then pumped into the injection well. At high pressures, CO_2 is relatively dense, and its weight can significantly contribute to the well's bottomhole pressure. However, as the CO_2 flows into the well, it exchanges heat with the surrounding geology and may undergo phase transitions. Therefore, flow scenarios in the well can be highly variable, leading to distinct pressure and temperature profiles that change with depth.

The flow of CO_2 in wellbores was first investigated for oil and gas problems: in particular, for improved oil recovery (Cronshaw and Bolling, 1982). The authors adopted a simplified flow model based on an approximate thermodynamic treatment. Recently, Lu and Connell (2008), Sasaki et al. (2009), Wiese et al. (2010), Bissell et al. (2011), and Lindeberg (2011) have further studied the wellbore flow of pure CO_2, or its mixtures, for geological storage. These studies take theoretical and numerical modifications into consideration. However, they are based on steady or quasi-steady flow models, which partly or fully neglect the effects of the storage and inertial terms in the flow equations. While the steady flow model is a good approximation for wellbore flow behaviour over time scales of months to years, it is inappropriate when the flow is in a significantly unsteady state (Paterson et al., 2010). A typical example is early time injection/production, in which the characteristic time scale is in hours or minutes. In this case, injection pressure and temperature may vary considerably with time. The injection rate may also change dramatically, leading to transient flow scenarios within the well. Pan et al. (2011) have recently developed a transient, coupled wellbore-reservoir flow model for simulating the dynamics of CO_2 injection and leakage through wellbores. However, this model is mechanistic and does not take into account thermal effects and phase transition during the flow process.

Transient thermal flow situations associated with CO_2 or its mixtures in wells have also been investigated recently. For example, Paterson et al. (2008) studied the transient CO_2 blowout phenomenon, in which CO_2 is rapidly released from a well, with the Joule–Thomson effect leading to the formation of dry ice particles. Munkejord et al. (2010) considered two-phase transient flow for multicomponent CO_2 mixtures, and studied the rapid depressurisation process of CO_2 mixtures in pipelines. However, neither of these models was aimed at the unsteady flow process that occurs during injection, but instead focused on transient flow

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over extremely short times, such as one second or a fraction of a second. For such transient flow phenomenon, a model's numerical scheme needs to take into account the hyperbolic attributes of flow equations, such as the characteristics of the wave propagation. Consequently, the computational time stepsize used, which is limited by the Courant–Friedrichs–Lewy condition, is approximately in the order of 10^{-3}–10^{-4} s. This would not be a practical approach for longer transient problems that we are currently concerned with.

In this paper, we propose a novel modelling scheme to deal with transient CO_2 wellbore hydraulics during geological storage. Our model can correctly represent the major flow characteristics involved in this flow process, and the scheme is computationally efficient. In particular, our model rigorously follows the thermodynamic principle for the isothermal flash process. The model contains both stability analyses (e.g. Baker et al., 1982; Michelsen, 1982a; Harding and Floudas, 2000) and phase split calculations (e.g. Michelsen, 1982b; Ammar and Renon, 1987; Henderson et al., 2001). When the fluid is in a two-phase state flow, the equilibrium of the relevant gas and liquid chemical potential is also rigorously followed for each phase. This process is fully coupled with the relevant flow equations.

Two example applications are presented in Section 4. One application is from a field trial in which CO_2 was injected into a 560-m-deep coal seam for enhanced coalbed methane recovery (ECBM) (Connell et al., 2011). The other is a physically meaningful theoretical problem. We use this example to further justify the capability of the proposed model and scheme in handling CO_2 wellbore flow in the presence of other minor gas species when phase transitions occur.

2. Model formulation

2.1. Well flow scenarios and basic model assumptions

The flow scenario for a single-phase fluid flow in a well is simple. However, when a gas–liquid two-phase fluid flows in a vertical or inclined wellbore, the flow scenario could be very complicated in reality. This is because the gas and liquid of the fluid may flow at different velocities and different flow patterns may be formed (e.g. Hasan and Kabir, 1992, 2002; de Henau and Baithby, 1995; Satitchaicharoen and Wongwises, 2004; Dyment and Boudlal, 2004; Lips and Meyer, 2011; Morales-Ruiz et al., 2012). Typical flow patterns for this situation include bubble flow (e.g. Zuber and Findlay, 1965; Hasan and Kabir, 1988), slug flow (e.g. Woods et al., 2000; Malekzadeh et al., 2012), churn flow (e.g. Hasan and Kabir, 1992) and annular flow (e.g. Weisman and Kang, 1981; Barnea et al., 1985). Several models have been developed for interpreting these flow scenarios, including various drift-flux models that have been widely employed in the petroleum industry (e.g. Zuber and Findlay, 1965; Hasan and Kabir, 1988; Hasan and Kabir, 2002; Ouyang and Aziz, 1999; Ouyang and Aziz, 2001; Shi et al., 2005). The concepts and approaches of these models can be extended and incorporated into the presented model where the thermal effect and phase transition critically influence the flow profiles. In doing so, several model approximations and assumptions are first made as follows. (1) The flow concerned is chemically nonreactive. (2) The velocity of the condensed fluid in wells is significantly lower than the propagation speed of the perturbation (sonic wave) in the fluid. This assumption can be justified in practice, as the typical velocity of injecting fluid is normally in the order of metres per second, while its sonic counterpart is in the range of several hundred metres per second. Hence, the characteristics of the flow in relation to the propagation of wave perturbations are not concerned. (3) Conventional irreversible thermodynamics (Meixner and Reik, 1959; De Groot and Mazur, 1962) applies. In other words, a local thermodynamic equilibrium can be effectively established, and consequently, the time-dependent thermodynamic process (including phase transition) can be described by the relevant relationships derived from the theory of equilibrium thermodynamics (Bataille and Kestin, 1977; Bilicki et al., 2002). (4) The potential non-equilibrium relaxation effects (e.g. Downar-Zapolski et al., 1996) in an unsteady flow process are ignored.

2.2. Mass, momentum, and energy balance equations

In this sub-section, the wellbore flow equations are derived from a general form for two-phase flow, and the single phase (i.e. the pure gas phase or liquid phase) flow is a specific case. As addressed in the last sub-section, in a two-phase flow there are generally two distinct velocities involved; one is for the gas phase and the other for the liquid phase. We denote the pertinent (in situ) gas and liquid velocity as v_G and v_L, respectively. Thus, for a mixture with Nc-species, the relevant mass, momentum, and energy balance equations can be derived following the approaches presented in the literature (e.g., Yadigaroglu and Lahcy, 1976; Allen et al., 1988; Munkejord et al., 2010). These flow equations, plus the supplementary relations such as the drift flux model, the equation of state (EoS), and the thermodynamic restrains given in Section 2.3, consist of a closed set of equations for a set of $(4 + N_C)$-argument described by the mean velocity (v_m), the density of mixture (ρ_m), pressure (p), temperature (T), and the total liquid mole fraction (λ) in the mixture, as well as $(N_C - 1)$ mole fractions of N_C-species, denoted respectively by y_i ($i = 1, 2, \ldots, N_C - 1$), in the gas phase of the mixture.

2.2.1. Mass balance equations

$$\frac{\partial}{\partial t}(\alpha_i \rho_m) + \frac{\partial}{\partial z}(\alpha_i^G f_G \rho_G v_G + \alpha_i^L f_L \rho_L v_L) = 0, \quad (i = 1, 2, \ldots, N_C). \tag{1}$$

Here, t is time and z denotes the one-dimensional coordinate along the length or depth of the well where the inlet is set to be the origin; α_i is the mass fraction of species-i; α_i^G and α_i^L are its mass fraction in gas and liquid phase, respectively; the density of mixture ρ_m relates to the gas phase density (ρ_G) and the liquid phase density (ρ_L) by

$$\rho_m = f_L \rho_L + f_G \rho_G, \tag{2}$$

where f_G and f_L are the gas and liquid volume fraction, respectively. Obviously, one has $f_G + f_L = 1$ and $\sum_i^{N_C} \alpha_i = \sum_i^{N_C} \alpha_i^G = \sum_i^{N_C} \alpha_i^L = 1$.

Summation over all the N_C species in Eq. (1) gives the total mass balance equation, which is

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \rho_m v_m}{\partial z} = 0. \tag{3}$$

Here, v_m is the mass-weighted *mean velocity* of the mixture (e.g., Yadigaroglu and Lahcy, 1976; Allen et al., 1988) defined by

$$v_m = (f_G \rho_G v_G + f_L \rho_L v_L)/\rho_m. \tag{4}$$

It is noted that the total mass balance equation (3), when using the mass-weighted mean velocity, is of exactly the same form for the homogeneous model without the slip effect.

2.2.2. Momentum balance equation

$$\frac{\partial}{\partial t}(f_G \rho_G v_G + f_L \rho_L v_L) + \frac{\partial}{\partial z}(f_L \rho_L v_L^2 + f_G \rho_G v_G^2 + p)$$
$$= -f_W + (f_G \rho_G + f_L \rho_G) g \sin\theta. \tag{5}$$