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Coupled calculation model for transient temperature and pressure of carbon dioxide injection well

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ABSTRACT

Based on the law of thermodynamics, this study establishes a numerical calculation model for the temperature and pressure of a carbon dioxide (CO_2) injection well. Our model assumes that the well structure has a three-layer casing completion, and that the heat generated by the fluid friction losses is absorbed by the CO_2 and tubing according to a contact coefficient. The heat transfer in the wellbore and formation is considered to be transient, and the model is solved using a fully implicit finite difference method. The results of numerical experiments show that the CO_2 pressure and temperature are significantly affected by the injection rate, injection temperature, and tubing roughness. Therefore, it should be possible for engineers to adjust the injection temperature or injection rate to ensure that the CO_2 reaches the supercritical state at the downhole. Although the Joule–Thomson effect and frictional heat proportional absorption effect also influence the CO_2 pressure and temperature, they can be neglected at the engineering scale.

1. Introduction

Carbon dioxide (CO_2) is widely used in the field of fossil energy exploitation for enhanced oil recovery [1] and enhanced coalbed methane recovery [2–4], and supercritical carbon dioxide is a promising operating fluid in drilling and fracturing technologies [5–13]. Many such applications involve CO_2 flowing through the wellbore and heat transfer in and around the wellbore. Therefore, there is a significant benefit to establishing a temperature and pressure prediction model for CO_2 injection wells.

At present, the methods used to study the heat transfer of CO_2 flow in a tube are generally experimental [14–18] or mathematical [5,6,12,19,20]. Although experimental methods can directly measure many heat transfer parameters (CO_2 and tube wall temperature, heat transfer coefficient, etc.), they still have many limitations, such as the dimensional effect, and experimental equipment cannot fully reflect the formation within a wellbore. Fortunately, mathematical methods can compensate for these limitations. The first temperature prediction model for drilling processes was established by Raymond [21]. Inspired by this model, researchers have successively developed wellbore temperature and pressure prediction models [22–25]. Although these models consider the fluid to be water rather than CO_2, they provide the basis for a temperature and pressure field prediction model for CO_2 injection wells.

Wang et al. [6] developed a coupled model for calculating the wellbore temperature and pressure during drilling with supercritical CO_2. The physical CO_2 parameters were calculated using the Span–Wagner equation, and the heat transfer in the wellbore was assumed to be steady while that around the wellbore was unsteady. This assumption is reasonable for long-term injection wells, particularly as the thermal resistance of the casing and tubing was neglected. Dou et al. [19] established a simple wellbore pressure and temperature prediction model for CO_2 injection wells using the model assumptions and basic equations from Wang's model. Motivated by Wang's model, Song et al. [5] established a wellbore pressure and temperature calculation model for managed pressure drilling with supercritical CO_2. Unlike Wang's model, they also considered the influence of the casing and tubing thermal resistance on heat transfer.

The models described above are suitable for simulating the long-term injection of CO_2. However, for short-term injection conditions such as fracturing, the unsteady heat transfer process in the wellbore is not negligible. Therefore, Guo and Zeng [12] established a transient temperature and pressure coupling model for supercritical CO_2 fracturing, and predicted the physical CO_2

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parameters using the REFROP software. However, their model neglects axial heat conduction in the annulus, and is only suitable for single-casing well completion conditions. In real-life situations, multi-layer casing completion is applied to ensure the security of the wells. Additionally, current models assume that the heat generated by fluid friction is only absorbed by the fluid; however, it is more reasonable to assume that the friction heat is absorbed by both the fluid and the tubing.

Inspired by previous studies and aware of their limitations, this research develops a coupled model for the transient temperature and pressure of CO_2 injection wells. Our model considers a three-layer casing completion structure, and calculates the physical CO_2 parameters using the Span–Wagner and Vesovic equations. The heat generated by fluid friction is absorbed by both the CO_2 and tubing according to a contact coefficient.

2. Physical model

The physical model of a CO_2 injection well is illustrated in Fig. 1. The process of CO_2 injection is as follows: (1) Before injection, the wellbore is full of CO_2 and reaches a temperature balance with the formation; (2) CO_2 is injected to the downhole through the tubing, and the fluid in the annulus remains stationary; (3) The heat transfers in the wellbore and formation are both transient; (4) The CO_2 temperature, pressure, and flow velocity remain constant in the same section of tubing.

3. Mathematical model

3.1. Pressure calculation model

Based on the continuity equation and flow equation, the pressure control equation for CO_2 flowing in the tubing can be written as follows:

$$\frac{dp_1}{dz} = \rho_1 g \sin\theta - f\frac{\rho_1 v_1^2}{4r_1} - \rho_1 v_1 \frac{dv_1}{dz}, \tag{1}$$

where [26]

$$f = 8\left\{(8/Re)^{12} + \left[\left(2.457\ln\left[(7/Re)^{0.9} + \frac{0.27\Delta}{2r_1}\right]\right)^{16} + (37530/Re)^{16}\right]^{-3/2}\right\}^{1/12} \tag{2}$$

In Eqs. (1) and (2), r_1 is the inner radius of the tubing; ρ_1 is the CO_2 density; v_1 is the CO_2 volume flow velocity; Re is the Reynolds number; and Δ is the absolute roughness of the tubing.

3.2. Heat transfer model

(1) Transient heat transfer inside the tubing

According to the first law of thermodynamics, and considering the Joule–Thomson effect, the equation of heat transfer within tubing can be described as [12]

$$\frac{Q_1}{\pi r_1^2} - \rho_1 v_1 c_1 \frac{\partial T_1}{\partial z} + \alpha_J \rho_1 v_1 c_1 \frac{\partial p_1}{\partial z} + \frac{2h_1(T_2 - T_1)}{r_1} = \rho_1 c_1 \frac{\partial T_1}{\partial t} - \alpha_J v_1 c_1 \frac{\partial p_1}{\partial t}, \tag{3}$$

where

$$h_1 = \frac{0.027\lambda_1 Re^{0.8} Pr^m}{2r_1}, \tag{4}$$

$$Q_1 = Q\frac{b}{1+b}, \tag{5}$$

$$Q = q\Delta p_f, \tag{6}$$

and [27]

$$b = \sqrt{\frac{\lambda_1 \rho_1 c_1}{\lambda_2 \rho_2 c_2}}, \tag{7}$$

where c_1 and c_2 are the heat capacities of CO_2 and the tubing, respectively; T_1 and T_2 are the temperatures of CO_2 and the tubing, respectively; λ_1 and λ_2 are the thermal conductivities of CO_2 and the tubing, respectively; α_J is the Joule–Thomson coefficient; h_1 is the convection coefficient inside the tubing; Pr is the Prandtl number; ρ_2 is the density of tubing; Q is the total energy produced by the fluid friction losses of a unit length of tubing; Q_1 is the proportion of Q absorbed by the CO_2; q is the flow rate inside the tubing; and Δp_f is the gradient of the friction pressure drop.

(2) Heat transfer in the tubing

According to the law of conservation of energy, the energy balance in the tubing can be described as follows:

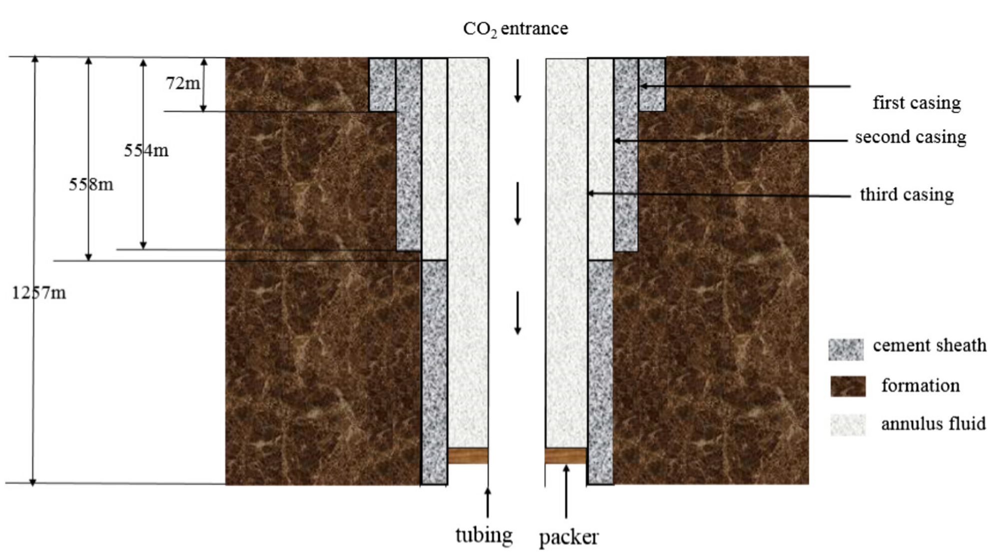

Fig. 1. Physical model of CO_2 injection well.