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Coupling model for calculation of transient temperature and pressure during coiled tubing drilling with supercritical carbon dioxide

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ABSTRACT

Based on thermodynamics, heat transfer mechanisms, and fluid mechanics, a transient temperature and pressure coupling calculation model for supercritical carbon dioxide coiled tubing drilling is established in this study. In this model, the Joule-Thomson effect is considered, the CO_2 physical properties are varied with the temperature and pressure, and the heat transfer in the wellbore and formation are both considered unsteady. The model is solved using the fully implicit finite difference method. The results show that the wellbore CO_2 temperatures predicted by Gupta's model and Wang's model are both lower than that of the proposed model. The primary reason for this discrepancy is that the previous models considered the heat transfer in the wellbore as a steady state and ignored friction heat. In the shallower and deeper sections of the well, the wellbore temperature changes rapidly with the depth, whereas in the middle section of well, the wellbore temperature increases linearly with increasing depth. The wellbore temperature changes with circulation time, but the wellbore pressure is unaffected by the circulation time. The injection rate and nozzle diameter both have a significant effect on the downhole temperature and tubing pressure, and an injection rate that is too larger or a nozzle diameter that is too small may lead to CO_2 that cannot exist in a supercritical state.

1. Introduction

Supercritical carbon dioxide (SC-CO_2) drilling is a novel drilling technique that uses the SC-CO_2 as a drilling fluid [1]. SC-CO_2 has many unique physicochemical properties; its very low viscosity and diffusivity are close to those of the gas, and it has a high density that is close to that of the liquid [2]. Compared to conventional drilling technology, using SC-CO_2 as a drilling fluid provides the following advantages: (1) SC-CO_2 cuts rock at a much lower pressure than water [3–6], which can improve drilling speed; (2) it does not cause damage to the reservoir even if CO_2 incursion occurs; (3) using CO_2 as a drilling fluid complies with global environmental policy and can reduce greenhouse gas emissions [7].

CO_2 can only become a supercritical fluid when the temperature and pressure are both higher than their critical values (T_c = 30.98 °C and P_c = 7.38 MPa) [8–10]. However, the heat transfer process and pressure variations during SC-CO_2 drilling are complex. As CO_2 flows through the nozzle, it causes a significant drop in pressure and temperature [11], and thus, the CO_2 may not reach a supercritical state at the downhole when the pressure drop and temperature are too high. Therefore, it is important to accurately predict the temperature and pressure of the CO_2 during SC-CO_2 drilling.

Some temperature and pressure prediction models for the drilling process have been developed [12–14], but the drilling fluid in these models is water rather than CO_2. Because CO_2 is a compressible fluid, its physical properties are greatly affected by temperature and pressure. Therefore, it is necessary to establish a temperature and pressure computational model for SC-CO_2 drilling. At present, there have been few studies of temperature prediction models for SC-CO_2 drilling. Gupta [5] established a temperature and pressure calculation model to study the feasibility of SC-CO_2 drilling. However, that model assumed that the CO_2 physical parameters (thermal conductivity, viscosity, etc.) were constant and ignored the Joule-Thomson effect. Wang et al. [15] developed a wellbore temperature and pressure calculation model for SC-CO_2 drilling that took the Joule-Thomson effect into account. In their model, the CO_2 physical parameters are varied with temperature and pressure. Subsequently [1], consideration of the formation water influx into the annulus led to the establishment of

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Nomenclature

A	nozzle cross-section area, m^2
c_1	heat capacity of CO_2 inside the coiled tubing, J/(kg K)
c_2	heat capacity of coiled tubing, J/(kg K)
c_3	heat capacity of CO_2 in the annulus, J/(kg K)
c_4	casing heat capacity, J/(kg K)
c_p	isobaric heat capacity, J/(kg K)
c_v	volumetric heat capacity, J/(kg K)
G_f	geothermal gradient, K/m
h_1	convection coefficient inside the coiled tubing, W/(m^2 K)
h_2	convection coefficient outside the coiled tubing, W/(m^2 K)
h_3	convection coefficient inside the casing, W/(m^2 K)
K	isentropic index, dimensionless
Nu	Nusselt number, dimensionless
p_u	CO_2 pressure at nozzle upstream, Pa
p_d	CO_2 pressure at nozzle downstream, Pa
Pr	Prandtl number, dimensionless
q_1	CO_2 flow rate inside the coiled tubing, m^3/s
q_m	CO_2 mass flow rate, kg/s
Q_1	energy produced by the fluid friction losses of unit length coiled tubing, W/m
Q_2	energy produced by the fluid friction losses per unit length of annulus, W/m
r_1	coiled tubing inner radius, m
r_2	coiled tubing outer radius, m
r_3	casing inner radius, m
r_4	casing outer radius, m
r_5	cement sheath outer radius, m
R_c	gas constant, 0.1889 kJ/(kg K)
Re	Reynolds number, dimensionless
T_1	temperature of CO_2 inside the coiled tubing, K
T_2	coiled tubing temperature, K
T_3	temperature of CO_2 in the annulus, K
T_4	casing temperature, K
T_s	surface temperature, K
T_u	CO_2 temperature at nozzle upstream, K
T_d	CO_2 temperature at nozzle downstream, K
v_1	CO_2 flow velocity in the coiled tubing, m/s
v_3	CO_2 flow velocity in the annulus, m/s
ω	iteration factor, dimensionless
ρ_1	CO_2 density in the coiled tubing, kg/m^3
ρ_2	density of coiled tubing, kg/m^3
ρ_3	CO_2 density in the annulus, kg/m^3
ρ_4	casing density, kg/m^3
δ	reduced density, dimensionless
τ	inverse reduced temperature, dimensionless
α_J	Joule-Thomson coefficient, K/Pa
φ_o	ideal part of Helmholtz energy, dimensionless
φ_r	residual part of Helmholtz energy, dimensionless
μ_0	viscosity at the zero-density limit, Pa s
Δ_1	coiled tubing absolute roughness, m
Δ_3	casing absolute roughness, m
λ_0	thermal conductivity at the zero-density limit, W/(m K)
λ_1	thermal conductivity of CO_2 inside the coiled tubing, W/(m K)
λ_2	thermal conductivity of coiled tubing, W/(m K)
λ_3	thermal conductivity of CO_2 in the annulus, W/(m K)
λ_4	thermal conductivity of casing, W/(m K)
λ_5	thermal conductivity of cement sheath, W/(m K)
$\Delta\mu$	excess viscosity, Pa s
$\Delta\lambda$	excess thermal conductivity, W/(m K)
$\Delta_c\mu$	enhancements of viscosity, Pa s
$\Delta_c\lambda$	enhancements of thermal conductivity, W/(m K)

a wellbore flow model for coiled tubing drilling. However, the effects of the casing and drill pipe thermal resistance on heat transfer were not considered [1,15]. Ni et al. [16] built on this by considering the effect of the casing and tubing thermal resistance on heat transfer to establish a coupling model to investigate the fluid flow and heat transfer during SC-CO_2 coiled tubing drilling. Song et al. [17] also accounted for the effect of the casing and tubing thermal resistance on heat transfer and developed a temperature and pressure coupling calculation model for SC-CO_2 pressure controlling drilling. Although previous studies [1,15–17] have preliminarily determined the variation in CO_2 temperature and pressure from the construction parameters, all of these studies have assumed that the heat transfer in both the wellbore and the formation are steady. In addition, the current models all ignore the heat generated by fluid friction.

Building on these previous studies and aware of the possible limitations, a full transient pressure and temperature coupling calculation model for SC-CO_2 coiled tubing drilling is proposed in this study. In the proposed model, the influence of the casing and tubing thermal resistance on heat transfer is considered, and the CO_2 physical properties are varied with temperature and pressure. In addition, the heat transfer in the wellbore and formation are both treated as unsteady. Finally, the model simulation results of a case study were analyzed and compared with results of previous studies to verify the reliability of the model.

2. Physical model

A schematic of coiled tubing drilling with SC-CO_2 is shown in Fig. 1. The specific operation process is as follows: (1) the liquid CO_2 flows out of the tanker, pressurized with a triple plunger pump, and then flows into the coiled tubing; (2) high pressure CO_2 flows from the wellhead to the downhole through the coiled tubing; (3) CO_2 is ejected from the nozzle on a drilling bit, which improves drilling speed; and (4) CO_2 flowing through the nozzle results in a drop in pressure and temperature, and the CO_2 flows back to the ground along the annulus.

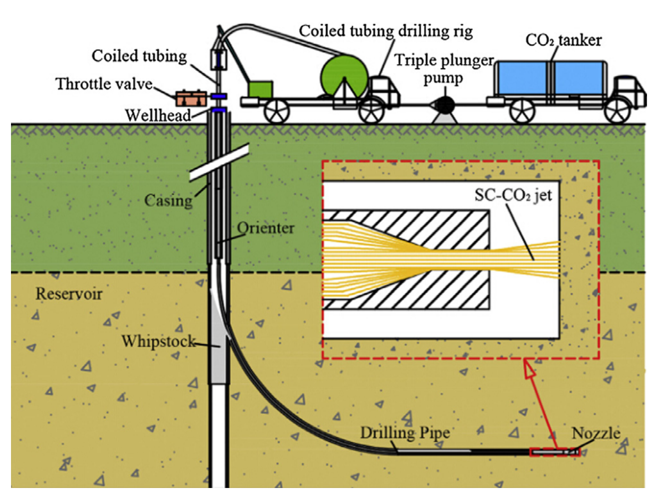

Fig. 1. Schematic of coiled tubing drilling with SC-CO_2 [18].