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RESEARCH PAPER

Pressure controlling method for managed pressure drilling with supercritical carbon dioxide as the circulation fluid

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Abstract: Heat transfer along the wellbore was analyzed, and then a closed mathematical model, which fully couples the hydrostatic pressure, temperature, physical properties of CO_2 and friction, was established to keep bottom-hole pressure constant during drilling process. Based on the pressure profile in wellbore achieved for a certain surface back pressure, a pressure controlling method for managed pressure drilling with supercritical carbon dioxide was presented. The influences of mass flow rate, well depth and inlet temperature on the annulus pressure profile and surface back pressure were investigated. The results show that, the pressure profile is almost in linear correlation with well depth in the annulus, which provides convenience for well control. The needed back pressure (applied by surface choke) decreases with increasing mass flow rate and decreasing well depth. The impact of inlet temperature on the annulus pressure profile, surface back pressure and flow friction is negligible. It also shows that the density of CO_2 increases significantly and abruptly at a critical pressure. It is suggested that the storage pressure of CO_2 in surface tank be larger than the critical pressure for a certain temperature.

Key words: supercritical carbon dioxide drilling; managed pressure drilling; wellbore heat transfer; annulus pressure; surface back pressure

Introduction

Carbon dioxide (CO_2) has been used as a drilling fluid to get higher rate of penetration (ROP) and enhanced oil recovery (EOR) since the beginning of the 21st century[1–4]. As an effective means to develop hard-producing reservoirs, it has a broad application prospect[5–7]. The combination of supercritical CO_2 drilling and managed pressure drilling can increase its adaptability in pressure sensitive formations[8–9], and avoid downhole complexities like wellbore collapse and circulation loss etc[9–10]. The constant bottom-hole pressure (CBHP) drilling is a kind of managed pressure drilling (MPD) which realizes constant pressure management through applying backpressure at the outlet of the annulus[11], and its main feature is that it can work with low density drilling fluid to realize underbalanced fast drilling[12–14].

For MPD with CO_2, the CBHP control mechanism is obviously the most crucial point, which has not been reported until now. Wang Ruihe et al[15] established a CO_2 wellbore heat transfer model, Wang Z Y et al[16] analyzed the variation pattern of wellbore phase distribution, Ni H J et al[17] built a wellbore CO_2 circulation flow model. All these research results provide references for the study on supercritical CO_2 managed-pressure drilling.

Heat transfer along the wellbore was firstly modelled in this study, and then in the hydraulics calculations, we developed a closed mathematical model to fully couple the hydrostatic pressure, temperature, physical properties of CO_2 (density, viscosity, thermal capacity and conductivity) and friction of both cemented and uncemented well section. Thirdly, pressure management method was studied, and the effect of flow rate, well depth, injection temperature on wellhead backpressure and annulus pressure profile were examined, to provide theoretical support for supercritical CO_2.managed-pressure drilling.

1. Mathematical model

Assumptions include that: (1) the geothermal gradient is constant as well depth increases; (2) the influence of cuttings on heat transfer in annulus is negligible because of their low volume fraction; (3) the temperature of formation rock, more than 5 m away from the wellbore axis, is assumed constant.

During supercritical CO_2 drilling, hypothermic liquid CO_2

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is pumped from surface tank to bottom hole through tubing, and then it is jetted into annulus. SBP, applied by wellhead choke, helps to control the state of CO_2 and its physical properties[1, 3]. In the circulation, heat transfers from formation rock to CO_2 in the annulus and then to CO_2 in the tubing. Both heat conduction and thermal convection are involved in the heat transfer.

1.1. Physical properties of CO_2

When the down-hole temperature is above 304.2 K and pressure is higher than 7.38 MPa, CO_2 will enter into super-critical state (Span and Wagner, 1996; Wang and Ni, 2013). Physical property of CO_2 changes with pressure and temperature, which will influence hydrostatic pressure, flow friction and heat transfer further more.

Span and Wagner[18] presented implicit equations for CO_2 density and isobaric heat capacity, which are cited by National Institute of Standards and Technology (NIST) and are most accurate by far. The density calculation formula is:

$$p(\delta,\tau)=\rho RT\left[1+\delta\frac{\partial\Phi_{\mathrm{r}}(\delta,\tau)}{\partial\delta}\right] \tag{1}$$

where $\delta=\rho/\rho_{\mathrm{c}}$ $\tau=T_{\mathrm{c}}/T$

The equation for isobaric heat capacity of CO_2 is given by,

$$\frac{MC_p}{R}=\frac{\left(1+\delta\frac{\partial\Phi_{\mathrm{r}}}{\partial\delta}-\delta\tau\frac{\partial^2\Phi_{\mathrm{r}}}{\partial\delta\partial\tau}\right)^2}{1+2\delta\frac{\partial\Phi_{\mathrm{r}}}{\partial\delta}+\delta^2\frac{\partial^2\Phi_{\mathrm{r}}}{\partial\delta^2}}-\tau^2\left(\frac{\partial^2\Phi_{\mathrm{o}}}{\partial\tau^2}+\frac{\partial^2\Phi_{\mathrm{r}}}{\partial\tau^2}\right) \tag{2}$$

Based on Vesovic and Wakeham model[19], Fenghour and Wakeham[20] presented modified equations for viscosity and thermal conductivity of CO_2 to get enhanced accuracy. The viscosity calculation formula is:

$$\eta(T,\rho)=\eta_0+\Delta\eta(T,\rho)+\Delta\eta_{\mathrm{c}}(T,\rho) \tag{3}$$

where the zero-density viscosity η_0 is calculated by

$$\eta_0=\frac{1.006\,97\sqrt{T}}{G_\eta^*(T^*)} \tag{4}$$

where $\ln G_\eta^*(T^*)=\sum_{j=0}^{4}(a_j\ln T^*)^j$ $T^*=T/251.196$

In equation (3), the excess viscosity considering the effect of temperature is calculated by the following formula:

$$\Delta\eta(T,\rho)=d_{11}\rho+d_{21}\rho^2+\frac{d_{64}\rho^6}{T^{*3}}+d_{81}\rho^8+\frac{d_{82}\rho^8}{T^*} \tag{5}$$

Similar to the viscosity, the thermal conductivity of CO_2 is expressed as

$$\lambda(T,\rho)=\lambda_0+\Delta\lambda(T,\rho)+\Delta\lambda_{\mathrm{c}}(T,\rho) \tag{6}$$

1.2. Mathematical model of heat transfer

Heat conduction and convention are both involved in heat transfer process, and the geothermal gradient is assumed to be constant. The temperature change of CO_2 is calculated by

$$Q_{\mathrm{sa}}-Q_{\mathrm{ap}}=C_{\mathrm{p}}m_{\mathrm{t}}\Delta T_{\mathrm{a}} \tag{7}$$

$$Q_{\mathrm{ap}}=C_{\mathrm{p}}m_{\mathrm{t}}\Delta T_{\mathrm{p}} \tag{8}$$

The temperature of formation rock can be calculated based on geothermal gradient. The thermal conductivity between constant temperature formation rock and casing (or wellbore surrounding rock) can be calculated by

$$Q_{\mathrm{es}}=\frac{T_{\mathrm{e}}-T_{\mathrm{s}}}{\frac{1}{2\pi\lambda_{\mathrm{ca}}l}\ln\frac{r_{\mathrm{a2}}}{r_{\mathrm{a1}}}+\frac{1}{2\pi\lambda_{\mathrm{ce}}l}\ln\frac{r_{\mathrm{s}}}{r_{\mathrm{a2}}}+\frac{1}{2\pi\lambda_{\mathrm{t}}l}\ln\frac{r_{\mathrm{e}}}{r_{\mathrm{s}}}} \tag{9}$$

Obviously, casing, cement sheath and rock are all involved in equation 9. When it comes to uncemented wellbore, equation 10 can be simplified as

$$Q_{\mathrm{es}}=\frac{T_{\mathrm{e}}-T_{\mathrm{s}}}{\frac{1}{2\pi\lambda_{\mathrm{t}}l}\ln\frac{r_{\mathrm{e}}}{r_{\mathrm{s}}}} \tag{10}$$

Convection dominates the heat transfer between casing (or wellbore surrounding rock) and CO2 in the annulus, and it is expressed as

$$Q_{\mathrm{sa}}=\frac{T_{\mathrm{s}}-T_{\mathrm{a}}}{\frac{1}{2\pi h_{\mathrm{s}}r_{\mathrm{s}}l}} \tag{11}$$

Both conductivity and convection are involved in the heat transfer between CO_2 in the annulus and tubing,

$$Q_{\mathrm{ap}}=\frac{T_{\mathrm{a}}-T_{\mathrm{p}}}{\frac{1}{\pi h_{\mathrm{i}}d_{\mathrm{i}}l}+\frac{1}{2\pi\lambda_{\mathrm{t}}l}\ln\frac{d_{\mathrm{o}}}{d_{\mathrm{i}}}+\frac{1}{\pi h_{\mathrm{o}}d_{\mathrm{o}}l}} \tag{12}$$

The throttle effect of bit jet is taken into consideration, and the pressure drop and temperature drop are expressed as,

$$m_{\mathrm{t}}=Ap_2\sqrt{\frac{2\kappa}{R_{\mathrm{s}}T_1(\kappa-1)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}}-\left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}}\right]} \tag{13}$$

$$\Delta T_{\mathrm{j}}=-\int_{p_1}^{p_2}\mu_{\mathrm{JT}}\mathrm{d}p \tag{14}$$

where $\mu_{\mathrm{JT}}=\frac{1}{C_{\mathrm{p}}}\left(T\frac{\partial V}{\partial T}-V\right)$

1.3. Control equations of wellbore flow

Based on Eulerian method, the control equations include continuity equation, momentum equation and energy equation. The continuity equation for compressible gas flow is given by

$$\mathrm{div}(\rho\boldsymbol{v})=0 \tag{15}$$

The modified momentum equation is expressed as

$$\mathrm{div}(\rho v_r\boldsymbol{v})-\rho\boldsymbol{v}\cdot\mathrm{grad}v_r=0\ (r=1,\ 2,\ 3) \tag{16}$$

The modified energy equation for steady flow is written as,

$$\sum_{r=1}^{3}\frac{\partial(\rho v_r h)}{\partial x_r}-\mathrm{div}(K\mathrm{grad}T)=0 \tag{17}$$

Standard k-ε model is appropriate for compressible fluid flow and is then introduced to enclose the equations[21].

1.4. Solution procedure

As the heat transfer between annulus and tubing is involved, their flow field model is coupled and must be solved at the same time. Both tubing and annulus are divided into many flow units (every two meters), and the coupled mathematical models are calculated from the wellhead to the bottom in the first half loop (as follows). In every flow unit, the temperature