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Research Article

Numerical Simulation of Superheated Steam Flow and Heat Transfer in a Balanced Steam Injection Flow Control Device

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Dual-string steam injection pipe is widely used in the production of superheated steam injection in heavy oil horizontal wells. Due to the nonuniform steam injection volume at the heel end and the existence of an interlayer and other factors in the reservoir, the distribution of steam cavity is not uniform, so it is necessary to control the flow of the steam injection well. Based on the basic principles of fluid mechanics and heat transfer, a three-phase nozzle outflow control device model is established in this paper. The steam flow and heat transfer law in the flow control device is numerically simulated, and the outflow dynamic law of horizontal well OCD completion in heavy oil reservoir is obtained. On this basis, the influence of OCD aperture parameters, steam injection pressure, and steam injection velocity on OCD throttling effect is studied. The results show that OCD has a good control effect on balancing pressure drop and improving steam injection uniformity. When the throttle aperture occupies 1/3 of the pipe diameter, the throttle effect is the best and the heat loss is low. Increasing the steam injection pressure can rapidly enhance the pressure reduction rate of the throttle hole. The throttling effect of increasing steam injection volume is not obvious, and the energy loss becomes higher. The study of this paper provides a reference for parameter optimization and prediction of steam distribution in the flow control device of horizontal wells.

1. Introduction

In recent years, after the large-scale implementation of steam injection technology in horizontal wells of heavy oil reservoirs, due to the influence of reservoir heterogeneity and variable mass flow in the horizontal wellbore [1], uneven production of horizontal reservoirs generally exists in the process of general steam injection [2, 3]. A large number of horizontal well monitoring data show that 80% of horizontal wells are unevenly utilized, and only 1/3 to 1/2 of the total well sections are well utilized [4].

To solve the above problems, double-pipe steam injection string is widely used in horizontal wells, namely, one long steam injection string at the heel end and one short steam injection string at the toe end of the steam injection well, to effectively improve the uneven steam injection phenomenon caused by the loss along the well and the heterogeneity of the reservoir.

However, the dual-steam injection string creates a dumbbell-shaped steam chamber, so the flow control devices [5–7] can be installed as part of a sand screen assembly in either a steam injection well or a production well, or in both wells at the same time, resulting in more uniform steam chamber expansion. The outflow control device, or OCD for short [8, 9], is mainly deployed in steam injection wells, and the direction of fluid flow is from the horizontal wellbore to the reservoir.

By adding an outflow control device (as shown in Figure 1) between the heel and toe of the injection well, the injection points can be evenly distributed, alleviating the bell-shaped steam cavity caused by the traditional dual injection tube design [10–12]. In addition, the OCD completion promotes the consistency of the steam injection profile with the height of the oil layer, promotes the growth of the steam cavity, and improves the oil-steam ratio [13].

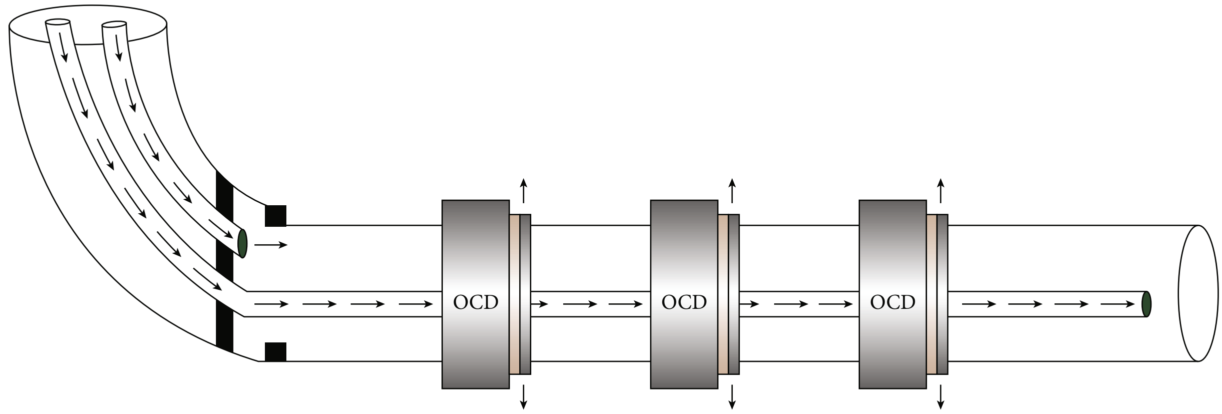

Figure 1: Schematic diagram of outflow control device.

2. Model Description

2.1. OCD Completion Parameter Calculation Model of Horizontal Well. Assume that the steam injection volume of the horizontal well element is as follows:

$$q_{i\mathrm{OCD}} = \frac{\sum q_{\mathrm{is}}}{L}, \quad (1)$$

where $q_{i\mathrm{OCD}}$ is the formation suction velocity, q_{is} is the steam suction velocity in the microsection under conventional completion, and L is the length of horizontal well [14–16].

If $q_{i\mathrm{OCD}}$ of the microsegment is smaller than q_i in conventional completion mode, it indicates that the microsegment has a larger steam output, and OCD device should be installed to take flow-limiting measures.

By putting $q_{i\mathrm{OCD}}$ into Equation (1), the steam injection pressure $P_{i\mathrm{OCD}}$, steam temperature $T_{i\mathrm{OCD}}$, and steam dryness $X_{i\mathrm{OCD}}$ in wellbore under OCD well mode can be obtained [17, 18]. Meanwhile, the annular steam pressure between screen tube and reservoir can be obtained as follows:

$$P_{i\mathrm{ann}} = \frac{-q_{i\mathrm{OCD}} \times I_s}{J_L} + P_r, \quad (2)$$

where $P_{i\mathrm{ann}}$ is the annular steam pressure between screen tube and reservoir, J_L is the microsegment extraction index, I_s is the reservoir inspiration index of microsegment (dimensionless), and P_r is the original formation pressure.

The calculation formula of J_L and I_s is shown as follows:

$$J_L = \frac{2\pi\sqrt{K_h/K_v}K_v\alpha((K_{ro}/B_o\mu_o) + (K_{rw}/B_w\mu_w))}{\mathrm{In}(r_{eh}/r_w) - 0.75 + S}, \quad (3)$$

$$I_s = \frac{2\ln\left(A_O/r_w^2\right) - 3.86}{\ln\left(A_O/r_w^2\right) - 2.71}, \quad (4)$$

where K_h is the horizontal permeability of reservoir, K_v is the vertical permeability of reservoir, K_{ro} is the relative permeability of crude oil, K_{rw} is the relative permeability of the formation water, μ_o is the formation oil, μ is the formation water viscosity, B_o is the formation crude volume coefficient, B_w is the formation water volume coefficient, α is the unit conversion factor, r_{eh} is the drain radius of the horizontal parallel segment, S is the horizontal wellbore skin factor, A_o is the microsegment drainage area of horizontal well, and r_w is the sieve tube diameter [19–23].

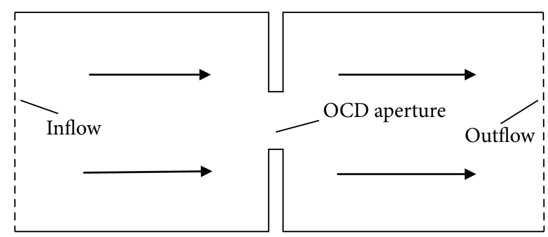

Figure 2: Simplified model of nozzle-type OCD structure.

Table 1: OCD structure basic data.

Name	Value	Unit
Initial reservoir pressure	1.5	MPa
Initial reservoir temperature	297	K
Steam injection pressure	2	MPa
Superheated steam temperature	500	K
Tubing diameter	240	mm
OCD's port size	50	mm
Steam injection volume	100	m^3/d
Steam dryness	100	%

According to the pressure drop balance relationship, the additional drop $P_{i\mathrm{add}}$ of OCD in each segment can be obtained.

$$P_{i\mathrm{OCD}} - P_{i\mathrm{ann}} = P_{i\mathrm{add}}. \quad (5)$$

2.2. Additional Pressure Drops of OCD. The nozzle type-OCD is used to calculate the attached pressure drop of the OCD by using the Bernoulli equation [24, 25].

$$P_{\mathrm{add}} = \frac{8\rho Q^2}{\pi^2 d^4 n^2 C_D^2}, \quad (6)$$

where P_{add} is the additional pressure drops, ρ is the fluid density, Q is the fluid volume flow, d is the diameter of

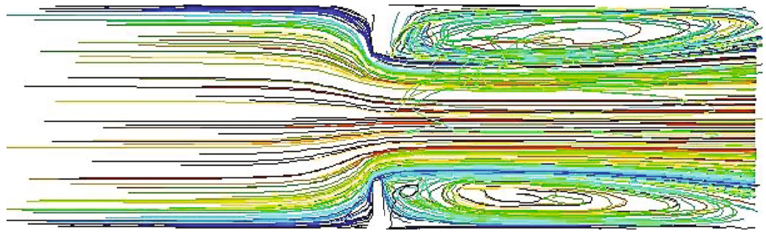

FIGURE 3: Streamline of steam flow through OCD nozzle.

nozzle orifice, n is the number of nozzle orifices, and C_D is the flow coefficient.

2.3. Calculation Model of Pressure Drop in Horizontal Wellbore. The calculation model of the pressure drop in the tubing of horizontal wells is as follows (ignoring the gravity pressure drop) [26–28]:

$$A_2X_2 = b_2,$$
$$\begin{bmatrix} 1 & & & 0 \\ -1 & 1 & & \\ & \ddots & \ddots & \\ 0 & & -1 & 1 \end{bmatrix} \begin{bmatrix} p_{t,1} \\ p_{t,2} \\ \vdots \\ p_{t,N} \end{bmatrix} = \begin{bmatrix} \frac{32\rho f_1}{\pi^2 d_w^5} q_{w,1}^2 L_1 + \frac{32\rho q_{\text{in},1}}{\pi^2 d_w^4} q_{w,1} + P_{wf} \\ \frac{32\rho f_2}{\pi^2 d_w^5} q_{w,2}^2 L_2 + \frac{32\rho q_{\text{in},2}}{\pi^2 d_w^4} q_{w,2} \\ \vdots \\ \frac{32\rho f_N}{\pi^2 d_w^5} q_{w,N}^2 L_N + \frac{32\rho q_{\text{in},N}}{\pi^2 d_w^4} q_{w,N} \end{bmatrix}, \quad (7)$$

where f_j is the friction factor in section j, $P_{t,j}$ is the tubing pressure in section j, $q_{\text{in},j}$ is the inlet flow rate of section j into the tubing, and $q_{w,j}$ is the flow rate in the microelement pipe of section j.

The boundary conditions of tubing pressure distribution are shown in

$$p_{t,0} = p_{wf}, \quad (8)$$

where $p_{t,0}$ is the wellhead pressure and p_{wf} is the pressure in the tubing at the heel end, namely, the bottomhole flow pressure [29–32].

3. OCD Simulation Analysis

3.1. The Basic Parameters. Based on the structural characteristics of the horizontal well OCD and numerical simulation accuracy requirements of the completed section, a three-dimensional model of the nozzle flow control device is established (see Figure 2) [33]. Related calculation parameters are shown in Table 1.

3.2. Analysis on Dynamic Characteristics of OCD Outflow in Horizontal Wells. Based on the actual mine parameters, the superheated steam flow in the flow control device is numerically simulated by using a multiphase flow model. The flow diagram of the steam flow is shown in Figure 3. As shown in the figure, steam flows smoothly before entering the hole, and annular flow will be generated near the edge of the pipe wall after passing through the hole. The velocity near the wall decreases, and the velocity in the center reaches the maximum, which is higher than that before entering the hole.

The main factors influencing the flow control device are the throttling effect with OCD aperture, steam injection rate, and steam injection pressure. Based on the frictional pressure drop and heat loss calculation, the flow control device of the three-dimensional numerical model is established. The contrast analysis of the influence of various parameters on the flow control effect is changed, to establish uniform steam injection OCD structure parameters and a steam injection parameter optimization method.

3.3. Influence of Changing OCD Aperture on Current-Limiting Effect. Pore size is the key parameter of OCD design, which has an important influence on the pressure drop, heat loss, and steam cavity development and expansion along the steam injection horizontal well. Considering the same steam injection pressure, steam injection volume, and other parameters, the influence of different OCD apertures on the throttling effect was studied, and the throttling effect of steam valve was simulated under five pore sizes of 20 mm, 50 mm, 80 mm, 110 mm, and 140 mm. The variation of temperature field and pressure field in OCD with different pore sizes is shown in Figure 4.

As can be seen from the Figure 4, with the increase of the steam injection pore size, the pressure sweep range is larger and the pressure drop range is more obvious. At this time, the pressure gradient gradually decreases, forming a low-pressure area between the outlet edge of the aperture and the pipe wall, and the pressure near the edge of the aperture gradually increases. As can be seen from the temperature cloud map, the increase of pore size makes the heat loss smaller, the heat diffusion faster, and the heat coverage area more. The temperature and pressure changes on the pipeline axis line are shown in Figures 5 and 6.

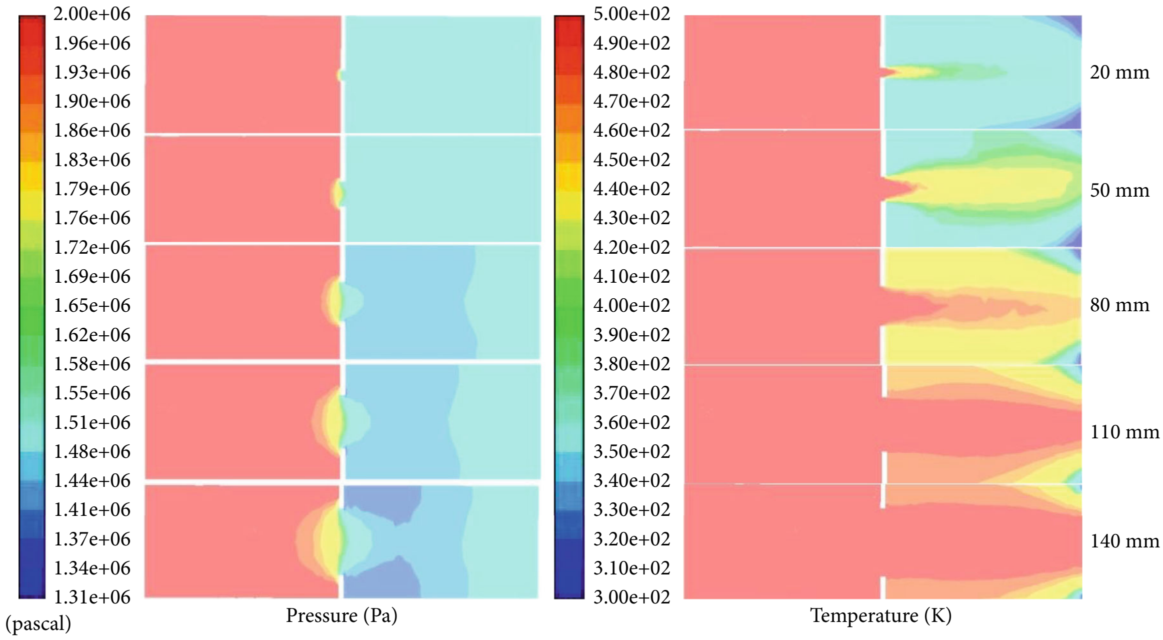

FIGURE 4: Pressure field and temperature field distribution of steam flow in OCD.

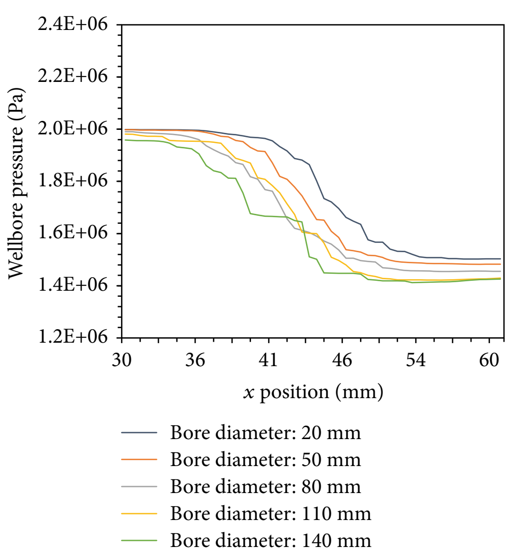

FIGURE 5: The relationship between pressure and pore size in OCD.

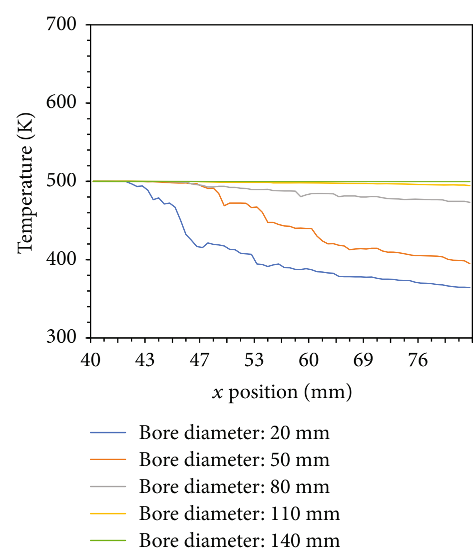

FIGURE 6: The relationship between temperature and pore size in OCD.

Figure 5 shows the aperture used to increase the flow control device for the pressure drop of the OCD. From the figure, it can be seen that as the pore size increases, the pressure drop increases. Among the pore sizes, for diameters of 110 mm and 140 mm under pressure fluctuations, the change of the throttling effect is smaller, and the simulation result difference is not large. Figure 6 shows that for diameters of 110 mm and 80 mm for the temperature change under different apertures, with the increase of the aperture, the heat loss becomes smaller. When the aperture is between 20 and 50 mm, the heat energy loss is intense and the temperature difference is large. When the aperture is between 80 mm and 140 mm, the temperature drop is not obvious. Therefore, when the aperture is 80 mm, better throttling effect can be achieved.

3.4. Effect of Steam Injection Pressure Change on Outflow Control Device. Taking the steam injection speed of 100 m^3/d, steam dryness of 0.95, steam injection temperature of 500 K, and OCD aperture of 80 mm as design parameters, the steam flow in the flow control device with steam injection pressure of 2 MPa, 2.5 MPa, and 3 MPa, respectively, was simulated. The simulation results are shown in Figures 7 and 8.

As can be seen from Figure 7, increasing the steam injection pressure can increase the throttling strength, and the steam pressure drop through the pore is more obvious. Figure 8 shows the variation of steam flow velocity through the hole with steam injection pressure. It can be seen from

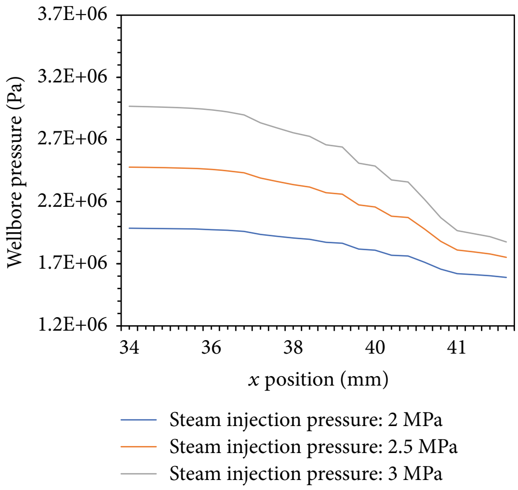

Figure 7: The relationship between OCD internal pressure and steam injection pressure.

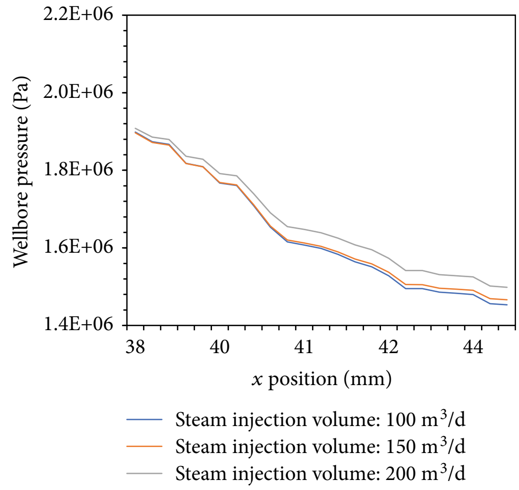

Figure 9: The relationship between pressure variation and steam injection volume in OCD.

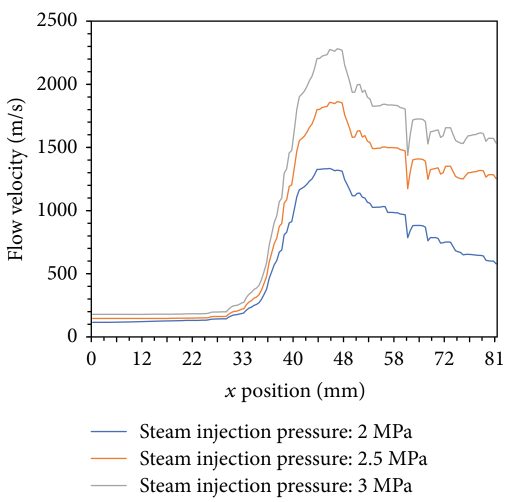

Figure 8: The relationship between OCD velocity and steam injection pressure.

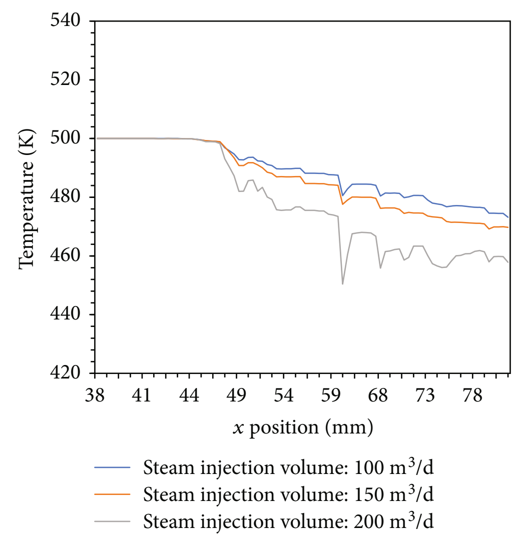

Figure 10: The relationship between temperature variation and steam injection volume in OCD.

the figure that the increase of steam injection pressure will lead to a larger increase of flow velocity near the valve hole and a smaller decrease of velocity after passing the valve.

3.5. Effect of Steam Injection Volume Change on Outflow Control Device. In order to explore the influence of steam injection speed on OCD throttling effect, the steam injection pressure is set as 1.9 MPa, the temperature of superheated steam is 500 K, the pore size is 80 mm, and the internal throttling effect of the outflow control device is simulated when the steam injection volume is 100 m^3/d, 150 m^3/d, and 200 m^3/d, respectively. The simulation results are shown in Figures 9 and 10.

Figure 9 shows the pressure change curve in the flow control device under different steam injection volumes. With the increase of injection volume, the pressure drop decreases faster, and the pressure drop changes of 150 m^3/d and 200 m^3/d are close to each other. Figure 10 shows the temperature variation curve in the flow control device under different steam injection volumes. The temperature fluctuates greatly near the throttle hole. With the increase of steam injection volume, the heat loss is accelerated and the temperature drop is increased.

4. Summary and Conclusions

In this paper, the dynamic outflow law of dual-pipe steam injection OCD completion of the horizontal well in heavy oil reservoir is studied, mainly simulating the outflow control effect of OCD on the target section of the horizontal well with steam injection, as well as the influence of changing steam injection parameters and OCD structural parameters on the throttling control effect. The following conclusions are drawn from the study:

(1) OCD can effectively alleviate the horizontal well completion method in the process of steam injection in the steam cavity of development that is not a balanced phenomenon, through the OCD device installed on the screen, and adjust the OCD nozzle diameter, steam injection pressure, and steam injection rate on the steam injection volume larger through your fingers with the client and the implementation of current limit, reducing the cause of excessive amount of vapor variable mass flow pressure drop loss. The attenuation range of the steam pressure in the wellbore is delayed, so that the steam pressure in the middle of the horizontal well is increased, and the steam injection volume and heating radius are increased, so that the formation along the horizontal section is evenly heated, and the production degree of the reservoir is improved

(2) Changing the nozzle aperture has a significant impact on the current-limiting effect. By comparing the inner diameters of the five groups of nozzles with different sizes, it is found that the larger the aperture, the lower the heat loss. When the aperture is 80 mm, that is, the ratio of the aperture to the pipe diameter is 1 : 3, the better the throttling effect and the lower the heat loss are, which can be used as a priority reference design scheme

(3) Changing the steam injection pressure has a great influence on the flow-limiting effect. With the increase of steam injection pressure, both the pressure drop range and the steam injection speed become larger. Uniform development of the steam cavity can be achieved by appropriately changing the steam injection pressure. The increase of steam injection volume has little effect on the current-limiting effect, and the heat loss range increases with the increase of steam injection speed

The simulation results in this paper can provide a reference for the optimization of the uniform steam injection. Since there is no comparison of various types of FCD throttling effects, relevant research work will be continued in the future.

Data Availability

Data can be obtained from corresponding author.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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