ISSN: 2688-8645

Study on the Influence of Steam Injection Mode Difference on the Heat Transfer Behavior of Wellbore Steam Circulation Electric Heating

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Abstract

Aiming at the problem of insufficient understanding of the influence of different steam injection methods on the heat transfer law of wellbore steam circulation electric heating in SAGD technology for heavy oil thermal recovery, based on the theory of heat transfer and fluid mechanics, this paper establishes a numerical calculation model of wellbore steam circulation electric heating to simulate the process of electric heating and steam synergistic heat transfer in horizontal steam injection wells. The difference of temperature field distribution between wellbore and electric heater of short tube steam injection, double tube steam injection and long tube steam injection was studied. The results show that the heating effect of short tube steam injection on steam is weaker than that of long tube steam injection, and the temperature of electric heater is higher. It is necessary to cooperate with high steam injection speed or low power density operation to avoid overtemperature. The heating effect of double-tube steam injection is similar to that of long-tube steam injection under the condition of halving steam injection volume. The temperature overrun of heater can be improved by increasing steam injection volume, reducing power density and optimizing steam distribution ratio. The research work in this paper provides a theoretical basis for the optimization of steam injection mode and heat transfer law in the process of electric heating assisted development of heavy oil SAGD technology.

Keywords

Heavy Oil Reservoir; Electric Heater; Heat Transfer; Steam Injection Mode.

1. Introduction

Compared with conventional crude oil, heavy oil has the characteristics of high viscosity, large specific gravity and poor fluidity. In the international oil and gas industry, heavy oil is usually called heavy oil 0[2]. As a major difficult-to-produce oil and gas resource, heavy oil is abundant in the world, accounting for about 71% of the world 's recoverable resources. It is mainly distributed in the Americas and the Middle East. China 's heavy oil resources rank fourth in the world [3] [4]. At present, thermal recovery technologies such as steam huff and puff, steam flooding and steam assisted gravity drainage (SAGD) are mainly used for heavy oil recovery [5] [7]. In recent years, there are more and more researches on the electric heating assisted mining technology of heavy oil. This technology has been proved to be an effective solution to improve the formation temperature, reduce the viscosity of heavy oil and improve the mining efficiency. Its compact structure, small footprint, green and low-carbon characteristics make it gradually become the key development direction of low-carbon and efficient development of heavy oil [8]. However, at present, there are still some problems in the electric heating technology of heavy oil, such as unclear injection-production parameters, unclear relationship between steam injection process and electric heater interaction, which make the technology fail to be applied on a large scale. Therefore, it is particularly important to study the heat transfer law of wellbore steam circulation electric heating.

Many studies have been carried out on heavy oil electric heating technology and steam injection methods at home and abroad. Since the technology was first proposed by Lucas for heavy oil development in 1966 [9], the application of downhole electric heating technology in the field of reservoir development has been continuously deepened. Bridges et al. [10] explored the feasibility of RF / electromagnetic heating technology to heat oil sands. Wanadar et al. [11]further proposed the method of electromagnetic heating using horizontal wells. The research shows that this technology has higher recovery in heavy oil with moderate viscosity. Sahni et al. [12] showed that the heating effect of electromagnetic heating technology in low injection efficiency or thin heavy oil reservoir is better than that of low frequency resistance heating. Rangel et al. [13] proposed a resistance heating assisted heavy oil recovery technology, which provides an idea for the combination of electric heating and other EOR methods. Aiming at the problems of large steam consumption and uneven preheating during SAGD start-up, Wu [14] [15] et al.proposed a method of SAGD start-up by downhole resistance heating. The research shows that electric heating assisted SAGD preheating can achieve uniform heat transfer. Stone et al. [16] carried out a correlation analysis of the control strategy for the dual-tubing steam injection process. It was found that the uniformity of the steam injection profile can be significantly improved by adjusting the steam injection pressure difference and flow distribution ratio between the long and short tubes. Li Yang et al. [17] pointed out that in the SAGD production stage, if the overall utilization degree of the horizontal section is high, the double-tube steam injection mode can be adopted, which can effectively improve the overall utilization effect of the horizontal section. If the utilization degree of the front section of the horizontal section is better, the method of separate steam injection in the long pipe can be selected. On the contrary, if the utilization degree of the back end of the horizontal section is dominant, the method of separate steam injection in the short pipe is suitable. Zhao Rui et al. [18] proposed SAGD technology for fishbone steam injection horizontal wells, which can effectively expand the swept volume of steam and improve the uniformity of horizontal wells. Zhou et al. [19] confirmed that the multi-branch horizontal well structure can effectively improve the utilization degree of the horizontal section of the production well.

At present, the research only focuses on the influence of heavy oil electric heating technology and steam injection mode on SAGD process, and lacks the study of wellbore heat transfer behavior combining the two. In this paper, a numerical model of wellbore steam circulation electric heating is established to reveal the influence of steam injection mode on the heat transfer behavior of wellbore steam circulation electric heating. The research work in this paper provides theoretical support for the matching of heavy oil heating steam injection mode and parameters.

2. Technical Principle of Downhole Electric Heater

The working principle of the downhole electric heater is to rely on the impedance characteristics of the cable core wire to achieve heating[20] [21]. When the current flows through the core wire, the electric energy is converted into heat energy and transmitted to the outer sheath of the cable through heat conduction. After the heat reaches the outer sheath, it continues to spread outward through steam convection. In the wellbore steam circulation electric heating system of heavy oil SAGD steam injection process, the heat generated by the downhole electric heater is used to reheat the wet steam with low dryness in the tubing to improve the heat carrying capacity of the steam in the wellbore, so as to improve the steam quality and enhance the heavy oil recovery.

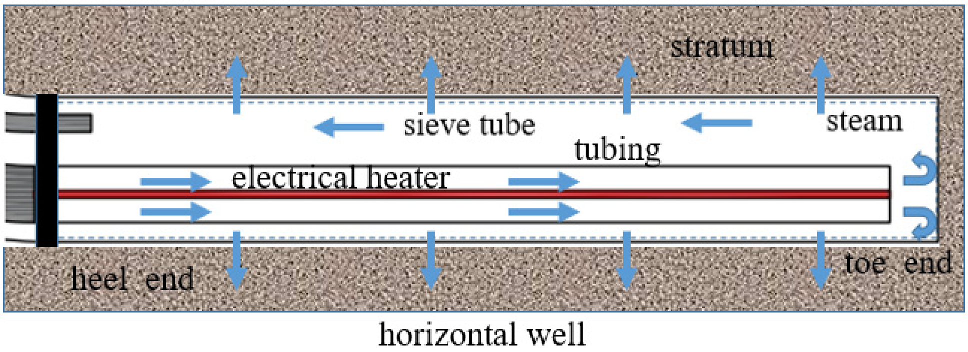


Fig 1. Electrical heating diagram of wellbore steam circulation

Based on the electric heating process of heavy oil in horizontal wells and the actual flow characteristics of steam in the wellbore, the steam flow in the steam injection pipe and wellbore can be simplified into one-dimensional steady-state flow. The heat transfer between steam, steam injection pipe and wellbore is mainly heat conduction and heat convection, and the proportion of thermal radiation in formation heat transfer is very low and negligible. The flow and heating process of steam in tubing and wellbore satisfies the basic control equations of mass conservation, momentum conservation and energy conservation [22].

2.1. Flow Field Control Equation

Mass conservation equation :

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho V)=0 \tag{1}$$

In the formula: ρ is the average density of steam, $\mathrm{kg/m^3}$; V is the scalar of steam velocity, $\mathrm{m/s}$.

Momentum conservation equation :

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v v)=-\nabla P+\nabla\tau+\rho g+F \tag{2}$$

In the formula: v is the steam velocity vector, $\mathrm{m/s}$; P is the pressure distribution on the surface of the fluid micro-mass, Pa; τ is the viscous stress on the surface of the fluid element, $\mathrm{Pa\cdot s}$; g is the acceleration of gravity, $\mathrm{m/s^2}$; F is the combined external force acting on the fluid element, N.

Energy conservation equation:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot(v(\rho E+P))=\nabla\cdot(k_{eff}\Delta T)+S_{\mathrm{h}} \tag{3}$$

In the formula: T is the temperature of the fluid element, K; λ is the thermal conductivity of the fluid element, $\mathrm{W/m\cdot k}$; C_p is the specific heat capacity at constant pressure., $\mathrm{J/kg\cdot K}$; S_T is the viscous dissipation term of fluid element.

2.2. Heat-transport Equation

Heat conduction refers to the phenomenon that when two objects at different temperatures are in contact with each other or there is a temperature difference inside the same object, the energy transfer is generated by the thermal motion of microscopic particles such as molecules and atoms inside the object. The heat transfer form inside the electric heater and inside the tubing is mainly heat conduction, and its expression is:

$$q=-\lambda\frac{dT}{dx} \tag{4}$$

In the formula: q is the heat flux density, W/m^2.

Thermal convection refers to the phenomenon that heat particles propagate heat energy from one place in space to another through the flow medium. When the injected wet steam flows through the surface of the electric heater, the heat on the surface of the electric heater sheath is absorbed by forced convection heat transfer, and the high temperature fluid reflow process transfers the heat to each structure of the wellbore through convection heat transfer. The heat transfer form between electric heater and steam, steam and tubing, wellbore is thermal convection :

$$\frac{Q}{t}=hA(T-T_m) \tag{5}$$

In the formula: Q/t is the heat transferred per unit time, W; h is the convective heat transfer coefficient, $W/m^2\cdot k$; A is the heat transfer area, m^2; T_m is the temperature of the surrounding medium, K.

3. Numerical Calculation Model of Wellbore Steam Circulation Electric Heating

Based on the short radius horizontal well, a numerical calculation model of 100 m long wellbore steam circulation electric heating is established. The flow and heat transfer law of steam in the tubing and cylinder during the steam circulation heat transfer stage was studied by numerical simulation. The wellbore steam circulation electric heating model is shown in Figure 2.

3.1. Computation Module

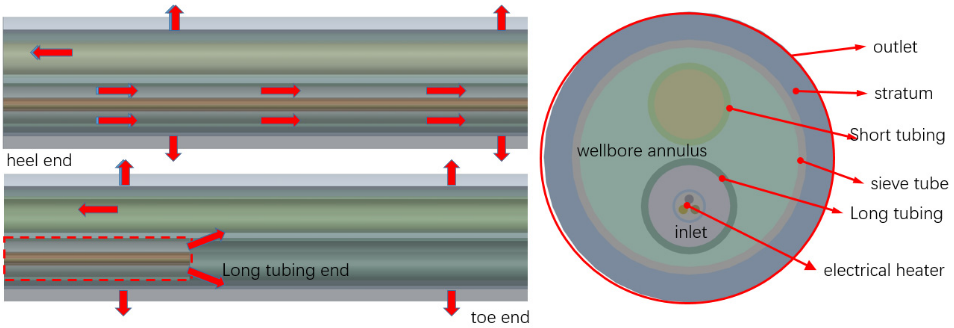


Fig 2. Diagram of wellbore steam circulation electric heating calculation model

3.2. Grid Division and Independence Verification

The global hexahedral structured grid is selected for discretization, and the grid adopts the method of common nodes. Considering that the velocity and temperature near the wall change greatly, and accompanied by the evaporation and condensation phase transition process of wet steam, in order to capture the complex boundary layer flow and heat transfer characteristics, the mesh near the wall is locally refined, and the mesh division is shown in Fig.3.

In order to verify the grid independence of the model, a total of five different sizes of grids were divided. The working conditions of the model are set as follows : the steam injection speed is 40 t/d, the steam dryness at the heel end is 0.6, the steam injection temperature is 224 °C, the steam injection pressure is 2.5 MPa, and the heating power is 2 kW/m. The specific number of grids and the grid size are shown in Table 1. When the steam dryness of the inner outlet of the long tubing reaches a stable value, the calculation convergence can be judged. When the number of grids is more than 1458000, the fluctuation range of tubing outlet dryness is less than 2 %, so it can be considered that the grid size at this time is independent of the calculation results. Considering the calculation time and calculation accuracy, this paper selects the grid size of 0.83 mm and the number of grids of 1458000 to carry out the subsequent calculation.

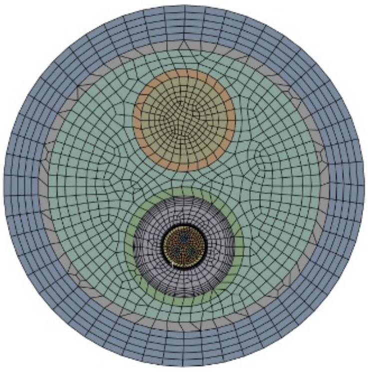


Fig 3. Grid division diagram

Table 1. Grid independence verification results

Name	Axial size of mesh (mm)	Grid number	Outlet dryness
Scheme 1	2.5	541600	0.75
Scheme 2	1.25	972000	0.77
Scheme 3	0.83	1458000	0.81
Scheme 4	0.625	1944000	0.82
Scheme 5	0.5	2435000	0.82

3.3. Calculate Boundary Conditions

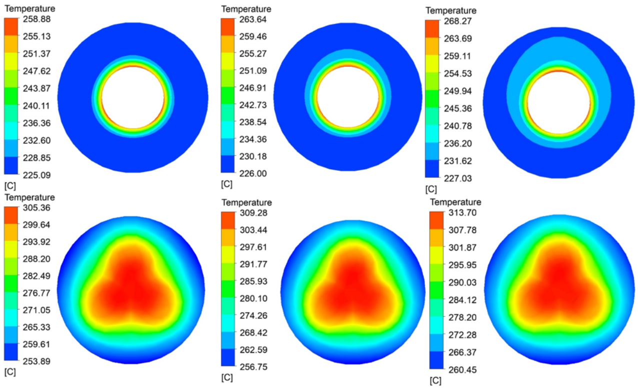
In the process of numerical simulation, the influence of gravity on flow and heat transfer is comprehensively considered, and the heat transfer simulation of wellbore steam circulation electric heating is carried out by using pressure-based solver. In this study, the VOF multiphase flow model is used to solve the problem, in which water vapor is the main phase and liquid water is the secondary phase. The inlet of the model adopts a mass flow inlet, the fluid is a two-phase mixed medium of water vapor and liquid water, the inlet temperature is set to the saturation temperature under the corresponding pressure, and the steam dryness is 0.6. The outlet boundary adopts a pressure outlet, and the pressure value is set according to the pressure corresponding to the saturation temperature.

Table 2. Material parameters

Name	Material quality	Diameter (mm) ×Length (m)	Thermal conductivity (W/m·k)
Core wire	Cr20Ni80	7×100	16.5
Sheath	316L	25.4×100	14.2
Medium	MgO	21.4×100	3.6
Long tubing	N80	73×100	16.3
Short tubing	N80	63×40	16.3
Sieve tube	TP90H	177.8×100	16.3

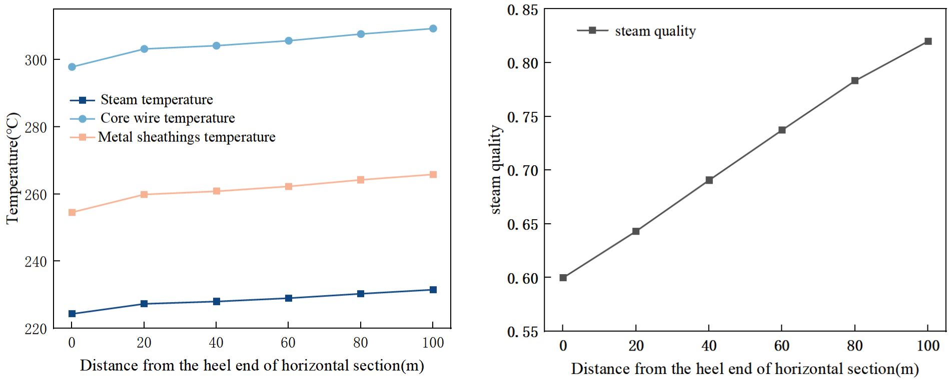
3.4. Numerical Simulation of Electric Heating Effect of Wellbore Steam Circulation

It can be seen from Fig.4 that the steam temperature in the tubing increases gradually by means of long-tube steam injection. Driven by the gravity field and the interphase density difference, the cross section shows obvious thermal stratification. The high-temperature and low-density steam accumulates in the upper part, while the relatively low-temperature steam is deposited at the bottom of the tube. It can be seen from Figure 5 that the main temperature of the steam in the tubing is maintained near the saturation temperature of 224 °C, and the steam temperature difference between the inlet and outlet of the tubing is 4 °C. The steam dryness increases linearly along the axial direction. The temperature of the electric heater and the steam dryness gradually increase along the axial direction of the horizontal section. The steam dryness at the outlet of the tubing is 0.82, which is 0.22 higher than that at the inlet. This is because the steam utilizes the heat of the electric heater through the latent heat of vaporization, and the steam temperature is maintained at the saturation temperature. The endothermic heat is mainly used for the evaporation of droplets, and the steam dryness is improved. This shows that the electric heating of wellbore steam circulation is helpful to improve the heat carrying capacity of bottom hole steam and improve the effect of heavy oil recovery.



(a) 0 m (b) 50 m (c) 100 m

Fig 4. Temperature cloud diagram of inner section of tubing



(a)Fluid and electric heater in oil pipe (b)Steam dryness in tubing

Fig 5. Variation curves of wellbore steam circulation electric heating fluid, electric heater temperature and steam dryness

4. Analysis of the Influence of Steam Injection Mode on Heat Transfer

In the SAGD production stage, the main role of steam injection wells is to continuously inject high-quality steam into the reservoir to maintain the temperature and pressure of the steam chamber, and the selection of steam injection methods directly affects the heating effect and process suitability. According to the different position of steam injection port, SAGD production process can be divided into three ways : short pipe steam injection, long pipe steam injection and double pipe steam injection. The effects of several steam injection methods on the heating effect of electric heating assisted SAGD were studied and compared.

4.1. Short Tube Steam Injection

As shown in Figure 6, short tube steam injection refers to the use of short tubing to inject steam, and the electric heater is lowered from the position of the long tubing and placed directly in the wellbore annulus. Steam enters the wellbore annulus from the end of the short tubing, then flows along the toe end of the horizontal well, and steam enters the formation along the sieve tube.

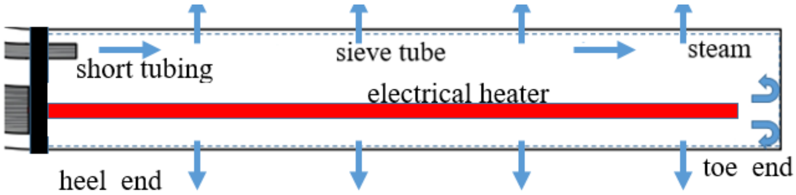
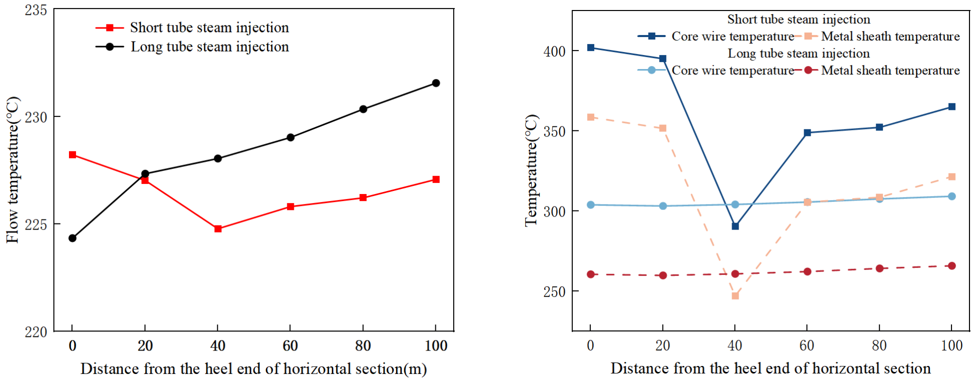


Fig 6. Short tube steam injection diagram

It can be seen from Fig.7 that the average temperature of steam is lower than that of long tube steam injection. The monitoring data are intercepted at the same position as the long tubing, and the steam temperature shows a trend of decreasing first and then increasing. The steam temperature in the middle and rear sections of the horizontal well is lower than the steam temperature of the long tube steam injection. The temperature of the core wire and sheath of the short pipe steam injection decreases first and then increases along the heel end of the horizontal section to the toe end, and the temperature at the outlet of the short pipe is the lowest. The results show that the heating effect of short tube steam injection is weaker than that of long tube steam injection, and the temperature of electric heater is higher at the heel end.



(a)Fluid temperature in tubing (b)Electric heater temperature

Fig 7. Comparison of temperature field between short tube steam injection and long tube steam injection

To ensure that other parameters remain unchanged, the steam injection speed and the power density of the electric heater are taken as variables. The influence of steam injection speed and electric heater power on the core wire and sheath of the electric heater under short tube steam injection is obtained by simulation calculation. It can be seen from Fig.8 that with the increase of steam injection speed, the maximum temperature of the core wire and the sheath shows a decreasing trend. Usually, the operating temperature of the electric heater does not exceed 400 °C.When the steam injection rate is less than 40 t/d, the surface temperature of the electric heater sheath exceeds 400 °C, which is easy to cause damage to the heater. With the increase of heating power, the maximum temperature of the core wire and the sheath increases, and the temperature difference between the core wire and the sheath of the electric heater increases gradually. When the heating power density increases from 1 kW/m to 3 kW/m, the temperature difference between the core wire and the sheath increases from 18.3 °C to 53.3 °C, and the sheath temperature at 3 kW/m exceeds 480 °C. This shows that the steam injection speed should not be too low and the heating power density should not exceed 3 kW/m when using short tube steam injection.

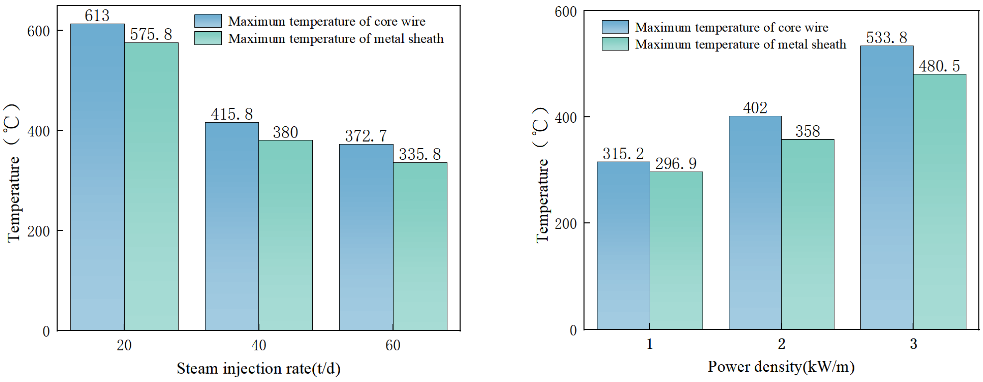


Fig 8. The maximum temperature change trend of metal sheath and core wire

4.2. Double-tube Steam Injection

Double tube steam injection (Fig.9) This is a widely used method in SAGD production stage, that is, a long tube and a short tube are put into the wellbore at the same time, and the steam injection intensity at different positions is controlled by adjusting the steam injection speed ratio of different strings. In this section, double-pipe steam injection is adopted. Under the condition of constant total steam injection speed, uniform steam distribution is adopted, that is, the steam injection speed of short tubing and long tubing is 20 t/d.

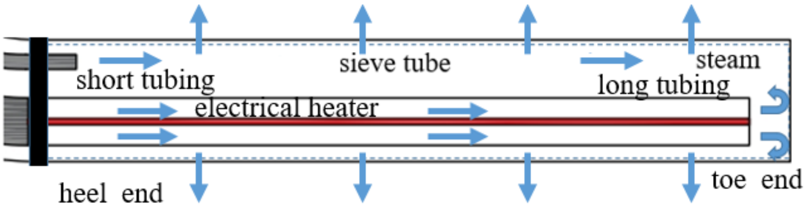
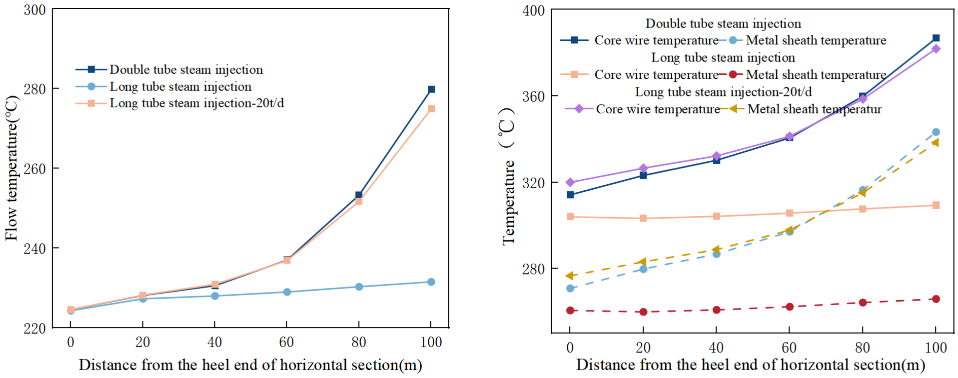


Fig 9. Double-tube steam injection diagram

It can be seen from Fig.10 that the average temperature of steam in the tubing is higher than that of the long tube steam injection mode under the same working conditions. The wet steam temperature and dryness in the long tubing show a trend of slowly rising first and then rapidly rising along the heel end to the toe end of the horizontal section. The outlet steam temperature of the end of the long tubing with double tube steam injection is 279.8 °C, which is 48.3 °C higher than that of the long tube steam injection. Under the premise that the total steam injection speed is constant, the steam injection speed of the long tubing is halved due to the consistent steam injection ratio of the long tubing, and the temperature of the core wire and sheath of the electric heater shows a linear upward trend. Compared with the single-tube steam injection, the maximum temperature of the core wire and the sheath increased significantly, and the average temperature of the cross section reached 386 °C and 343 °C. The temperature of the electric heater with double-tube steam injection and steam injection speed of 40 t/d is close to that of the long-tube steam injection of 20t / d. This shows that when the same power density is used to achieve the same heating effect, the steam injection volume required for double-tube steam injection is larger.



(a)Fluid temperature in tubing (b)Electric heater temperature

Fig 10. Comparison of temperature field between double-tube steam injection and long-tube steam injection

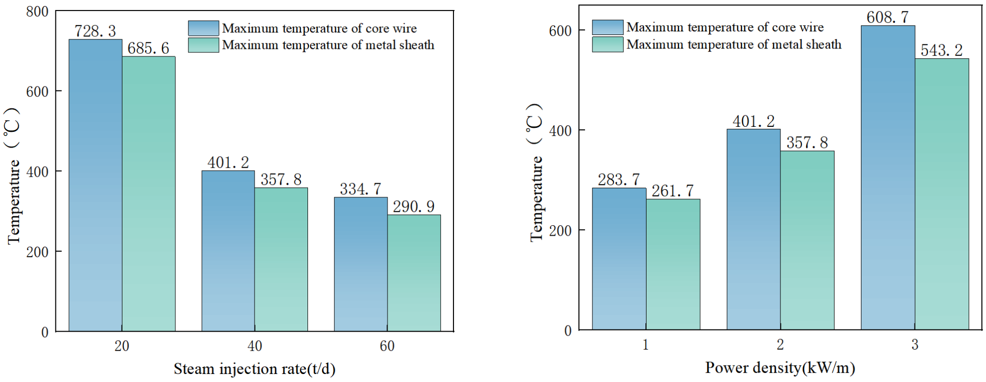


Fig 11. The maximum temperature change trend of metal sheath and core wire

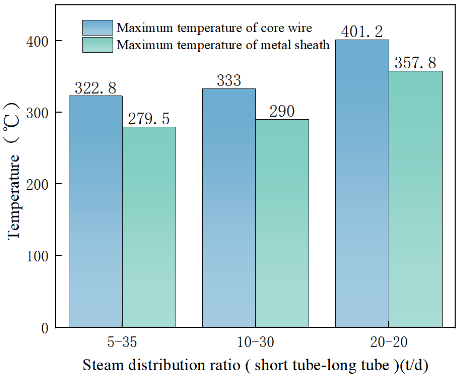


Fig 12. Temperature changes of heaters with different steam distribution ratios

It can be seen from Fig.11 that under the premise of constant heating power density, with the increase of steam injection speed, the maximum temperature of core wire and sheath gradually decreases and the decreasing range gradually decreases by using the method of double pipe steam injection and uniform distribution of long and short oil pipes. When the total steam injection rate is less than 40 t/d and the power density of the heater is 2 kW/m, the maximum temperatures of the core wire and the sheath are 728.3 °C and 685.6 °C, respectively, and the temperature of the sheath exceeds its operating temperature and maximum tolerance temperature at the same time. Under the premise of constant total steam injection speed, the temperature of the core wire and sheath of the electric heater increases gradually with the increase of power density. When the power density is greater than 2 kW/m, the surface temperature of the sheath is too high, exceeding the maximum operating temperature of 400 °C allowed by the material.

It can be seen from Fig.12 that under the premise of constant heating power density and total steam injection speed, when the steam distribution ratio of the long tubing increases from 1:1 to 7:1, the maximum temperature of the core wire and sheath of the electric heater decreases from 401.2 °C and 357.8 °C to 322.7 °C and 279.5 °C, respectively. This shows that controlling the steam distribution ratio can well control the temperature of the electric heater. In the case of low total steam injection speed and high power density of the heater, the steam distribution ratio of the long tubing can be increased to reduce the temperature of the electric heater.

5. Summary

Based on the theory of fluid mechanics and heat transfer, a numerical calculation model of steam circulation electric heating in 100 m wellbore is established. The temperature field distribution of steam electric heater in tubing under different steam injection modes is analyzed. The following conclusions are drawn:

(1) Using the method of numerical simulation, the heat transfer law of wellbore steam cycle electric heating under long tube steam injection is analyzed. The results show that the wellbore steam circulation electric heating technology can effectively improve the steam temperature in the horizontal wellbore and improve the steam dryness at the bottom of the well.

(2) The heating effect of steam injection in the short tube is weaker than that in the long tube, and the low steam flow rate at the heel end is easy to cause the heater to overheat. In the actual production process, it is necessary to cooperate with high steam injection speed or low power density operation. When the steam injection rate is less than 40t/d or the power density of the electric heater exceeds 3kW/m, the sheath temperature exceeds the upper limit of the operating temperature of 400 °C.

(3) The heating effect of double-tube steam injection is similar to that of long-tube steam injection (steam injection speed halved), and the problem of temperature overrun of electric heater can be improved by changing the steam distribution ratio of long and short tubing. When the total steam injection rate is 40t/d and the power density is 2kW/m, the steam distribution ratio is optimized to 7:1 (long tube: short tube), which can reduce the heater temperature to a safe range.

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