Study on the displacement characteristics of flue gas complex thermal fluid

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Abstract. One of the component of flue gas is CO₂ which can cause environment problem, and flue gas-assisted heavy oil thermal recovery can significantly improve the effect of heavy oil development. Therefore, research on features of flue gas composite hot fluid flooding are of great significance. This paper used one-dimensional core tube experiments to reveal the evolution of the temperature field and displacement zone during the development of flue gas composite thermal fluids. At the same time, it monitored the displacement pressure variation under different methods, and clarified displacement characteristics and oil displacement efficiency. The results show that with the injection of flue gas, the heat spread ranges of steam zone and hot water zone are expanded, and the heat utilization rate is improved. Oil flooding efficiency and maximum oil recovery rate of cold water/hot water-flue gas flooding efficiency is higher than that of cold water/hot water which at the same temperature, and the oil displacement efficiency and maximum oil recovery rate is improved. The hot water/hot water-flue gas flooding pressure variation and stable pressure variation are lower than cold water/cold water-flue gas flooding at the same temperature. Oil displacement efficiency of flue gas composite hot fluid flooding is obviously higher than pure steam flooding.

1. Introduction

With the development of industrialization worldwide, the negative effects of greenhouse gases cannot be ignored, and the control of carbon dioxide emissions has become a concern of all countries in the world. The flue gas contains 10%-15% carbon dioxide and 80%-85% nitrogen[1-2]. The flue gas complex thermal fluid can significantly improve the development effect of heavy oil and save a lot of nitrogen injection costs[3]. At present, the research on gas-assisted heavy oil thermal recovery has gained a lot of knowledge[4-6], but there are still many problems that have not been well resolved. Therefore, it is of great significance to carry out research on the displacement characteristics of flue gas composite hot fluid flooding. This paper uses one-dimensional core tube experiments to monitor temperature changes at different locations during the process of flue gas injection composite thermal fluid flooding, revealing the evolution of temperature fields and displacement zones during the process. At the same time, by monitoring the variation pressure under different ways of flooding, clarify the flooding characteristics and oil displacement efficiency of different displacement stages, and reveal the influence of flue gas on the temperature field and displacement characteristics.
2. Experimental materials and setup
The experimental oil is a simulated oil compounded from heavy oil and kerosene in a certain block of Shengli Oilfield. The viscosity of heavy oil varies with temperature as shown in Figure 1. The specification of the one-dimensional sand-filled pipe is Ф2.54cm×60cm, and there are five temperature measuring points and 4 pressure measuring points distributed on it.

![Figure 1. Viscosity-temperature curve of heavy oil](image)

3. Experimental procedure
(1) Fill the core model with fine sand of about 100 mesh, and weigh its weight.
(2) Check the air tightness of the core model, and vacuum for 6 hours.
(3) Conduct saturated water test on the core model, weigh the model weight after saturated water and calculate the pore volume.
(4) Use ISCO dual plunger pump to inject at a flow rate of 5 mL/min, measure the inlet pressure, and use Darcy’s law to calculate whether the filled core model meets the expectations.
(5) Connect the experimental instrument as shown in Figure 2, and inject steam and flue gas according to the experimental design parameters.
(6) During the experiment, monitor and record the temperature measuring points and the pressure measuring points on the sand filling pipe in each time.
(7) When the water content in the produced fluid exceeds 98% and the temperature on the sand-filled pipe reaches a stable level, stop the experiment.

The experimental parameters are shown in Table 1 through 3.

| Test No. | Displacement way                  | porosity/% | Permeability /10^3μm^2 | Steam injection rate /(mL·min⁻¹) | Flue gas injection rate /(mL·min⁻¹) |
|---------|----------------------------------|------------|------------------------|----------------------------------|------------------------------------|
| 1       | Steam flooding                   | 34.16      | 3300                   | 1.5                              | 0                                  |
| 2       | Flue gas complex thermal fluid flooding | 34.52  | 3357                   | 1.5                              | 20                                 |
Table 2. Experimental conditions and parameters of cold/hot/steam flooding

| Test No. | Displacement way       | Porosity /% | Permeability /10^{-3}\mu m^2 | Temperature of water injection /°C | Cold/hot/steam injection rate /(mL·min^{-1}) |
|---------|------------------------|-------------|-----------------------------|-----------------------------------|---------------------------------------------|
| 1       | Cold water flooding    | 37.25       | 1689                        | 60                                | 3                                           |
| 2       | Cold water flooding    | 36.65       | 2071                        | 80                                | 3                                           |
| 3       | Hot water flooding     | 35.02       | 1726                        | 100                               | 3                                           |
| 4       | Hot water flooding     | 34.72       | 1965                        | 140                               | 3                                           |
| 5       | Steam flooding         | 36.42       | 1854                        | 200                               | 3                                           |
| 6       | Steam flooding         | 35.19       | 2014                        | 250                               | 3                                           |

Table 3. Experimental conditions and parameters of cold/hot/vapor-flue gas flooding

| Test No. | Displacement way       | Porosity /% | Permeability /10^{-3}\mu m^2 | Temperature of water injection /°C | Cold/hot/steam injection rate /(mL·min^{-1}) | Flue gas injection rate /(mL·min^{-1}) |
|---------|------------------------|-------------|-----------------------------|-----------------------------------|---------------------------------------------|--------------------------------------|
| 1       | Cold water- flue gas flooding | 36.01 | 1829                        | 60                                | 3                                           | 20                                   |
| 2       | Cold water- flue gas flooding | 36.38 | 1927                        | 80                                | 3                                           | 20                                   |
| 3       | Hot water- flue gas flooding | 35.22 | 2018                        | 100                               | 3                                           | 20                                   |
| 4       | Hot water- flue gas flooding | 35.89 | 1796                        | 140                               | 3                                           | 20                                   |
| 5       | Steam- flue gas flooding | 36.19 | 1822                        | 200                               | 3                                           | 20                                   |
| 6       | Steam- flue gas flooding | 35.72 | 2006                        | 250                               | 3                                           | 20                                   |

Figure 2. Flow chart of one dimensional core tube experiment
4. Results and analysis

4.1. Study on temperature field and displacement zone evolution of one-dimensional core tube

We can see from Figure 3 that at the start of 20 minutes of flooding, the temperature at the front end of the model is the highest during steam flooding, and the temperature at the rear end of the model is the lowest. In the flue gas composite hot fluid flooding experiment, with the addition of flue gas, each temperature of the temperature measuring point decreases slowly. At 20 minutes, the temperature at the front end of the model (temperature measuring point 2) is significantly higher than that of the steam flooding by 52°C, and at 40 minutes and 60 minutes. The temperatures at the end (temperature measuring points 4 and 5) are significantly higher than that of the steam flooding by 62°C and 61°C in steam flooding. This is because the injection of flue gas. It improves the distribution of temperature field during the mining process, and expands the heat sweep range of the steam zone and hot water zone, thus improve heat utilization.

![Figure 3](image)

**Figure 3.** The temperature distribution curve of sand-filled tube model under different flooding modes

4.2. Study on flooding characteristics of cold water/ hot water-flue gas flooding stage

4.2.1. Study on the relationship between oil displacement efficiency and injection volume. We can see from Figure 4(a) that the oil displacement efficiency of the four flooding methods are 8.42%, 12.35%, 13.77%, and 15.82%, respectively. It can be seen that the oil displacement efficiency of the cold water/hot water flooding is not good, this is because the oil-water viscosity difference is large, the water content rises quickly, and the hyper-permeable channel is formed, and the water channeling phenomenon is serious. We can see from Figure 4(b) that the oil displacement efficiency of the four flooding methods are 16.07%, 19.26%, 21.4%, and 25.5%. Compared with pure cold water/hot water flooding, the oil displacement efficiency is improved. This is because the injected flue gas has a certain solubility in heavy oil, which can reduce the viscosity of crude oil and improve oil displacement efficiency.
4.2.2. Study on pressure variation- injection volume relationship. It can be seen from Figure 5(a) that the maximum flooding pressure changes of the four displacement methods are 4.47MPa, 3.8MPa, 4MPa and 3.8MPa, respectively. The stable pressure changes of the four flooding methods are 0.79MPa, 0.59MPa, 0.42MPa and 0.38MPa, this is because the flue gas's dissolution, viscosity reduction and elastic driving action are conducive to the penetration of cold water in the porous medium and enhance the fluidity of crude oil in the porous medium. We can see from Figure 5(b) that the maximum flooding pressure changes of the four flooding methods are 4.31MPa, 3.85MPa, 3.64MPa and 3.29MPa, respectively, and the stable pressure changes of the four flooding methods are 0.68MPa, 0.47MPa, 0.36MPa and 0.28MPa, compared with Fig. 5(a), both the flooding pressure changes and the stable pressure changes are reduced.

4.2.3. Study on the relationship between maximum oil recovery velocity and injected volume. It can be seen from Figure 6 that the addition of flue gas can increase the maximum oil recovery rate of the four liquid flooding by 6.4mL/min, 8mL/min, 6.4mL/min and 8.8mL/min, respectively. So that in a longer period of time, it can maintain a high oil flooding speed.
Figure 6. Diagram of maximum recovery rate of cold or hot water/cold or hot water-flue gas flooding at the same temperature

4.3. Study on the displacement characteristics of flue gas assisted steam flooding

It can be clearly seen from Figure 7 that the oil displacement efficiency of composite hot fluid flooding is significantly greater than that of pure steam flooding, which shows that the addition of flue gas can increase the oil displacement rate. The steam flooding mechanism mainly includes viscosity reduction, steam distillation and so on[7-9]. The flue gas flooding mechanism includes expanding the steam swept volume, maintaining reservoir pressure and so on[10-11]. Therefore, because of the steam distillation, the steam sweeps more areas, compared with cold water/hot water- flue gas flooding, which can effectively improve the uneven distribution of hot fluid caused by formation heterogeneity and reduce the residual oil saturation, resulting in higher oil displacement efficiency.

Figure 7. Hot water/steam flooding or hot water/steam- flue gas flooding oil displacement efficiency- injection volume diagram

5. Conclusion

(1) Compared with steam flooding, the flue gas composite hot fluid flooding improves the temperature distribution of the one-dimensional core tube, effectively increases the core temperature, expands the steam zone and the hot water zone, and increases the heat utilization rate. This is the main mechanism for the composite thermal fluid to enhance the recovery factor.

(2) The cold water/hot water flooding efficiency is up to about 16%. This is because the injected water is in the cold water/hot water state, the oil-water viscosity difference is large, and the water channeling phenomenon is serious, which seriously affects the oil displacement efficiency. Cold
water/hot water-flue gas flooding efficiency is higher than cold water/hot water flooding efficiency and maximum oil recovery rate, because the injection of flue gas can reduce crude oil viscosity and improve oil displacement efficiency.

(3) Compared with hot water/hot water-flue gas flooding, the pressure variation and stable pressure variation of cold water/cold water-flue gas flooding are reduced, and the hot water-flue gas flooding is better than hot water flooding. The pressure variation and the steady pressure variation have a downward trend.

(4) Due to the steam distillation effect of steam, the oil displacement efficiency of composite hot fluid flooding is significantly greater than that of pure steam flooding, and the steam sweeps more areas, which can effectively improve the uneven distribution of hot fluid caused by formation heterogeneity. The residual oil saturation is reduced, resulting in higher oil displacement efficiency.

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