Analysis of the characteristics of flue gas foam seepage and its influencing factors

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Abstract. The flue gas foam-assisted steam flooding technology is beneficial to inhibit the steam channeling, delay the steam overriding and improve the heat utilization rate. At the same time, it is also conducive to carbon dioxide storage, which has a broad application prospect. However, the current research on the seepage characteristics and influencing factors of flue gas foam-assisted steam flooding is insufficient. In this paper, the sand pack flooding experiments were carried out by changing the gas-liquid ratio, injection rate, temperature, permeability and other parameters. The results showed that in the case of low gas-liquid ratio, the number and size of foams are small and the connectivity between foams is poor. When the gas-liquid ratio is high, the gas-phase composition is high so that gas channeling occurs and the plugging effect is reduced. Experiments showed that when the gas-liquid ratio is 2:1, the resistance factor is the largest and the plugging performance is the best. When the injection rate is 3mL/min, the foam is stable, which is beneficial to the foam plugging. When the injection rate is lower than 3 mL/min, the foam is sparse and the foam liquid film is thin so that the plugging effect is poor. When the injection flow rate is higher than 3 mL/min, more foam with smaller size will be formed under the influence of shear action, and the Jamin effect on the pore throat will be weakened, which is difficult to be plugged by the foam system. With the increase of experimental temperature, the intermolecular force of the solution was strengthened, the foam volume was enlarged and the liquid film was thinned so that the foam stability and the plugging performance were weakened. Oil saturation has a greater impact on the plugging ability of the flue gas foam. The higher the oil saturation, the weaker the plugging ability is. The research can provide reference for the application of flue gas foam plugging technology.

1. Introduction
The high viscosity and poor fluidity of heavy oil make the development of heavy oil more difficult. Steam flooding is the main method to develop heavy oil at present. However, in the middle and late stage of steam injection development, due to the difference in density and fluidity between steam and oilwater, the phenomenon of overriding flow and fingering in the reservoir is caused and steam channeling occurs in the reservoir with serious heterogeneity. In order to inhibit the unavoidable channeling problem in the process of steam flooding and improve the swept volume of steam, some
novel and effective methods have been proposed, among which the more effective way is to use foaming agent to generate foam in the formation to reduce the fluidity of steam. The existence of foam can effectively slow down the breakthrough of steam. The addition of high temperature resistant foaming agent and flue gas can produce foam in the formation, thus forming stable and high strength foam plugging in the high permeable layer. In this paper, the effects of gas-liquid ratio, injection rate, temperature, permeability, reservoir property and oil saturation on foam sealing characteristics are studied through laboratory experiments, so as to analyze the seepage characteristics of foam.

2. Experimental materials and setup
ZK-25100 (foaming agent); Flue gas; 60 cm sand pack model; Multi-element thermal fluid displacement simulation system; Heating jacket; Temperature collector; Intermediate container; Pressure collector; ISCO double plunger pump; Foam generator; Nitrogen gas cylinder; Carbon dioxide cylinder; Drying tube; Barometer; Check valve; Back pressure valve; Pressure gauge; Measuring cylinder.

3. Experimental procedure
The experimental steps are as follows: 1) Debug experimental equipment to ensure the safety of back pressure valve, check valve and other equipment; 2) The sand pack model was filled with about 80 mesh of fine sand and weighed; 3) Check the air tightness of the model. If the air tightness of each joint is good, start to vacuum for 6 hours; 4) Perform a saturated water experiment on the evacuated sand pack model. When the model no longer sucks in water, weigh the model weight after saturated water to calculate the pore volume; 5) Use ISCO double plunger pump, inject at a flow rate of 10 mL·min⁻¹, measure the pressure at the inlet, when the pressure gauge coefficient is stable, use Darcy’s law to calculate whether the filled core model meets the expected experimental requirements; 6) Connect the experimental instruments according to the flow chart, place the sand pack model in the heating jacket, set the experimental temperature to 300 ℃, connect the injection end to the pressure acquisition system, and connect the outlet end to the 3 MPa back pressure valve. After the temperature stabilizes, perform the foam seepage characteristic experiment.

| Serial number | length /cm | Permeability /10⁻³µm² | Porosity /% | Backpressure /MPa | Experiment temperature /℃ | Foaming injection speed /(mL·min⁻¹) | Gas-liquid ratio |
|---------------|------------|------------------------|-------------|--------------------|---------------------------|-----------------------------------|-----------------|
| 1             | 60         | 3275                   | 32.42       | 3                  | 300                       | 3                                 | 1:2             |
| 2             | 60         | 3251                   | 33.37       | 3                  | 300                       | 3                                 | 1:1             |
| 3             | 60         | 3210                   | 33.15       | 3                  | 300                       | 3                                 | 2:1             |
| 4             | 60         | 3235                   | 32.47       | 3                  | 300                       | 3                                 | 3:1             |
| 5             | 60         | 3237                   | 33.15       | 3                  | 300                       | 3                                 | 4:1             |
| 6             | 60         | 3315                   | 32.57       | 3                  | 300                       | 1.5                               | 2:1             |
| 7             | 60         | 3275                   | 33.45       | 3                  | 300                       | 3                                 | 2:1             |
| 8             | 60         | 3215                   | 33.17       | 3                  | 300                       | 6                                 | 2:1             |
| 9             | 60         | 3324                   | 32.75       | 3                  | 200                       | 3                                 | 2:1             |
| 10            | 60         | 3217                   | 33.43       | 3                  | 250                       | 3                                 | 2:1             |
| 11            | 60         | 2354                   | 33.25       | 3                  | 300                       | 3                                 | 2:1             |
| 12            | 60         | 2500                   | 32.37       | 3                  | 300                       | 3                                 | 2:1             |
| 13            | 60         | 3500                   | 33.14       | 3                  | 300                       | 3                                 | 2:1             |
| 14            | 60         | 5500                   | 32.32       | 3                  | 300                       | 3                                 | 2:1             |
Fig. 1 Flow chart of sand pack experiment

4. Results and analysis

4.1. The effect of gas-liquid ratio on foam seepage characteristics

It can be seen from Figure 2 that the overall trend of the resistance factor with the gas-liquid ratio increases first and then stabilizes. In the steady state of foam flooding, the resistance factor at gas-liquid ratio of 1:2 is 65.5, the gas-liquid ratio is 1:1, the resistance factor is 80.5, the gas-liquid ratio is 2:1, the resistance factor is 92.5, and the gas-liquid ratio is 3:1. The lower resistance factor is 82.3, and the gas-liquid ratio is 4:1. The lower resistance factor is 80.4. When the gas-liquid ratio is less than 2:1, as the gas-liquid ratio increases, the resistance factor increases; when the gas-liquid ratio is greater than 2:1, as the gas-liquid ratio increases, the resistance factor decreases.

This indicates that when gas-liquid is relatively low, foam can be formed in the process of displacement, but the foam mainly exists in the form of a single foam system with poor connectivity or relatively isolated foam system. Meanwhile, the foam liquid film thickness formed becomes thinner, the apparent viscosity becomes lower, and the foam quality is poor. When the gas-liquid ratio is relatively high, the gas-phase content is relatively high. Compared with the condition of low gas-liquid ratio, although foam is formed, too high gas-phase content will cause gas channeling and reduce the sealing ability of foam, which will have a negative impact on oil displacement. The ZK-25100 foam system selected in this paper has the highest resistance factor and the best blocking performance under the condition of 2:1 gas-liquid ratio.

Fig. 2 Relation between resistance factor and gas-liquid ratio

4.2. Influence of injection speed on foam seepage characteristics

As can be seen from Fig.3, in the stable state of foam flooding, the resistance factor at the injection rate of 1.5ml /min is 47.3, the resistance factor at the injection rate of 3ml /min is 92.5, and the resistance
4.2. The influence of injection rate on foam seepage characteristics

The resistance factor at the injection rate of 6ml/min is 52.4. It indicates that when the injection rate is less than 3 mL/min, the displacement pressure rises with the increase of the injection rate. When the injection rate reaches 6 mL/min, the displacement pressure in the gentle stage is lower than 3 mL/min.

The above experimental phenomena can be explained as follows: when the injection velocity of foam is too low, a large number of stable high-quality foam cannot be formed at the port of the core model, and the foam is sparse and the foam liquid film is thin, which results in poor blocking ability. When the injection velocity of foam is too high, the migration speed of foam in the reservoir is accelerated. Under the influence of shear action, the foam is broken through liquid film to form several small-sized bubbles. When the foam is transported to the pore throat, the size of the foam decreases, the jiamin effect weakens, and the blocking ability decreases, which is manifested as the decrease of the resistance factor on the macro level. The zK-25100 foam system selected in this paper has the highest resistance factor and the best blocking performance at the injection rate of 3 mL/min.

![Fig.3 Relation between resistance factor and injection speed](image)

4.3. The influence of temperature on foam seepage characteristics

It can be seen from Figure 4 that the resistance factor first rises and then stabilizes with the change trend of the experimental temperature. At 200 °C, 250 °C and 300 °C, when the injection volume reaches 2 PV, the resistance factor is stable, and the corresponding resistance factors are 121.3, 103.5 and 92.5 respectively.

The above-mentioned experimental phenomenon can be explained as: temperature has a greater influence on the sealing performance of the foam, the higher the temperature, the smaller the resistance factor. The main reason for this phenomenon is that the active ingredients in the solution strengthen the intermolecular force under high temperature conditions, which causes the foam to expand and increase in volume, which causes the liquid film of the foam to become thinner and easy to rupture, and the stability of the foam quality will change. Poor, macroscopically manifested as reduced plugging performance.

![Fig.4 Relation between resistance factor and temperature](image)
4.4. Influence of Permeability on Foam Seepage Characteristics

It can be seen from Fig. 5 that, in the process of foam displacement, the change curve of resistance factor is mainly divided into two stages: the rising stage and the gentle stage. When the foam injection volume reaches about 1 PV, the displacement phenomenon is stable, the resistance factor is 52.5 under the permeability of \(2500 \times 10^{-3} \mu \text{m}^2\), the resistance factor is 92.5 under the permeability of \(3500 \times 10^{-3} \mu \text{m}^2\), and the permeability is \(5500 \times 10^{-3} \mu \text{m}^2\). The lower resistance factor is 112.5, that is, the higher the permeability, the better the foam's plugging performance, which is consistent with the foam's "blocking big but not small" property.

The above-mentioned experimental phenomenon can be explained as: when the core permeability is low, the corresponding pore throat radius is small, and the foam is a power-law fluid. Under the influence of shear, the foam migrates in the low-permeability reservoir and the foam becomes thinner, lower viscosity, poorer stability, and reduced plugging effect. On the other hand, a smaller pore throat radius will cause the diameter of the produced foam to be smaller. When the foam enters a slightly larger pore throat, the size of the foam is small. Cannot form a good plugging effect; when the core permeability is high, the corresponding pore radius increases, the size of the foam generation becomes larger, the displacement resistance is reduced, and the shearing effect is less affected. The stability and sealing of the foam The plugging capacity has been improved. On the other hand, since larger-sized foam can be formed in the high-permeability layer, when it encounters a reservoir with a lower permeability during the migration process, the foam deforms at the pore throats. The appearance of "Ja min phenomenon" enhances the blocking effect.

![Fig.5 Relation between resistance factor and permeability](image)

4.5. Influence of reservoir properties on foam seepage characteristics

As can be seen from FIG. 6, the variation trend of the resistance factor with the amount of injection under different reservoir properties shows, in the core model of saturated water, with the increase of the amount of foam injection, the displacement pressure rises rapidly and finally remains flat. In the core of saturated oil model, because the foam has the nature of the "in oil defoaming", low degree of initial stage of mining, oil saturation, decline of foam stability, high quality, displacement pressure change is not obvious, with the continuous injection of bubble, core model oil saturation declines, foam stability, flow resistance increases, the macro is shown on the wave amplitude decreases, and injection pressure.
4.6. The Influence of Oil Saturation on Foam Seepage Characteristics

It can be seen from the variation trend of resistance factor with oil saturation in Fig. 7 that the resistance factor is in a continuous decreasing process with the increase of oil saturation. When the oil saturation ranges from 0 to 15%, the drag factor decreases less and the foam has better blocking performance. When the oil saturation is within the range of 10-35%, the resistance factor drops sharply, indicating that the foam has poor stability under the condition of high oil content. When the oil saturation is above 35%, the drag factor drops to a small extent, basically maintaining around 20.

The above-mentioned experimental phenomenon can be explained as: as the oil saturation increases, the resistance factor shows a downward trend. When the oil saturation is high, the crude oil and the foam will emulsify to form small oil droplets into the foam system, causing the foam to burst and the stability to deteriorate, which is consistent with the foam's "oil-influenced defoaming" property. When the oil saturation is low, the influence of crude oil on the foam is small, and the foam can exist stably and the sealing performance is good. This also explains that when switching to flue gas foam assisted steam flooding in the later stage of steam flooding, due to the low oil saturation of the high permeability layer, crude oil has little effect on foam stability. At this time, stable foam bands can be formed, which can effectively block high Permeable layer, forcing steam and surplus foam to displace the next permeable layer, and the recovery degree increases; when foam and steam enter the low permeability layer, because of the higher oil saturation, crude oil affects the foam stability larger, stable foam bands cannot be formed at this time, and the blocking ability is reduced, but the foam solution is a surfactant. At this time, the emulsification of the magic solution and crude oil is strengthened, which reduces the oil-water interfacial tension and improves the rheology. The flow resistance is reduced and the oil displacement efficiency is improved.

5. Conclusion

(1) Comparing the plugging performance of flue gas foam with different gas-liquid ratios, the gas-liquid ratio is too low, the number and size of the foam formed are small, and the connectivity between the foams is poor; the gas-liquid ratio is too high, and the gas-phase composition is too high, "Gas channeling" appears, and the blocking effect is reduced. The ZK-25100 foam system selected in this
paper has the highest resistance factor and the best blocking performance under the condition of 2:1 gas-liquid ratio.

(2) Compared with the plugging performance of flue gas foam at different injection speeds, the resistance factor of ZK-25100 foam system was the largest at 3mL/min. The injection velocity is too low, the foam is sparse, the foam liquid film is thin, and the sealing effect is poor. If the injection velocity is too high and the foam is affected by the shearing action, more bubbles of smaller size will be formed, and the jasmine effect on the pore throat will be weakened, which is not easy to be blocked by the foam system.

(3) With the increase of the experimental temperature, the effective components in the solution strengthened the intermolecular force under the high temperature condition, the foam volume increased, the liquid film became thinner, the stability became worse, and the plugging performance was continuously weakened.

(4) The foam has the property of "no more blocking". When the permeability is in the range of 5500×10^-3 m², the plugging performance of ZK-25100 foam increases with the increase of permeability.

(5) Oil saturation has a great influence on the plugging ability of flue gas foam. The higher the oil saturation is, the weaker the plugging ability is.

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