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Original Paper

The mechanisms of thermal solidification agent promoting steam diversion in heavy oil reservoirs

Zhan-Xi Pang [a,*], Qian-Hui Wang [a], Qiang Meng [b], Bo Wang [c], Dong Liu [d]

[a] State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), Beijing, 102249, China
[b] Liaohe Oilfield Institute, CNPC China, Panjin, 124000, Liaoning, China
[c] Henan Oilfield Institute, Sinopec China, Nanyang, 473400, Henan, China
[d] Tianjin Branch of China National Offshore Oil Company (CNOOC) Ltd., Tianjin, 300452, China

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A B S T R A C T

At high cycles of steam huff & puff, oil distribution in reservoirs becomes stronger heterogeneity due to steam channeling. Thermal solidification agent can be used to solve this problem. Its solution is a low-viscosity liquid at normal temperature, but it can be solidified above 80 °C. The plugging degree is up to 99% at 250 °C. The sweep efficiency reaches 59.2%, which is 7.3% higher than pure steam injection. In addition, simultaneous injection of viscosity reducer and/or nitrogen foams can further enhance oil recovery. The mechanism of this technology depends on its strong plugging ability, which changes the flowing pattern of steam to effectively mobilize remaining oil. Viscosity reducer and nitrogen foams further expand the sweep range and extends the effective period. Therefore, thermal solidification agent can plug steam channeling paths and adjust steam flowing direction to significantly enhance oil recovery at high cycles of steam huff & puff.

1. Introduction

Heavy oil resources are widely distributed worldwide, representing over 20% of global oil resources (Dong et al., 2019; He et al., 2022; Wang et al., 2023). However, in contrast to conventional crude oil, the development of heavy oil reservoirs presents great challenges due to high viscosity and low hydrogen-to-carbon ratio, as well as high content of asphaltenes, sulfur, and heavy metals under reservoir conditions (Speight, 2009; Wang et al., 2013; Bai et al., 2022). Typically, it is essential to reduce oil viscosity for developing heavy oil reservoirs. Therefore, the thermal recovery methods, such as, steam huff & puff, steam flooding, in-situ combustion and steam-assisted gravity drainage, are widely used in heavy oil reservoirs (Tagavifar et al., 2016; Wu et al., 2018; Lu et al., 2019; Moussa et al., 2019). The principle of thermal recovery involves injecting high-temperature steam into the formation, which can heat the oil layer to reduce heavy oil viscosity and improve its mobility.

In the early stages of steam injection, the heat is highly effective to mobilize heavy oil resulting in an optimal oil recovery factor. However, as the steam injection progresses, the thermodynamic conditions of reservoir changes to increase the possibility of steam channeling (Wang et al., 2016; Pratama and Babadagli, 2020). This phenomenon involves steam flowing along high-permeability layers and steam override, leading to the production of hot water and even steam from production wells. This can reduce heat efficiency and significantly influence on the oil production of surrounding wells (Li et al., 2020; Pang et al., 2021). Thus, in order to address the problem, it is necessary to reduce formation heterogeneity and control steam channeling during developing heavy oil reservoirs.

In order to expand the swept volume of steam and alleviate the steam channeling between wells, it is essential to effectively plug the paths of high permeability during steam huff & puff (Gharibshahi et al., 2019). In recent years, chemical blocking methods were emerged as the successful technique for heavy oil reservoirs (Cheng et al., 2022; Wang et al., 2020). Various chemical methods have been utilized in heavy oil field tests, including high-

* Corresponding author.
E-mail address: pxiad9827@cup.edu.cn (Z.-X. Pang).

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temperature gels, foams, solid particles and etc (Petkova et al., 2012; Zhao et al., 2014, 2018; Sharifipour et al., 2019). The gels are composed of high-temperature polymers and crosslinking agents. Despite their successful implementation in many heavy oil reservoirs, the gels are susceptible to shear degradation and dilution effects (Al-Muntasheri et al., 2008). Generally, the temperature range of gel systems is applicable below 200 °C. Nitrogen foams are identified as one of the most effective agents for controlling high-temperature profiles and improving steam sweep efficiency in heavy oil reservoirs (Zhao et al., 2022). Foams are found to reduce steam mobility to suppress steam override due to their low-density characteristics and to prevent steam breakthrough due to their strong plugging ability (Liu et al., 2020). In field applications, the technology of nitrogen foams is proved to be particularly effective in weakening steam override, balancing steam injection profiles, expanding steam swept volume, and enhancing oil recovery (Zhang et al., 2023b). Scholars studied the phenomenon of steam override in heavy oil reservoirs and the plugging mechanisms of foams through a two-dimensional visualization apparatus during steam injection (He et al., 2020; Araujo et al., 2021; Wang et al., 2023). However, the application of foam systems requires large amounts of N_2 or CO_2, and the effective period of foam systems in porous media is significantly shortened at high-temperature. Furthermore, the thermal stability of foaming agents further limits the effective period of foam systems (Li et al., 2011; Zhao et al., 2015). Solid particles are another important agent for steam channeling in heavy oil reservoirs. However, their poor injection performance limits their effectiveness during steam injection in heavy oil reservoirs, despite their strong resistant high temperature. A significant amount of remaining oil still occupies near-wellbore even after multiple cycles of steam huff & puff. When the paths of steam channeling are formed among wells, it becomes increasingly difficult to recover the remaining oil. As the cycles of steam huff & puff increase, the types of steam channeling become increasingly complex and the number of steam channeling wells gradually increases, which leads to a serious impact on the production stability of heavy oil reservoirs (Li et al., 2023; Zhang et al., 2023a).

The technology of thermal solidification agent is used to plug steam channeling paths and improve oil displacement efficiency during higher cycles of steam huff & puff in heavy oil reservoirs. The use of chemical systems, such as, foams and viscosity reducers, further improves the development effect of steam huff & puff (Tao et al., 2022). Additionally, the thermal solidification agent possessed the potential to serve as good alternatives to conventional chemical agents for controlling steam channeling paths among wells in heavy oil reservoirs.

2. Basic physical properties

In the processes of steam huff and puff, there is a phenomenon of steam channeling due to the inhomogeneity among oil layers and within one oil layer. In higher permeability oil layer, there is a stronger ability of steam injection, while in lower permeability oil layer, there is a weaker ability of steam injection and even no steam injection. After several cycles of steam injection, a path of steam channeling gradually forms, resulting in the interference among wells. Therefore, the oil production will be greatly reduced during steam huff and puff. At present, one of the most effective methods to solve this problem is a new technology of high temperature agent for profile control. As a kind of agent being stable at high temperature, it must have the characteristics of long-term resistance at steam temperature (above 300 °C), and meanwhile, it should have a certain resistance strength for steam washing, in order to ensure that steam does not enter the blocked oil layer.

The thermal solidification agent is a kind of high-molecular substance that is generated through the polycondensation reaction of low-molecular substance (Cao et al., 2012). It shows the morphology of thermal solidification agent at different states, as shown in Fig. 1. In general, it is a kind of white solid before dissolving into water, as shown in Fig. 1(a). However, it can easily dissolve into water and become low viscosity transparent solution whose viscosity is lower than 30 mPa·s, as shown in Fig. 1(b). Therefore, the solution can easily be injected into porous media and quickly becomes solidification state under high temperature or steam injection, as shown in Fig. 1(c). At lower temperature, if the agent is injected into high-permeability oil layers, then it becomes a hard and non-permeable solid under higher temperature over 80 °C to plug high-permeability zones. This agent presents a plugging performance of high strength and long effective period. Therefore, it can be suitable for sealing high-permeability layers, fractures, holes and even large channels.

The thermal solidification agent is a composite system of solid-phase inorganic resin-gel through the crosslinking effect at high temperature. It includes a high strength skeleton that is solidified from the thermosetting resin and some inorganic substances that can combine with the resin. The agent has a long effective period to tolerate high temperature and strong steam washing. Therefore, the agent can be employed to realize deep profile control and resist steam from channeling.

In order to strengthen the resistant ability of high temperature and the strong plugging ability of steam channeling, the optimum components are studied according to the experiments of solidification time. The experiments are carried out to analyze the influence of different components on the solidification time. The components include the thermal solidification resin, the crosslinking agent and the inorganic substances.

(1) The thermal solidification resin

As the main component, the thermal solidification resin influences the solidification time in a certain and mainly impacts on the solidification strength. The own properties of resin have a greater impact on the solidification strength, mainly including the polymerization degree and the length of molecular chain. The solidification reaction is carried out at the formation temperature of 50 °C. The concentration of crosslinking agent is 10%. The experimental results are listed in Table 1. The results show that if the resin concentration is less than 10%, the thermal solidification agent still be at liquid state. When the resin concentration is 12%, the solidification strength is slightly worse. When the resin concentration is above 15%, the solidification time is lower than 12 h and the strength is very large. According to the experimental results, the resin concentration is selected from 15% to 20%.

(2) The crosslinking agent

The experiment is carried out at 50 °C. The resin concentration is 15%. The concentrations of crosslinking agent are chosen 2%, 4%, 6%, 8%, 10% and 12%. The results are listed in Table 2. The results show that the solidification time gradually decreases as the concentration of crosslinking agent increases. When the concentration is from 10% to 12%, the solidification time is lower than 12 h. Therefore, the concentration of crosslinking agent is selected 10%.

(3) The inorganic substances

The experiment is carried out at 60 °C, and the resin concentration is 15%. The concentrations of crosslinking agent are chosen 10%. The concentrations of inorganic substances are chosen 5%, 10%, 15%, 20% and 25%. The results are listed in Table 3. The results show

(a) Original state **(b)** Liquid state **(c)** Solid state **(d)** After solidification in porous media

Fig. 1. The morphology of thermal solidification agent under different states.

Table 1
The influence of resin concentration on solidification time.

Concentration, %	5	10	12	15	20	25
Solidification time, h	No solidification	No solidification	20	12	12	11

Table 2
The influence of the concentration of crosslinking agent on solidification time.

Concentration, %	2	4	6	8	10	12
Solidification time, h	59	52	31	23	12	8

Table 3
The influence of the concentration of inorganic substances on solidification time.

Concentration, %	5	10	15	20	25
Solidification time, h	12	12	12	12	11

that the solidification time presents a trend of slight reduction as the concentration increases. However, the inorganic substances greatly influence the solidification strength.

Based on the above experimental results, the experiments are carried out to measure the properties of the thermal solidification agent. The experimental results are listed in Table 4. The results demonstrate that the thermal solidification agent maintains a degree of volume retention of 100% after one day across the temperature range from 80 to 300 °C, without exhibiting any failure. After 15 and 30 days, the degree of volume retention peaks between 100 and 120 °C, with a slight decline at higher temperatures. Even at 300 °C, the thermal solidification agent retains a degree of volume retention of 94.5% after 30 days, which indicates an excellent stability.

At room temperature, the viscosity of water solution is below 30 mPa s. Therefore, it is a kind of low viscosity fluid that is easily injected into porous media. Above 80 °C, the agent quickly transforms solidification with plugging pressure gradient exceeding 3 MPa/m and temperature resistance above 300 °C. The details of relevant parameters are listed in Table 5.

The diversion processes of steam in porous media are demonstrated after the thermal solidification agent is injected into the sweep zone, as shown in Fig. 2. Due to its low permeability resistance, the thermal solidification agent predominantly flows into the high-permeability region (region A), as depicted in Fig. 2(a). When the solution of thermal solidification agent is injected into sweep zone, it occupies the pores in region A, as shown in Fig. 2(b). However, when steam is injected into sweep zone, thermal solidification agent quickly solidifies and occupies the pores in region A, as shown in Fig. 2(c). That causes steam to divert and flow into region B. As steam progressively diverts and flows into region B, the oil saturation decreases and the absolute permeability significantly decreases. When the thermal solidification agent plugs region B, steam is turned to another area with higher oil saturation, as demonstrated in Fig. 2(d). Ultimately, the steam channeling is suppressed and even plugged to expand the sweep efficiency and to improve oil recovery factor.

In summary, the thermal solidification agent is effective to plug high-permeability zones and water/steam channeling paths in a formation. Due to the high plugging strength and the extended effective period, the agent can be utilized to plug various types of formations and it is a suitable choice for a wide range of applications.

Table 4
The experimental results on thermal stability of thermal solidification agent.

Temperature, °C	Volume retention rate, %		
	After 1 day	After 15 days	After 30 days
80	100	96.3	94.8
90	100	97.5	96.0
100	100	100	98.5
120	100	100	98.8
150	100	99.5	98.5
200	100	98.8	97.8
250	100	97.5	96.3
300	100	96.4	94.5

Table 5
Basic parameters of thermal solidification agent.

Performance	Parameters
Initial viscosity	< 30 mPa s
Solidification temperature	> 8 °C
Plugging pressure gradient	> 3 MPa/m
Plugging degree	> 99%
Temperature resistance	> 300 °C
Washing-resistant ability	> 70 PV

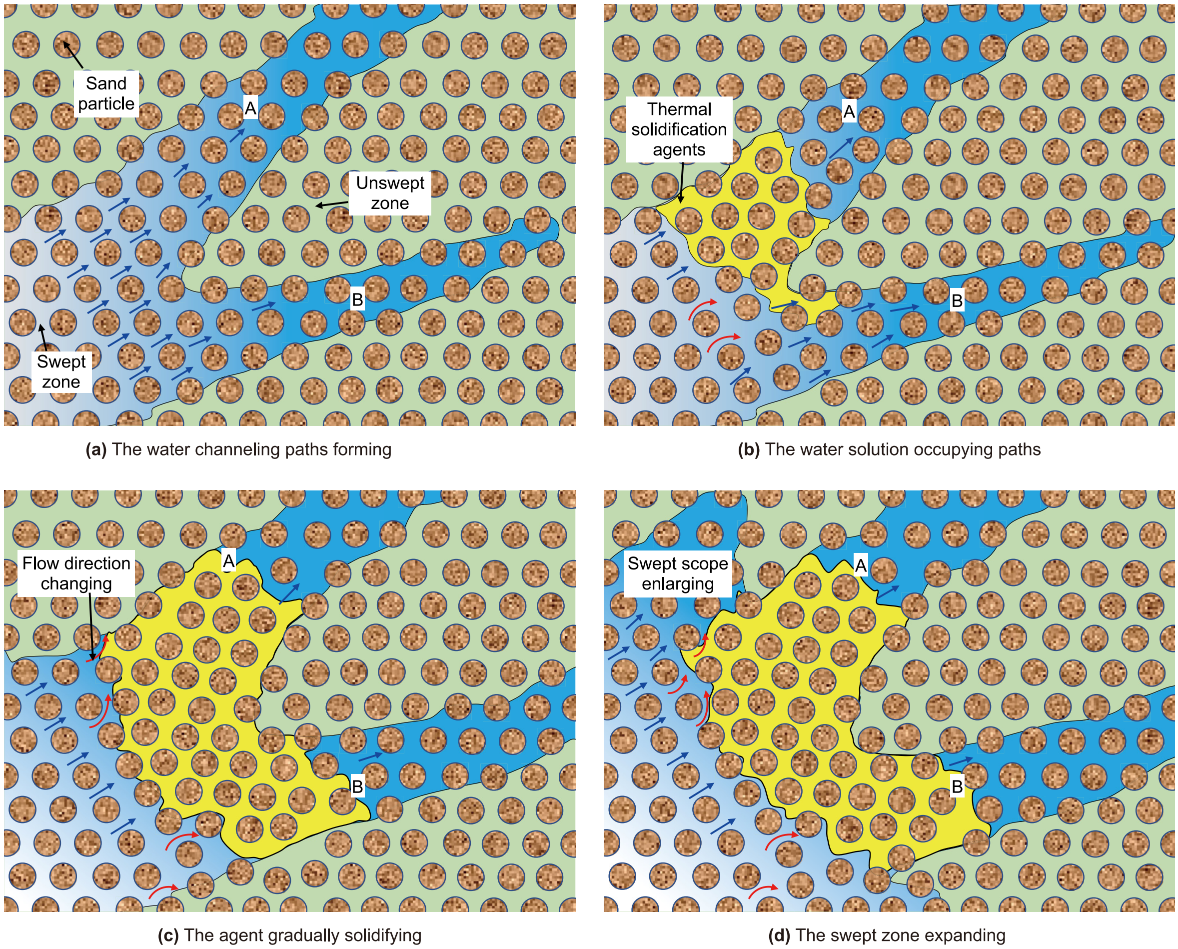


Fig. 2. The schematic of thermal solidification agent promoting steam diversion.

3. Experimental apparatus and procedures

The sample of heavy oil used in this study was obtained from a heavy oil reservoir in China. The oil sample was degassed before experiment. Its density is 0.969 g/cm^3 and the viscosity is 9616.1 mPa s. The formation water is classified as sodium bicarbonate type and the total salinity is approximately 6530 mg/L. The original temperature of the reservoir is approximately 30 °C. It is characterized as a conventional heavy oil reservoir with high porosity and permeability. After multiple cycles of steam huff & puff, the injected steam suffered from ineffective circulation and serious steam channeling. That led to the migration of solid particles and the formation of steam channeling paths in heavy oil reservoirs. To address this problem, a thermal solidification agent was utilized to plug steam channeling paths. In order to further improve the development effect of steam huff & puff, nitrogen foams or viscosity reducer can be injected following the thermal solidification agent.

3.1. The experiments of plugging ability

As shown in Fig. 3, the plugging experiments are conducted according to the schematic. The experimental devices are composed of four major systems, such as, injection system, physical model, data acquisition system and production system. The physical model is consisted of a 60-cm-long sand-pack with a 3.8-cm inner diameter. The thermostat is utilized to simulate reservoir temperature. The injection system is composed of a steam generator, a gas injection device, an injection pump, a tank of thermal solidification agent, a tank of formation water container and etc. For steam generator, the maximum temperature is 350 °C and the production flux of steam is 2 L/h. The gas injection device is employed to test sealing performance of whole experimental system. The data acquisition system is composed of pressure sensors, differential pressure sensors, data converters and a computer. The production system includes a back pressure valve for controlling outlet pressure to ensure the saturation state of steam injection, as well as a measuring cylinders and the other devices.

Experimental procedures are listed as follows.

(1) Measuring the initial porosity and the absolute permeability of sand-pack. First, after filling the sand-pack with quartz sands, the total mass is weighed. Then, the sand-pack is vacuumed to saturate the formation water, and then the total mass is weighed again. Therefore, the volume of saturated water is calculated according to the mass difference and the density of formation water. Next, the porosity of the sand-pack is calculated, and the absolute permeability is measured according to Darcy's law.
(2) Injecting thermal solidification agent into the sand-pack. An injection pump is used to inject the agent solution into sand-pack at a flux of 5 mL/min until the injection volume reaches 0.2 PV (approximately 10 min).

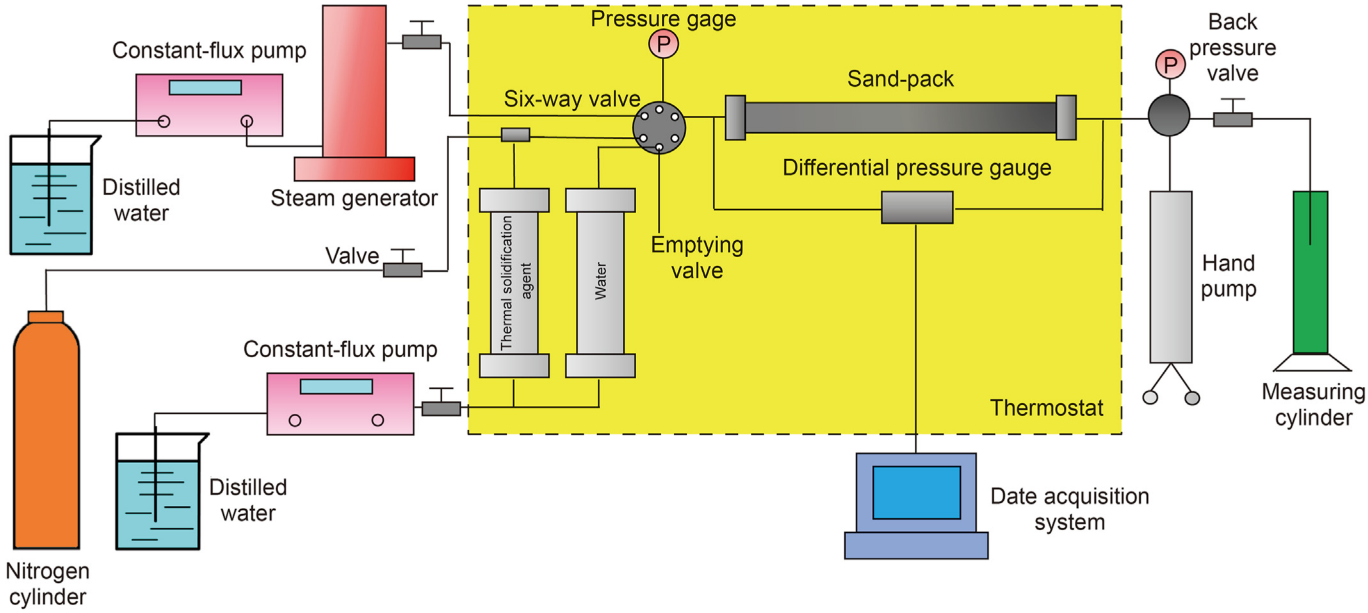


Fig. 3. The schematic of plugging ability experiment.

(3) Maintaining the temperature constant until the thermal solidification agent completely solidifies. The valves at both ends of sand-pack are closed and the thermostat is set to the experimental temperature for 24 h to make the thermal solidification agent fully solidify in the sand-pack.
(4) Testing the plugging ability of the thermal solidification agent. The steam generator and the electric heating belts wrapping around the pipelines are set to the experimental temperature. The experiments are implemented when the temperature of steam reaches the predetermined temperature. The experimental parameters, such as, mass flux, pressure, temperature and pressure difference, are continuously recorded to calculate breakthrough pressure and plugging degree.
(5) Measuring the permeability of water phase after plugging. Until the entire experimental system is cooled to room temperature, the permeability of sand-pack is measured again. The flow rate of water phase and the pressure difference are measured after water breakthrough again and the permeability of water phase after plugging is calculated according to Darcy's law.

3.2. 3D scaling physical simulation

As shown in Fig. 4(a), the experimental system is divided into four units.

(1) Injection unit, which is comprised of a steam generator, two constant-flux pumps, a nitrogen cylinder, a booster pump, a gas storage tank, an air compressor, a gas mass flowmeter, a foaming agent container, a formation water container, a viscosity reducer container, an electric heating belt, some valves, etc.
(2) Data acquisition unit, which is consisted of some pressure sensors and temperature sensors, a data conversion module, a data acquisition system and a computer.
(3) Reservoir model, which includes a thermostat, a 3D model, and three well models. For the 3D model, the inner width is 36 cm. The resistant pressure and temperature are over 5 MPa and 300 °C, respectively.
(4) Production unit, which includes a backpressure control device, a drying oven, a stopwatch, some measuring cylinders, a balance and etc.

As shown in Fig. 4(b), inside the 3D model, there are three straight wells to simulate steam huff & puff. A high-permeability strip is located between Well 1 and Well 2 to cause steam channeling. Beginning from Well 1, the three wells are implemented steam huff & puff in sequence for eight continuous cycles.

The field parameters are converted into the experimental parameters by using similarity criteria, and the experimental parameters are listed in Table 6.

The experimental procedures are listed as follows.

(1) A sand-pack is filled with a certain number of quartz sands to measure its permeability and porosity. And then the particle sizes of quartz sands are continuously adjusted to satisfy the permeability-porosity requirements of 3D physical simulation.
(2) After the oil sample is degassed, dehydrated and removed sands, the mixtures of heavy oil and quartz sands at a specific volume ratio are mixed thoroughly to form the predetermined oil saturation.
(3) The simulated wells are wrapped with a fine mesh and then are installed at designated positions inside the 3D scaling model.
(4) A layer of clay is filled into the bottom of the 3D scaling model to simulate the bottom layer in heavy oil reservoir. Then, the model is filled with the mixtures of oil sands. During the processes, every layer of oil sands is compacted and is installed the thermocouples at the specified positions until the designed thickness.
(5) The other layer of clay is filled into the top of the oil layer to simulate the cap layer in heavy oil reservoir. Then, the clay layer is compacted to seal the oil layer in 3D scaling model.
(6) After the 3D scaling model is filled, all experimental devices are connected by pipelines according to the experimental

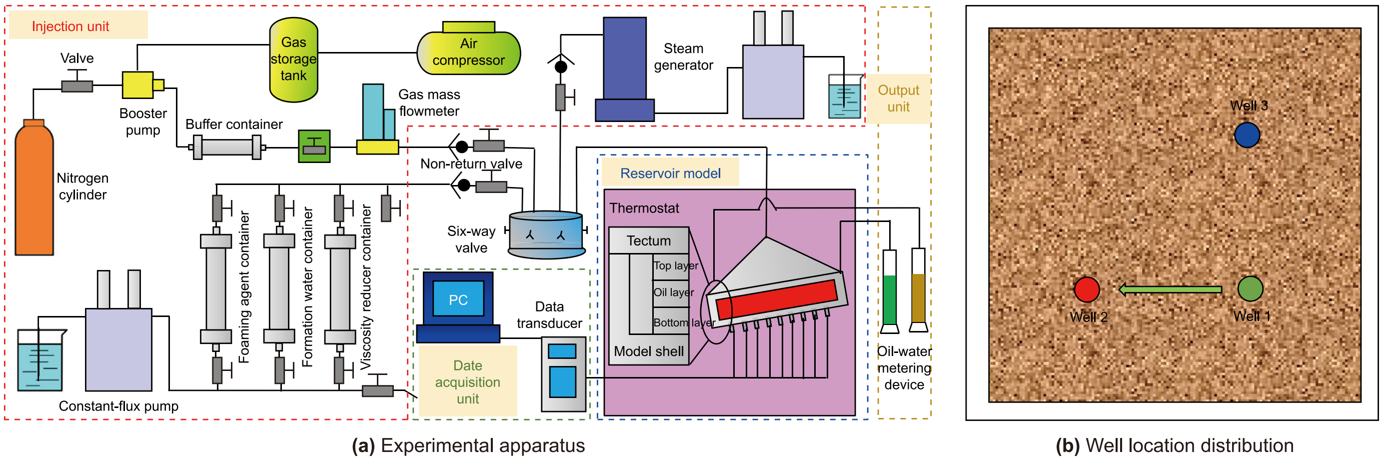


Fig. 4. The schematic of 3D scaling physical simulation and well location distribution.

Table 6
The table of 3D physical simulation parameters.

Parameter	Field	Model
Net pay, cm	2000	6.5
Porosity, %	32	35
Initial oil saturation, %	70	100
Mobile oil saturation, %	40	40
Absolute permeability, μm^2	2.1	20.0
Irreducible water saturation, %	30	30
Oil viscosity at 30 °C, mPa s	9616.1	9616.1
Oil density at 30 °C, g/cm^3	0.95	0.95
Steam temperature, °C	300	300
Initial temperature, °C	30	30
Steam quality, decimal	0.7	0.7
Comprehensive compression coefficient, 1/MPa	0.00005	0.009
Thermal diffusion coefficient of rock, m^2/h	0.00197	0.00197
Latent heat of steam, kJ/kg	1402.2	1402.2

schematic. Then nitrogen gas is introduced to check for airtightness under a certain pressure.

(7) Before steam huff & puff, the temperature of the thermostat is set to 30 °C, and the temperatures of steam generator and electric heating belts are both set to 300 °C. The experiment is carried out when the steam reached the designed temperature.

(8) The experiment of steam huff & puff is implemented in the sequence of Well 1, Well 2, Well 3 and so on. The three wells are switched on in turn for steam injection, soaking, production. Each cycle is terminated when no liquid is produced and the next cycle is carried out. The volume of liquid, oil, and water is measured by the volume cylinders.

(9) Until the steam channeling path connecting between Well 1 and Well 2, the solution of thermal solidification agent is injected into oil layer from Well 2. After 24 h, the experiments of steam huff & puff are sequentially carried out beginning from Well 2, followed by Well 1, and then Well 3, and so on. The experiments are implemented for three cycles.

(10) The experiments of viscosity reducer assisted steam huff & puff are carried out. After the solution of thermal solidification agent is injected into oil layer from Well 2. After 24 h, a specific amount of viscosity reducer is co-injected with steam into each well. The experiments are implemented for three cycles.

(11) Finally, the experiments of nitrogen foams assisted steam huff & puff are carried out. After the solution of thermal solidification agent is injected into oil layer from Well 2. A specific amount of nitrogen foams is firstly injected into the three wells and then steam is injected into the wells. The experiments are implemented for three cycles.

4. Experimental results and analysis

4.1. Plugging performance

(1) The influence of temperature on plugging performance

To investigate the effect of temperature on the plugging performance of the thermal solidification agent, a series of experiments are carried out at temperatures of 150, 200, and 250 °C. The experimental results are shown in Table 7 and Fig. 5.

The plugging pressures difference of sand-pack are shown in Fig. 5. The plugging pressure difference displays a slight downward trend when the injection volume exceeds 35 PV. As listed in Table 7, the plugging pressure difference gradually decreases with temperature increasing, which indicates that the plugging performance of the thermal solidification agent is greatly affected by temperature. When the temperature is lower than 200 °C, the plugging pressure difference only slightly decreases. However, it decreases to a larger degree when the temperature is at 250 °C. Generally, the plugging degree at all three temperatures remains higher than 99%, which indicates that the thermal solidification agent retains strong plugging ability even at high temperatures and can be effectively used for resisting steam from channeling between wells. These results confirm a strong plugging performance to decrease steam mobility and a strong resistant flushing ability during steam injection in heavy oil reservoirs with varying permeability.

(2) The influence of permeability on plugging performance

Experimental investigations are carried to examine the impact of permeability on the plugging performance of a thermal solidification agent under three different permeability conditions, such as, 1288×10^{-3}, 2865×10^{-3}, and 4682×10^{-3} μm^2.

As listed in Table 8, the plugging pressure difference gradually decreases with increasing permeability, but the plugging degree remains above 99% under the three permeability conditions. It indicates that the thermal solidification agent exhibits strong

Table 7
The plugging pressure difference at different temperature.

Temperature, °C	Porosity, %	Permeability before plugging, 10^{-3} μm^2	Permeability after plugging, 10^{-3} μm^2	Plugging degree, %	Plugging pressure difference, MPa
150	37.45	2370	2.10	99.91	2.00
200	32.97	2133	13.13	99.38	1.20
250	38.06	2482	10.50	99.62	0.40

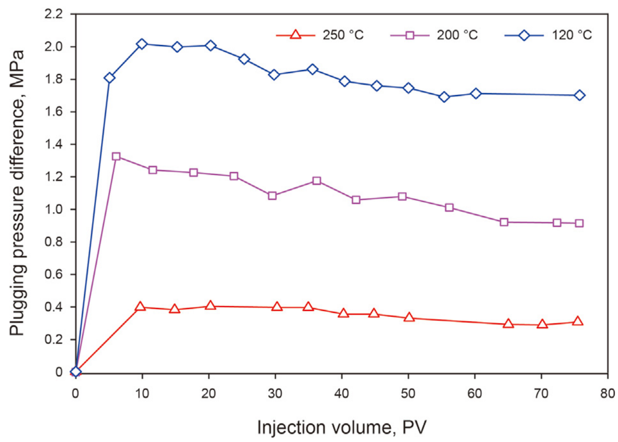


Fig. 5. The curves of plugging pressure difference vs. injection volume at different temperature.

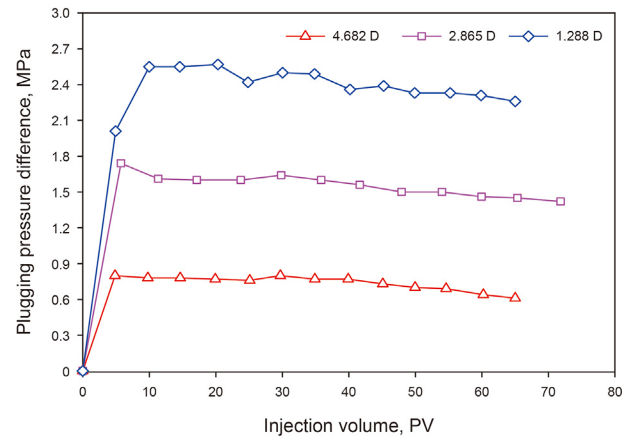


Fig. 6. The curves of plugging pressure difference vs. injection volume at different permeability.

plugging ability in high-permeability reservoirs and can be used to control steam breakthrough. As observed in Fig. 6, the plugging pressure difference at both ends of the sand-pack remains almost constant when the steam injection volume is lower than 35 PV under the three permeability conditions. However, when it exceeds 35 PV, the plugging pressure difference shows a slight downward trend. The results demonstrate that the thermal solidification agent possesses a strong plugging performance and a strong resistant flushing ability in heavy oil reservoirs.

During the injection of thermal solidification agent, it gradually solidifies under high-temperature conditions in heavy oil reservoirs. Therefore, the high-permeability steam channels are sealed off to make steam or hot water change flowing direction to a zone of higher oil saturation. According to the experimental results, the thermal solidification agent retains the strong plugging ability to exhibit a good adaptability for reservoirs with varying permeability and maintain a plugging degree over 99%. As a result, it effectively achieves a strong plugging performance for large channels.

(3) The influence of oil saturation on plugging performance

The influence of oil saturation on the plugging performance agent is studied by using the sand-pack model. First, steam flooding is carried out to form the different conditions of oil saturation at 200 °C. Then, 0.3 PV of the thermal solidification agent is injected into the sand-pack model at normal temperature. The thermal solidification agent is kept constant temperature of 120 °C for 12 h.

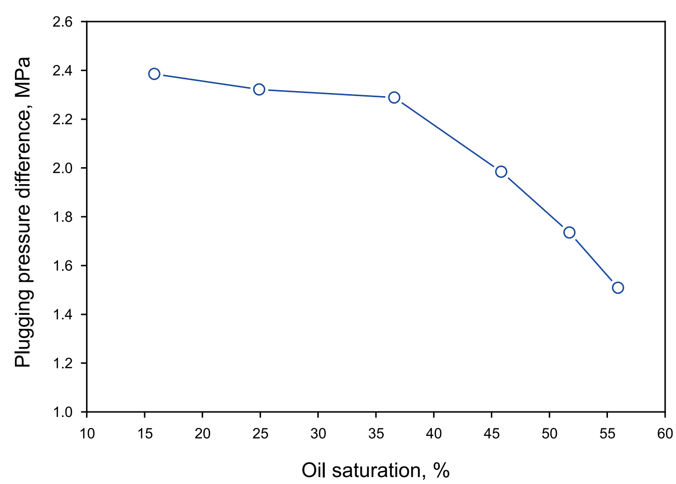


Fig. 7. The curves of plugging pressure difference vs. oil saturation.

Finally, the plugging pressure difference is measured at 200 °C. The experimental results are shown in Fig. 7. The plugging ability is very sensitive to oil saturation. As the oil saturation increases, the plugging pressure difference decreases slightly when the oil saturation is lower than 38%. However, it still maintains a relatively high level above 1.5 MPa when the oil saturation is higher than 56%, which can meet the needs of plugging steam channeling.

Table 8
The plugging pressure difference under different permeability at 200 °C.

Permeability before plugging, 10^{-3} μm^2	Porosity, %	Permeability after plugging, 10^{-3} μm^2	Plugging degree, %	Plugging pressure difference, MPa
1288	37.45	1.05	99.91	2.50
2865	32.97	10.53	99.63	1.60
4682	38.06	19.76	99.58	0.70

According to the above experimental results, under the high temperature of 300 °C, the degree of volume retention is still 94.5% after 30 days, which shows that the stability of resistant temperature is excellent. The plugging pressure gradient is 17.33 MPa/m when the permeability is 1.3 μm^2, and it still exceeds 10 MPa/m when the permeability is 3.5 μm^2. The pressure gradient still reaches 4.66 MPa/m after the injection volume of steam is over 75 PV, which shows that the plugging ability is strong. The plugging pressure gradient still reaches 3.33 MPa/m at 250 °C, and the pressure gradient still reaches 2.58 MPa/m after the injection volume of steam is over 75 PV, which shows that the thermal solidification agent has a great resistance of high temperature.

4.2. 3D experimental results

(1) Variation of bottomhole temperature

Fig. 8 illustrates the curves of bottomhole temperature vs. time for three simulated wells. The results reveal that the bottomhole temperature of Well 2 experiences a sudden rise during the steam injection of Well 1, which indicates thermal interference between the two wells. As the cycles increases, the degree of thermal interference gradually intensifies between Well 1 and Well 2. By the fifth cycle, the bottomhole temperature during steam injection from Well 1 is approximately equal to that of Well 2, which indicates that thermal communication is fully established between the two wells. Beginning from the sixth cycle, a bidirectional flowing path is formed between Well 1 and Well 2 resulting in a quick augment of the bottomhole temperature in Well 1 during steam injection from Well 2. For the bottomhole temperature curve of Well 3, it indicates no obvious channeling phenomenon during the processes of steam injection and production.

(2) Variation of temperature field

The temperature distribution in the different stages, such as, pure steam huff & puff, thermal solidification agent injection, viscosity reducer injection and nitrogen foam injection, is shown in Fig. 9.

As shown in Fig. 9(a), it can be seen that during the sequential processes of steam huff & puff, steam channeling is gradually formed between Well 1 and Well 2, which becomes fully mature by the end of the seventh cycle. In contrast, Well 3 does not reveal any channeling phenomenon with the other two wells. Consequently, its temperature field is relatively homogeneous near Well 3 and the heating zone gradually expands in a circular pattern.

Then, the thermal solidification agent is injected into Well 2 and the well is shut in for 24 h. Subsequently, the next three cycles of steam huff & puff are carried out to verify the performance of steam diversion. As shown in Fig. 9(b), the heating area of steam injection near Well 2 increases significantly after the thermal solidification agent injection. Furthermore, the degree of steam breakthrough between Well 1 and Well 2 becomes poor noticeably, and the thermal front of steam injection changes the flowing direction from Well 2 to Well 3. These results imply that it is effective to inject the thermal solidification agent to inhibit steam channeling after high-cycle steam huff & puff.

After injecting the thermal solidification agent into Well 2, the new three cycles of steam huff & puff are implemented. During these processes, a certain amount of viscosity reducer is injected into Well 1 and Well 2 along with steam injection. As shown in Fig. 9(c), the heating area of steam injection significantly increases after injecting the viscosity reducer. The steam channeling between the two wells is further weakened and the thermal front of steam chamber changes the flowing direction towards Well 3. The oil production rate significantly increases after injecting the viscosity reducer, and its essential mechanism is mainly derived from the emulsification effect of crude oil. Under the action of the viscosity reducer, the continuous oil phase is dispersed into spherical emulsion droplets that gradually become mobile along with the liquid production. Moreover, the dispersed emulsion can block the paths of steam channeling under the Jamin effect. In the zone of steam channeling, it basically reaches the state of residual oil. The viscosity reducer flows along with the condensed water of steam in the zone, and it continuously contacts with the residual oil and effectively initiates the residual oil of steam flooding.

Finally, nitrogen foams are injected into Well 1 and Well 2 simultaneously with steam after the thermal solidification agent injection during the last three cycles of steam huff & puff. As shown in Fig. 9(d), the range of steam front expands obviously after the addition of foams, and steam channeling between Well 1 and Well 2 is almost eliminated. It suggests that nitrogen foams can

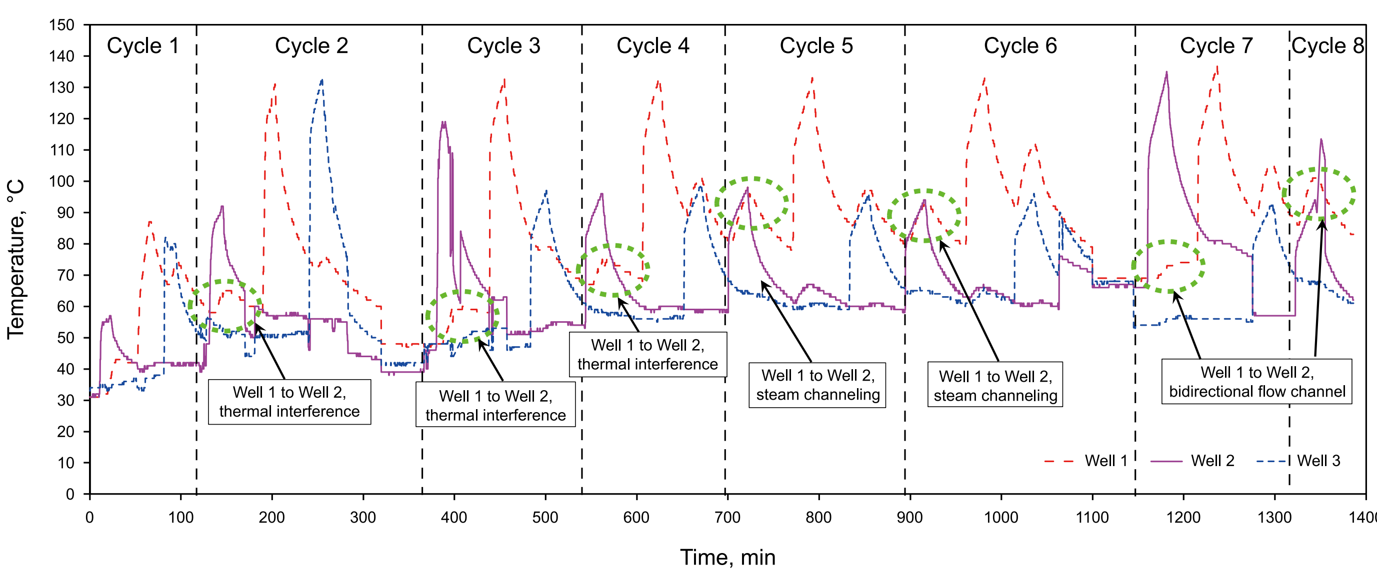


Fig. 8. The curves of bottomhole temperature for simulated wells.

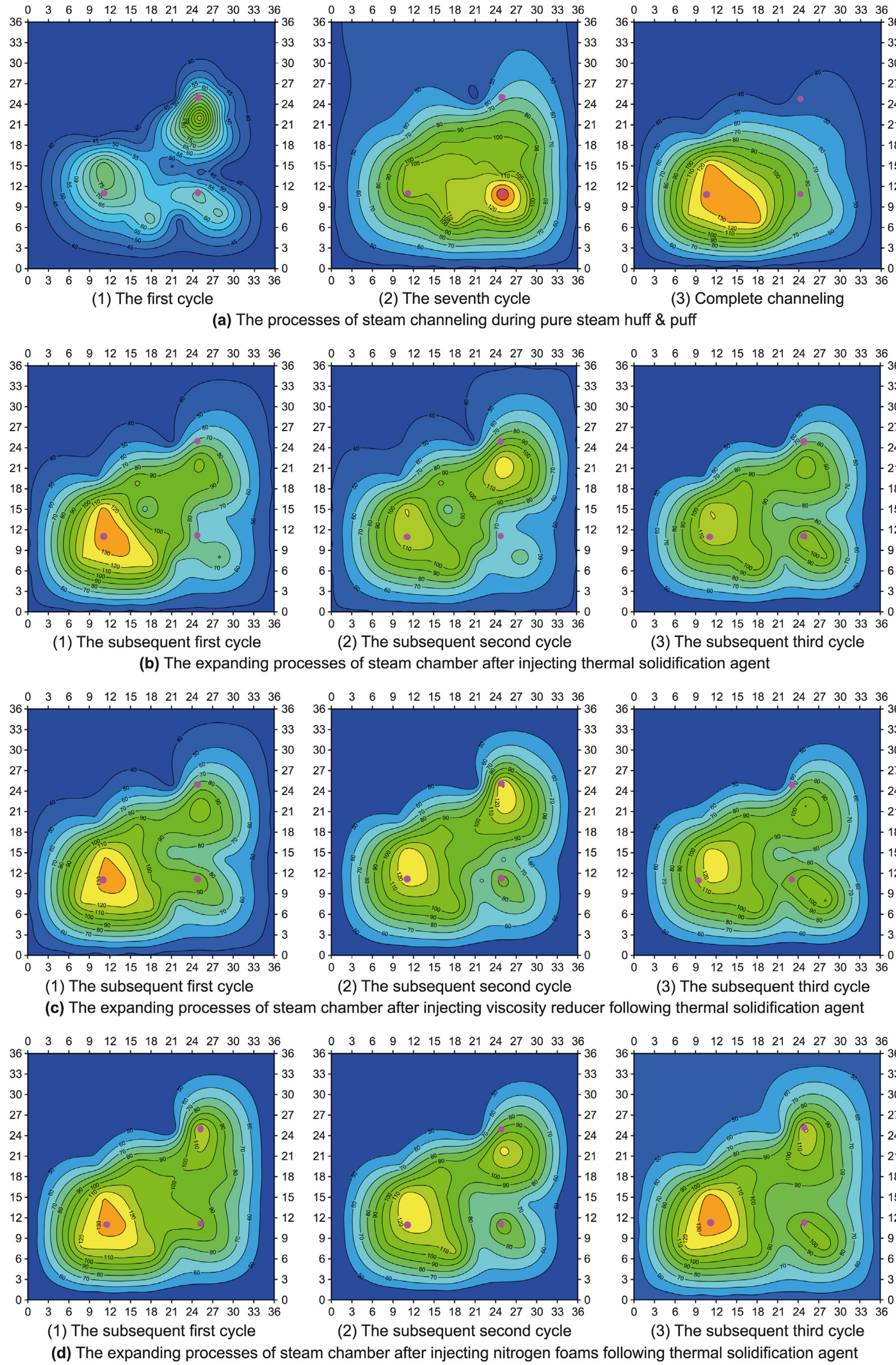


Fig. 9. The comparison diagrams of heating range during the different injection modes.

effectively block some of the bypassed or weak steam channeling paths during steam huff & puff. Consequently, the thermal front of steam chamber turns from Well 2 to Well 3, and the width of the channeling path between the two wells becomes smaller and smaller. The comprehensive mechanisms are related to the dynamic migration processes and the selectively plugging characteristics of foams in porous media. When bubbles migrate into pores, they are trapped at the narrow throats and the subsequent bubbles gather together in pores to form larger bubbles that can block the paths of steam channeling. As the bubbles grow larger, the plugging pressure difference increases to make them deform and even rupture at the throats. At last, the new bubbles enter the next pores to block the subsequent throats. Therefore, foams are in a dynamic process of migration, deformation, rupture and regeneration in porous media, which can further enlarge the swept range and enhance oil recovery.

(3) The production performance

Fig. 10 illustrates the comparison diagrams of the sweep efficiency and the oil recovery factor of different injection modes. As shown in Fig. 10(a), the sweep efficiency of pure steam injection can get to be 51.9% when the steam channeling is completely mature between Well 1 and Well 2. However, during the next three cycles of steam huff & puff after thermal solidification agent injection, the sweep efficiency increases significantly due to the effect of steam diversion. At the end of steam injection during the new third cycle, the sweep efficiency reaches 59.2%, which is 7.3% higher than pure steam. Moreover, during the next three cycles after viscosity reducer injection following thermal solidification agent, the sweep efficiency reaches 61.4% at the third cycle, which is 3.72% higher than only thermal solidification agent injection. However, the largest augment of the sweep efficiency can be observed with the implementation of nitrogen foams assisted measures. By the new third cycle, the sweep efficiency reaches 72.6%, which is 13.4% higher than only using thermal solidification agent. As the cycles of steam huff & puff increase, steam channeling tends to be mature resulting in the sharp reduction of oil production. Nevertheless, the thermal solidification agent can be used to effectively control steam channeling.

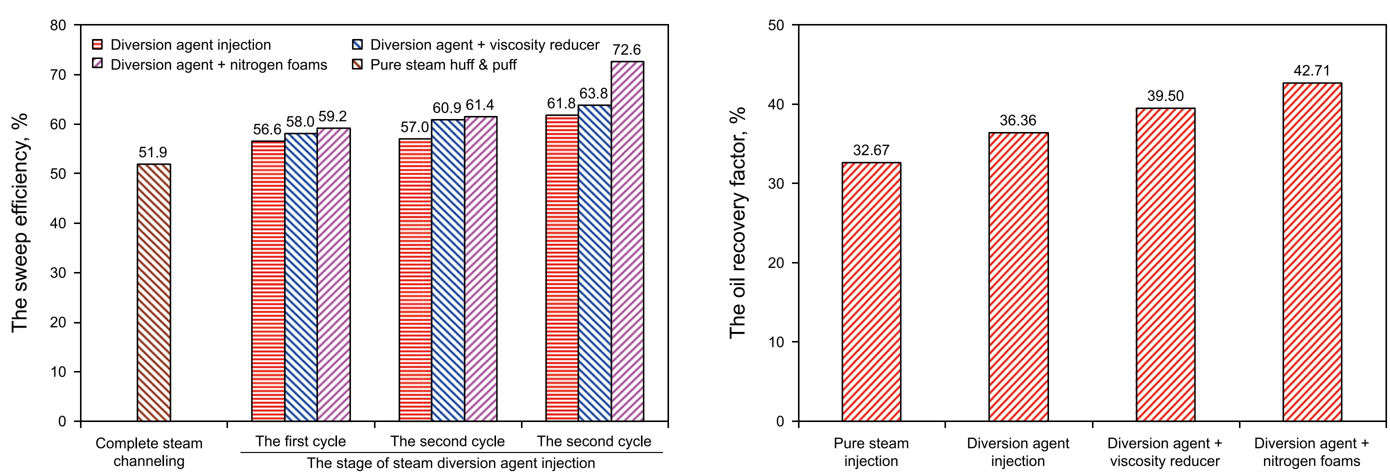
The results presented in Fig. 10(b) demonstrates that the oil recovery factor increases from 32.67% (the traditional steam huff & puff) to 36.36% (the thermal solidification agent injection). Combining thermal solidification agent with viscosity reducer, the oil recovery factor gets to 39.50%, which is 3.14% higher than the use of thermal solidification agent alone. Additionally, when nitrogen foams are introduced as an auxiliary measure for thermal solidification agent, the oil recovery factor increases to 42.71%, which is 3.21% higher than viscosity reducer assisted steam diversion. These experimental results confirm that it is suitable for inhibiting steam channeling through the injection of thermal solidification agent and it is feasible for further increasing oil recovery factor through the addition of viscosity reducer and/or nitrogen foams by followed steam injection.

5. The analysis of diversion mechanisms

(1) The thermal solidification agent exhibits the exceptional high-temperature resistance and the ultra-strong plugging performance resulting in the diversion of steam flowing into the oil remaining region. As shown in Fig. 11, the diversion mechanisms are analyzed according to the temperature field distribution before and after steam diversion. When the chemical agent is completely solidified in porous media, steam begins to change the flowing direction to enlarge the sweep volume of steam injection in heavy oil reservoirs. Consequently, the thermal sweep range significantly expands to promote an obviously augment of temperature near wellbore. Furthermore, the heating range of steam expands significantly outwards, while the temperature gradient rises significantly at the thermal front.

(2) Under the action of steam diversion, it is possible to transform flowing pattern from “unidirectional flow” to “curved flow" or even “multidirectional flow". As shown in Fig. 12(a), during the later stages of steam huff & puff, steam channeling paths gradually form between two wells to finally present a unidirectional flow zone. As shown in Fig. 12(b), after the injection of steam diversion agent, the agent of liquid state is firstly flowing into high permeability paths and gradually solidifies in the middle zone between two wells to block steam channeling paths through decreasing permeability.

(3) As the injection pressure increases, under the action of bypassing flow and profile control, the remaining oil is mobilized near the channeling path and the utilization degree of steam injection is raised. As shown in Fig. 13(a), the remaining oil occupies the middle zone between two wells and is hardly produced from any well during steam huff & puff. Therefore, the remaining oil on



(a) The sweep efficiency **(b)** The oil recovery factor

Fig. 10. The comparison diagrams of production performance during the different injection modes.

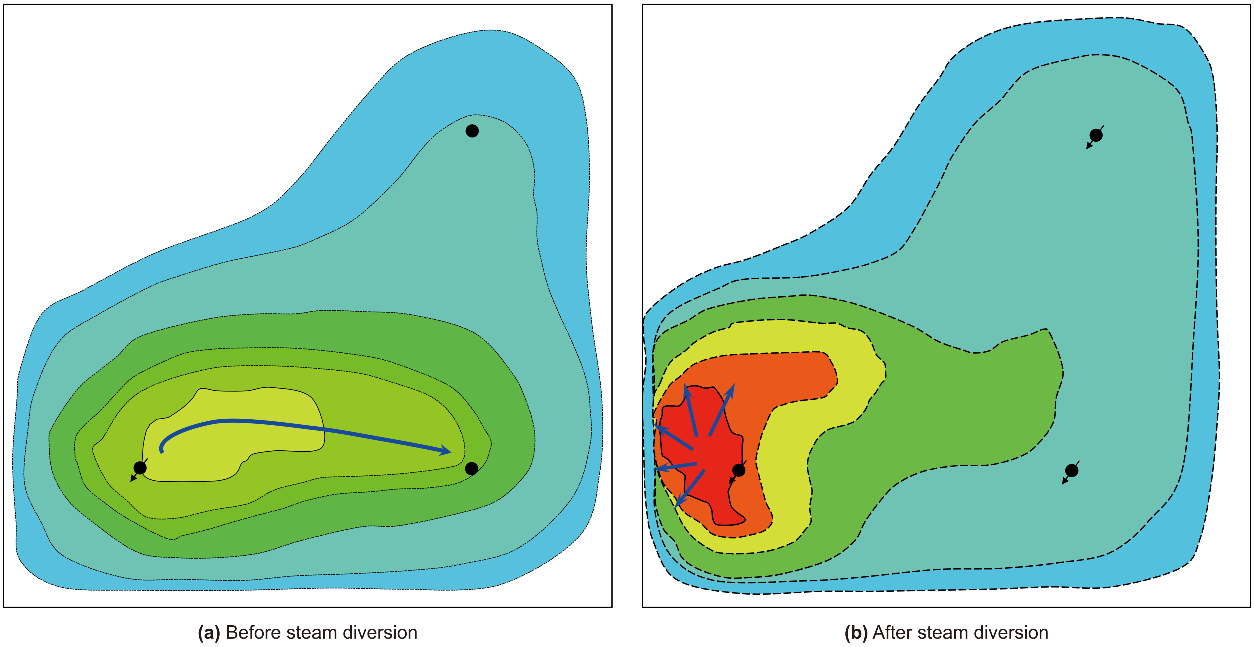


Fig. 11. The schematic diagram of temperature field distribution.

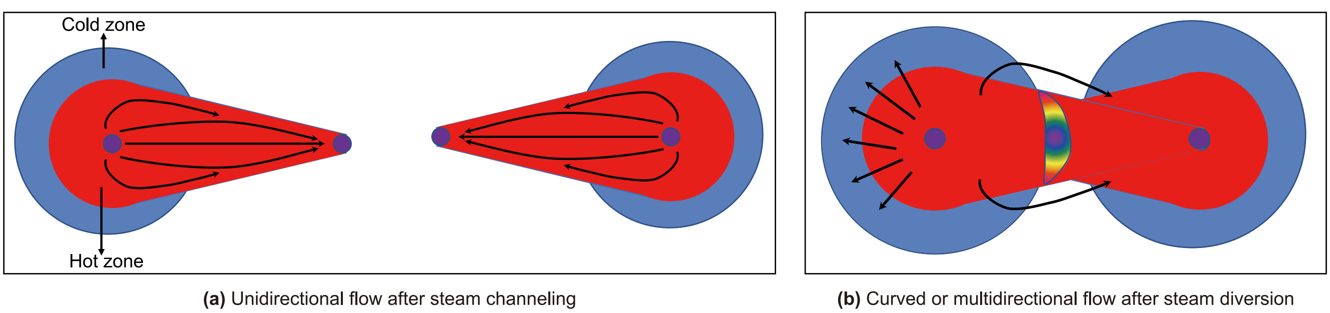


Fig. 12. The transformation of flowing pattern after steam diversion agent injection.

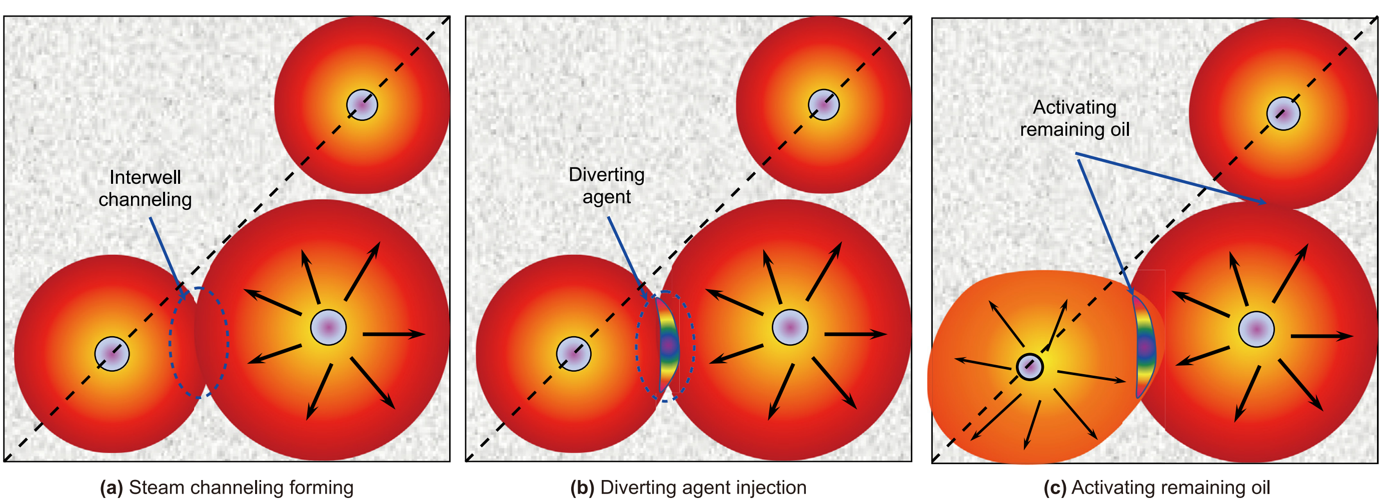
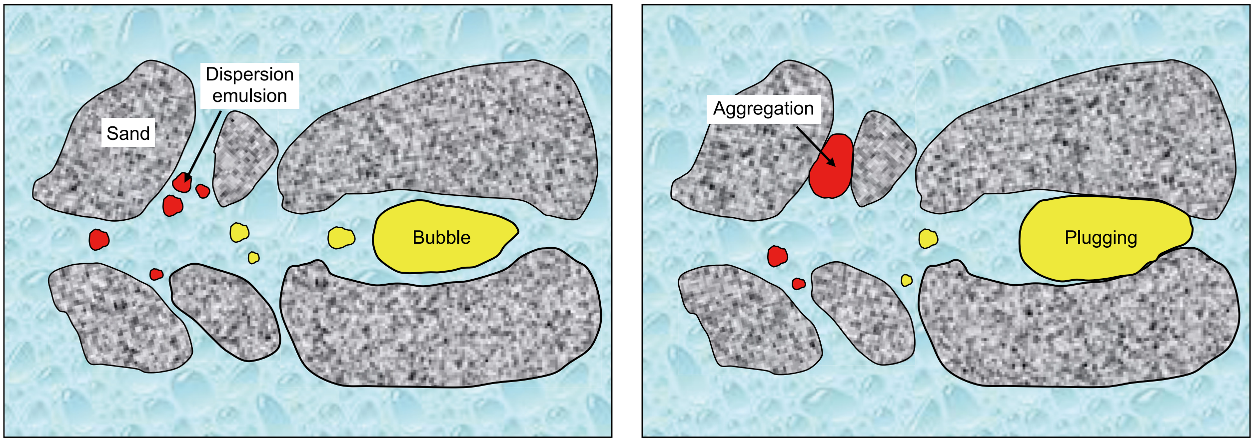


Fig. 13. The analysis of remaining oil being activated.

both sides of the channeling path is not effectively activated. As shown in Fig. 13(b) and (c), during steam injection after the injection of steam diversion agent, the wells of original channeling exhibit the effect of bypassing flow and profile control, the remaining oil on both sides of the path can be mobilized resulting from enlarging the heating zone of steam injection.

(4) After the injection of steam diversion agent, the introduction of viscosity reducer and nitrogen foams can further extend the



(a) The migration of foams and emulsion droplets **(b)** The plugging characterisctics at the throat

Fig. 14. The schematic diagram of microscopic plugging effect in porous media.

thermal sweep range, improve the mobility of heavy oil and prolong the effective period of oil production. The viscosity reducer is beneficial to reduce oil viscosity and generate dispersed emulsion droplets. Under the Jamin effect, the paths of steam channeling are plugged to enlarge the sweep range of steam injection. The bubbles enter the pores and are trapped at the narrow throats to coalesce and generate larger bubbles that can effectively block the paths of steam channeling. The analysis of microscopic mechanisms are shown in Fig. 14.

6. Conclusions

(1) After high-cycle steam huff & puff in heavy oil reservoirs, the thermodynamic conditions have been changed to lead to ineffective steam circulation and severe steam channeling between wells. The thermal solidification agent can block the steam channeling paths through solidification reaction after steam injection in porous media.

(2) The thermal solidification agent is a high molecular weight polymer through polycondensation reaction. It is at liquid state and can easily flow at low temperature, but it can gradually solidify to block high permeable paths. Its temperature resistance is up to 300 °C and its plugging degree reaches over 99%.

(3) After steam channeling during steam huff & puff, the sweep efficiency can reach 59.2%, which is 7.3% higher than pure steam injection. The sweep efficiency of viscosity reducer and nitrogen foams assisted measures reach 61.4% and 72.6%. For the three injection modes, the oil recovery factor reaches 36.36%, 39.50% and 42.71%, respectively.

(4) The mechanisms of steam diversion include: The ultra-strong plugging ability can change the flowing pattern through blocking the paths of steam channeling to activate the remaining oil. After adding viscosity reducer and nitrogen foams, the sweep efficiency can be expanded and the effective period can be prolonged. The steam channeling almost disappears under the action of dynamic migration and selective blocking of foams in porous media.

CRediT authorship contribution statement

Zhan-Xi Pang: Conceptualization, Funding acquisition, Investigation, Supervision, Writing – review & editing. **Qian-Hui Wang:** Investigation, Writing – original draft. **Qiang Meng:** Investigation, Validation. **Bo Wang:** Supervision, Validation. **Dong Liu:** Validation.

Declaration of competing interest

The authors declare no competing financial interest.

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