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Article

Investigating the dynamic performance of gravel-packing in sand control wells with multicyclic steam-soaked production

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Abstract: In a gravel-packed sand control well with steam-soaked production, reverse alternating displacement of steam and formation produced fluid may tend to change the dynamics at the gravel-sand interface. To investigate the effect of dynamic production conditions on gravel-pack performance, a series of experiments was performed using high temperature steam displacement apparatus with parameters similar to actual well conditions. In this research, gravel, formation sand, and screen mesh filter were combined as a sand retention media. Steam, water, and crude oil acted as the displacement fluid to simulate the alternating displacement process of steam and formation fluids. Experimental results resonate with the basic law of high temperature dissolution, adsorption blockage, and dynamic performance of the gravel-pack with the mode of steam-water and multicycle steam-oil displacement. The high temperature dissolution ratio of quartz sand was tested as 10.20% at a steam temperature of 300 °C, which is too small to influence the sand retention effectiveness of the gravel pack. Steam flow erosion and the reverse displacement by fluid lead to gravel-sand interface migration and sand invading the gravel pack, causing its permeability to decrease. After a single alternating displacement of steam-water, the gravel permeability drops to about 80% while the displacement of steam and crude oil damages the gravel permeability to 15% through adsorption blockage. We suggest that high temperature steam injection could partly undermine permeability by oil adsorption blockage despite the permeability recovery of 93%. Whereas the damage removing effect of steam decreases with an increase in displacement cycles and the oil adsorption blockage of the gravel pack, the damage removing effect of steam is much higher than high temperature water. Our research concludes that multicyclic steam operations could potentially destabilize the gravel-sand interface, which needs careful consideration for optimal sand control to maintain gravel pack integrity.

Keywords: Thermal recovery; steam-soaked production; gravel pack; reverse alternating displacement; adsorption blockage

1. Introduction

The latest advances in production technologies, coupled with the much-anticipated decline in future oil discoveries globally, have inspired new research to facilitate improvements in existing recovery techniques to meet the persistent global demand for energy. Notable challenges that continue to undermine oil producers are the control of fines migration, particularly during production in unconsolidated sands. The injection and cyclic injection of high-temperature steam can cause changes in the mechanical properties of the reservoir, resulting in variations in the sand production patterns of thermal recovery wells (Yan et al., 2025; Jia et al., 2024). To reduce the migration of fine particles of loose sand into the wellbore, experiments on the evaluation and optimization of efficient sand control methods for heavy oil reservoirs were conducted (Hu et al., 2022). One of the most effective sand control methods is gravel filling. This method of sand control acts by reducing the near wellbore velocities of sand while providing a graveled region of high-permeabilities around

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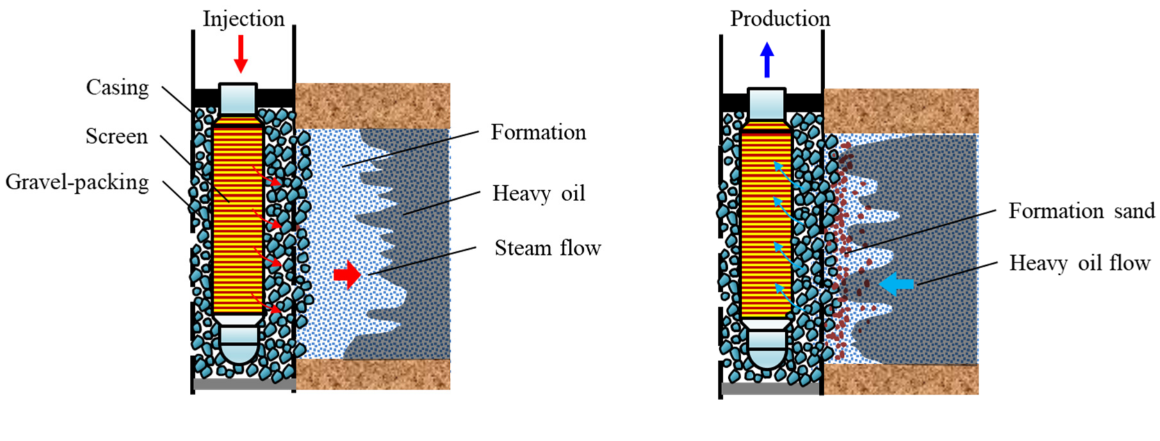
the liner/screen (Roostaei et al., 2018). The injection of steam for thermal enhancement of hydrocarbon production assists producers in reducing heavy oil viscosity (Wu et al., 2018), while the dynamic performance of the multicycle gravel pack allows an alternating production scheme for oil and produced fluids. However, for gravel-packed sand control wells with a steam-soaked operation, porosity, permeability, and interface stability of gravel packs, are considered as the main factors affecting sand control (Li et al., 2012; Oyeneyin et al., 1995). The blockage of gravel pack has a significant impact on well productivity (Sai et al., 2022). The fluid flow rate and viscosity are key parameters that affect the degree of blockage in the gravel layer (Dong et al., 2019). The properties of both gravel pack and gravel-to-sand interface can be affected by the reverse alternating displacement of high temperature steam and formation-produced fluid during the multicyclic steam-soaked operation. In terms of the dynamic performance of gravel packs, several studies have been conducted under varying production conditions. To address the problem of sand control medium clogging in heavy oil sand production wells, the mechanism and law of heavy oil-formation sand co-clogging of multiple types of sand control media, such as cut seams, wound wires, composite filter screens, and gravel layers under different conditions, were revealed (Dong et al., 2024). The mechanism of physical plugging caused by intrusion of formation sand was analyzed, and a permeability prediction model was underscored under conventional production conditions (Dong et al., 2011; Dong et al., 2017; Li et al., 2013; Wang et al., 2000; Meng et al., 2019). Then it evaluates the completion productivity of steam stimulation and sand control in heavy oil reservoirs (Wang et al., 2020).



(a) Steam injection (b) Production

Fig. 1. Heavy oil gravel packing sand control well steam injection production.

Furthermore, earlier research focusing on wettability alteration resulting from asphaltene precipitation in crude oils underscores even a deeper conceptualization of the influence on changing permeability of porous materials (Gao et al., 2016; Wu et al., 2004; Buckley et al., 1998) from which inferences can be made about gravel packs in porous materials. Earlier studies analyzing wettability changes in thermal recovery methods have noted a number of contrasting views on wettability and underscored its implications for hydrocarbon recovery (Abdallah et al., 2007; Punase et al., 2014). In unconsolidated sands, particularly quartz, temperature elevation during thermal recovery increases residual water saturation (more water wet) and oil-water relative permeability, while residual oil saturation decreases with temperature (Ponelis et al., 2015). Whereas high temperature steam could potentially increase reservoir permeability, the high temperature effect of steam on both gravel and formation could compromise the well integrity (Abdallah et al., 2007; Ponelis et al., 2015; Punase et al., 2014).

Higher increases in temperature could increase the upset of flow rate, which further aggravates the erosion of the gravel pack and screen holding the gravel (Bhowmick et al., 2018). This argument, in contrast, suggests that gravel and formation materials could suffer dissolution due to the collapse of chemical bonds aggregating formation materials, among others. In addition, other research emphasizes that whereas the rise in temperature could potentially increase the net recovery factor where in some case it has been linked to optimization using chemical additives, fracture design, follow-up processes like carbon dioxide injection, steam flooding among others (Alvarez et al., 2013), producers ought to create a reasonable balance between the steam to oil ratio and oil to steam ratio, to ensure economic recovery conditions are met (Elias et al., 2015). Moreover, based on the physical sand plugging mechanism, other research underscores a physicochemical compound mechanism (Zhang et al., 2004).

Factors such as permeability damage caused by the polymer and asphaltene adsorption at the surface of quartz sand were considered. Based on the relationship between plug permeability and time, a permeability changing model of the gravel pack at the initial stage of production was proposed, as well as a dynamic prediction of production in heavy oil wells (Gao et al., 2016; Pang et al., 2013; Si et al., 2013; Dong et al., 2016). In summary, there is a need to extensively study the dynamic changes for gravel packs with regard to the physical and physicochemical sand plug. Due to the limited existing research on reverse alternating displacement of steam and formation produced fluid, there is a need to systematically investigate the controlling parameters influencing sand control and steam-soaked production.

In this paper, experiments are performed to investigate the dynamic performance of changes in gravel-packed under different processes of multi-cyclic steam-soaked simulation. Plug and dynamic changes of permeability at gravel pack are investigated using high temperature dissolution, steam-water displacement, and multi-cyclic steam-oil displacement conditions, respectively, to support the determination of parameters during sand control and the steam-soaked process.

2. Experimental Principle and Method

2.1 Purpose

The experiment is simulated using input parameters from a heavy oil block at the Gudong area, Shengli Oilfield. Cyclic steam-soaked and gravel-packed sand control operations were implemented for this block. During actual production, the well shows a dramatic decline in oil production after the first period of production. Gas injection pressure was maintained at a high level in the second injection phase. Due to a lack of a scientific understanding of the mechanisms/processes of reverse alternating displacement of the gravel pack. Key conclusions that could be drawn point to wrong input parameters as well as ineffective sand retention designs or mechanisms as potentially significant to a clear understanding of the poor production at the block of interest.

Dynamic changes of the properties of the gravel pack were investigated with multi-cyclic steam-soaked simulation under production conditions. These included, among others, high temperature dissolution rate, sand intrusion depth after displacement under different conditions, plugs in gravels, and plug removal effect with high temperature steam. The purpose of our research was to provide a basis for optimizing parameters during steam soaking and sand control operations.

In addition, owing to the adsorption effect of heavy oil on the gravel layer, it is easy to cause blockage of the gravel layer and a decrease in permeability. High-temperature steam can reduce the viscosity of heavy oil, increase its fluidity, and thereby decrease the adsorption effect of heavy oil on the gravel layer. Therefore, in the experiment, 30 ℃ distilled water, 70 ℃ distilled water, and 200 ℃ high-temperature steam were respectively used to unclog the pre-clogged screen to verify the unclogging effect of high-temperature steam on the already clogged screen tubes.

2.2 Experimental Apparatus and Procedure

The multi-functional instrument for sand prevention and sand blocking evaluation was used in this experiment. The apparatus is composed of a constant-flux pump, steam generator, sand-packed columns, a constant-heated system, and a data acquisition system.

Both sides of the sand packed column are connected to the advection pumps and the diversion pipe, respectively, through steering throttle valves, and different fluids can be pumped from the forward and reverse directions according to the needs, so as to realize alternate displacement. A plurality of pressure-measuring holes was provided on the wall of the column to connect the pressure difference sensors to measure the pressure difference at different positions beside the column. The permeability of the medium beside the column can be calculated using Darcy's law.

The schematic diagram of the experiment is shown in Fig. 2. The sand-packed column is filled with formation sand, gravels, and a screen mesh filter as three layers. The diameter of the gravel pack and the formation sand pack is equal to the inner diameter of the gravel pack column, both are 30 mm, and the filling length is 200 mm and 100 mm, respectively. The gravel pack and the formation sand are in direct contact without any other medium between them. A screen filter is installed on the left side of the gravel pack to simulate a mechanical screen. A metal mesh is installed on the right side of the formation sand to fix the sand layer.

This apparatus is used for testing changes in permeability and visualizing the dynamic plugging process. The parameters set in the experiment are chosen based on certain ratios of formation sand, gravels, and screen mesh filter to fill the sand packed column at the beginning of the experiment. The sand-packed column is displaced by steam-water or steam-oil with regard to the purpose.

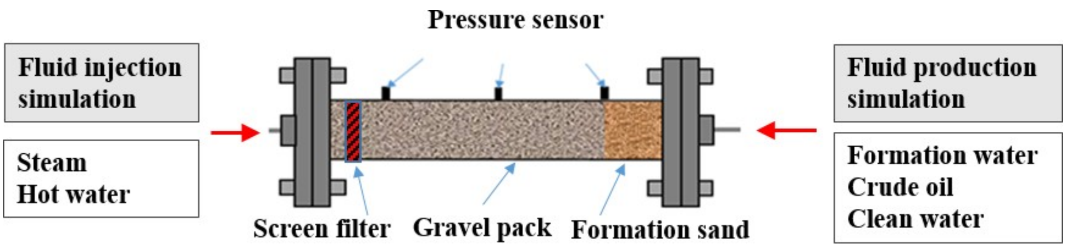


Fig. 2. Diagrammatic sketch of experiment.

The general procedure of the experiment is described as follows:

(1) Fill sand-packed columns with different ratios of formation sand, gravel, and screen mesh layers for different purposes. Then, connect the entire experimental setup as required. Wrap a heating jacket around the outside of the sand pack column to heat the entire sand pack column to 70 ℃.

(2) Use a constant-flux pump to pump distilled water to displace the medium with a constant displacement, and calculate the permeability of the medium beside the column as the initial permeability of the medium.

(3) Inject High temperature water or steam through one side of the core barrel, while formation fluid is produced from the other side. Use a steam generator to inject high temperature steam into the sand-packed columns, simulating steam injection.

(4) Set the temperature and flow velocity of the

displacing fluid on the basis of practical production. The temperature of sand-packed columns is controlled from 50 °C to 250 °C by a heating jacket in a constantly heated system.

(5) Use the constant-flux pump to pump distilled water again to displace the gravel layer beside the column with a constant displacement. Measure the flow rate along with the pressure difference and calculate the relative permeability of the gravel pack as the final permeability.

(6) If alternate displacement is required, after completing step 5, adjust the steering throttle valves on both sides of the sand pack column and pump the specified fluid through the constant-flux pump to displace the gravel layers from opposite directions.

(7) Observe the intrusion of formation sand and the movement of the interface between adjacent layers by pulling the formation sand, gravels, and the screen mesh filter out.

(8) If multiple rounds of alternate displacement are required, after completing step 5, repeat steps 3-7 to compare the changes in the permeability of the gravel layer in different flooding rounds.

During the displacement, due to the intrusion of formation sand into gravel media, the internal overflow space of the media was reduced, and the seepage resistance increased, and then the permeability of the medium decreases. This phenomenon indicates the plugging of the media. The dynamic permeability of the media can be calculated by the tested flow rate and pressure drawdown across the media.

High-temperature steam unblocking experiment also uses the multi-functional instrument for sand prevention and sand blocking evaluation as shown in Fig. 2, but the experimental principle and method have changed, as shown in Fig. 3. In the experiment, the pre-blocking screen was placed between the heavy oil and formation sand blocking zone, and clean gravel layer and gravel layer and formation sand mixing zone were added at both ends, respectively. Distilled water and steam with different temperatures were used to drive the screen, and the permeability change of the blocking zone was tested to verify the unblocking effect of high temperature steam on the blocked screen.

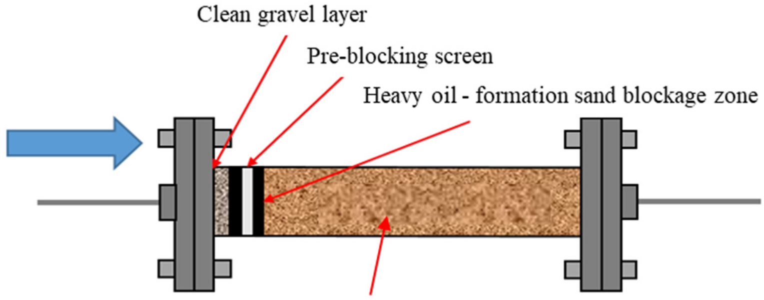


Fig. 3. Schematic diagram of the principle of high-temperature steam unblocking experiment.

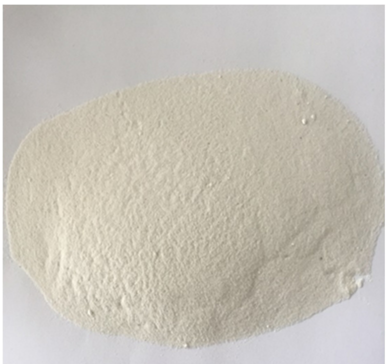
(a) Heavy oil (b) Formation water

Fig. 4. Experimental fluid.

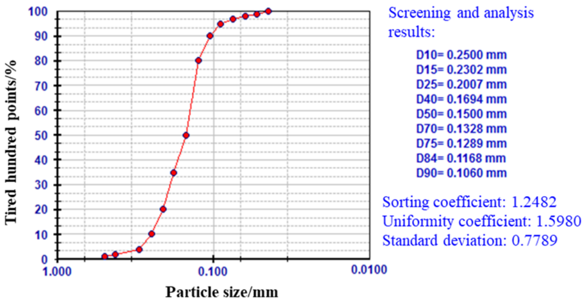
2.3 Experimental conditions and materials

Displacing fluids include water, oil, and steam. The oil is dehydrated crude oil that is derived from an Oilfield, with 924.6 mPa·s of viscosity under 70 °C. Water is classified as distilled water and a 420 mg/L sodium hydrocarbonate solution. The fluid used in the experiment is shown in Fig. 4.

A sand layer is manually packed into the container. The used man-made sand keeps unconsolidated with no consolidation agent and provides the formation sand source during the experiment. The sand was manually compounded with natural quartz and clay minerals according to the parameters of actual formation sand from the Gudong oilfield. The median size of the sand is 0.11 mm, and its coefficient of uniformity is about 7. The clay content is about 12% and the porosity is about 25%, roughly equal to the actual reservoir porosity. The parameters of the used sand have been set as close as possible to those of the actual formation sand, with an accuracy rating of more than 90%. The simulated formation sand used in the experiment is shown in Fig. 5(a), and the sieving curve of the formation sand is shown in Fig. 5(b).



(a) Formation sand sample (d50=0.15 mm)



(b) Formation sand sieving analysis data

Fig. 5. The formation sand configured for the experiment.

The used gravel is directly from the actual used gravel in an oil-field gravel-packing job, the size of which is 0.4~0.8 mm, with 0.613 mm of median size. For gravel-packed sand control design, the optimum gravel-sand median size ratio (GSR) is recommended to be about 5-8. In this experiment, the GSR is about 5.57. The gravel is also packed manually into the container with slight force by hand, which ensures the high compactness degree to simulate the actual gravel-packing in an oil well. The experimental filling gravel is shown in Fig. 6.

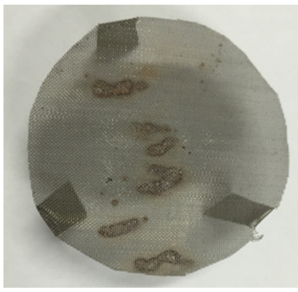
(a) Fill gravel

(b) Gravel intrusion phenomenon

Fig. 6. Samples of filling gravel for the experiment.

The target formation temperature is approximately 70 ℃. Bottom hole temperature during the steam-soaked operation ranges from 180 ℃ to 250 ℃, while steam temperature is controlled between 200 ℃ and 300 ℃ in the experiment. The steam is generated from clean water by an integrated steam generator, the steam flow rate and temperature of which can be controlled and adjusted freely by the control panel. The temperature of the heating jacket is kept in the range of 50 ℃ to 70 ℃. The outlet of the sand-packed column is connected with the atmosphere, while the displacing pressure is less than 10 MPa. This pressure depends on the experimental flow rate, the number of plugs in the gravel layer, and the flow resistance. After equalization of the flow velocity in typical wells, experimental displacing flow rates of oil and steam are 0.8 mL/min and 32.0 mL/min, respectively.

High-temperature steam unblocking experimental displacement fluids used were distilled water, heavy oil, and high-temperature steam. The injection temperatures of distilled water were 30 ℃ and 70 ℃, respectively, and the injection temperature of high-temperature steam was 200 ℃. The injection speed of the fluid is 32 mL/min for all. The screen used in the experiment is shown in Fig. 7.



(a) Clean screen

(b) Pre-blocking the screen

Fig. 7. The screen used for the experiment.

3. Experimental results and discussion

3.1 Results for high temperature dissolution in gravel pack

In this section, we investigate the influence of the gravel pack after high-temperature steam dissolution. Firstly, we measure the initial permeability of the gravel pack after hot water displacement. Secondly, the gravel pack is displaced with 32.0 mL/min of steam for 12 hours under steam temperatures of 170 °C, 200 °C, 270 °C and 300 °C respectively. After steam displacement, post-dissolution permeability is measured through another hot water displacement. Fig. 8 shows the different ratios of initial and final permeability and steam temperatures, as well as dissolution rates (ratio of mass differences of the gravel pack that is before and after the experiment) and steam temperatures.

The experimental result data are shown in Table 1.

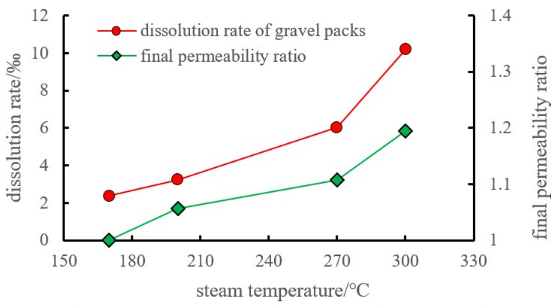


Fig. 8. Final permeability ratio and dissolution rate varying with steam temperature.

Table 1. Samples of filling gravel for the experiment.

Experiment number	Steam temperature/°C	Dissolution rate/%	Final penetration rate ratio
S1	170	2.387	1
S2	200	3.23	1.057
S3	270	6.02	1.107
S4	300	10.20	1.195

The gravel pack can be corroded by high temperature steam, and its permeability increases dramatically. According to the results shown in Fig. 8, dissolution rates show an increase with rising steam temperature when other displacement conditions are the same. The increasing positive gradient in the dissolution rate of the gravel pack, and the subsequently sharp gradient at temperatures higher than 270 °C, could perhaps suggest imminent failure of the gravel pack at higher temperatures with time. The implication of this could be that the efficiency of the gravel pack completions to block sand production would be compromised, since the gravel would be easily dissolved by hot steam. However, the dissolution rate of 10.20% at 300 °C of steam temperature, which is 4.3 times that at 170 °C of steam temperature, is still too low to worsen the effect of sand control. Besides, the percentage increase in permeability is approximately 20% compared with the permeability value before dissolution. This increase can be balanced out by formation produced micro sand particles during production (This is not considered in the experiment), pore throat structure, and permeability, which resulted in high temperature dissolution can be ignored.

3.2 Dynamic analysis for gravel packs after steam-water displacement

3.2.1 Single cyclic steam-water displacement

In order to investigate the sand intrusion depth in gravel packs caused by steam-formation fluid reverse alternating displacement, a steam-water system is considered as a displacing fluid. It is worth noting that since water is considered a formation produced fluid, it is easy to observe through and can avoid the influence caused by heavy oil adsorption, which is rather opaque. Displacing temperature, steam flow rate, and water displacing rate are set to 200 °C, 32 mL/min, and 8.0 mL/min, respectively. Fig. 9 shows the changes in pressure difference and permeability with time during single cyclic displacement (steam-water displacement).

According to the results shown in Fig. 9, the permeability of the gravel pack slightly dropped to about 80% of its initial value after a single cyclic steam-water displacement. In comparison with gravel and sand interaction, formation sand intrusion could explain the decrease in permeability of the gravel pack attributed to sand plugging in the gravel pores. Sparling investigated the permeability of common-sized gravel with different silty sand and concluded that gravel permeability would be seriously lowered after mixing a small amount of silty sand (Meng et al., 2019). Moreover, increased pressure gradient across the gravel pack in comparison with the sand pack could account for sand invasion and pore plugging in the gravel pack, reducing permeability (Roostaei et al., 2018). However, research argues that the drop in permeability during cyclic steam injection should not be unexpected since the production rate is expected to decline following each cycle. This was underscored by some research (Alvarez et al., 2013), which notes that despite the ability of steam to create additional structures in the formation, improving fluid flow, this change in permeability is short-lived as the well pressure subsequently falls along the cycles. This phenomenon resonates well with our research, as indicated in Fig. 9, evidenced by the decline in overall permeability at the end of the first cycle. The overall decline in the displacement pressure could also be attributed to the heat losses to the formation fluids during displacement. Moreover, at the beginning of steam injection, the pressure of inlet of sand sand-packed column fluctuates wildly since the gravel at the inlet side is impulsed by high temperature steam, which finally stabilizes as the gravels rearranges to a stable structure.

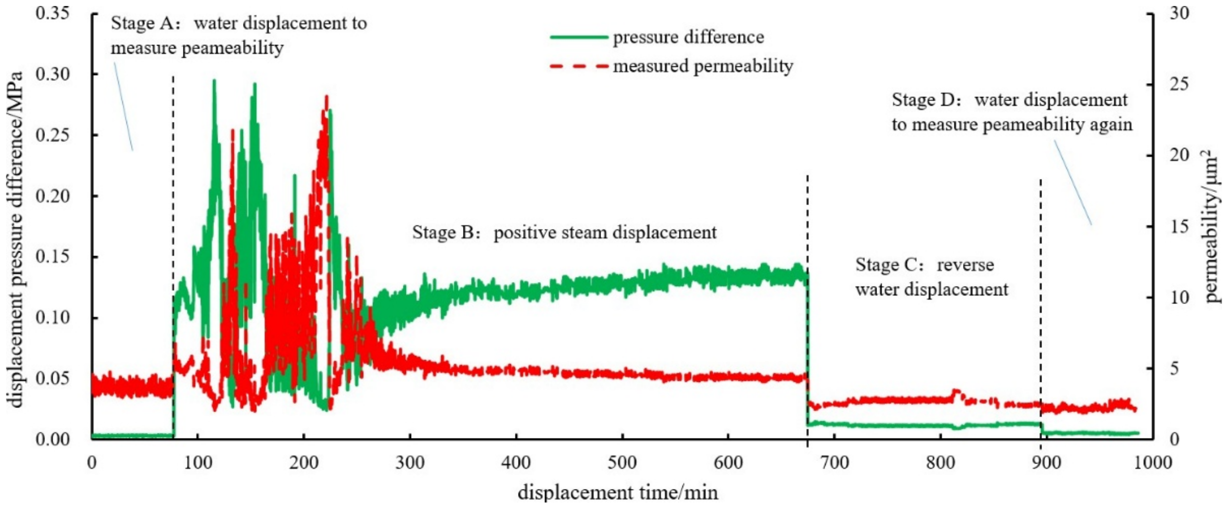
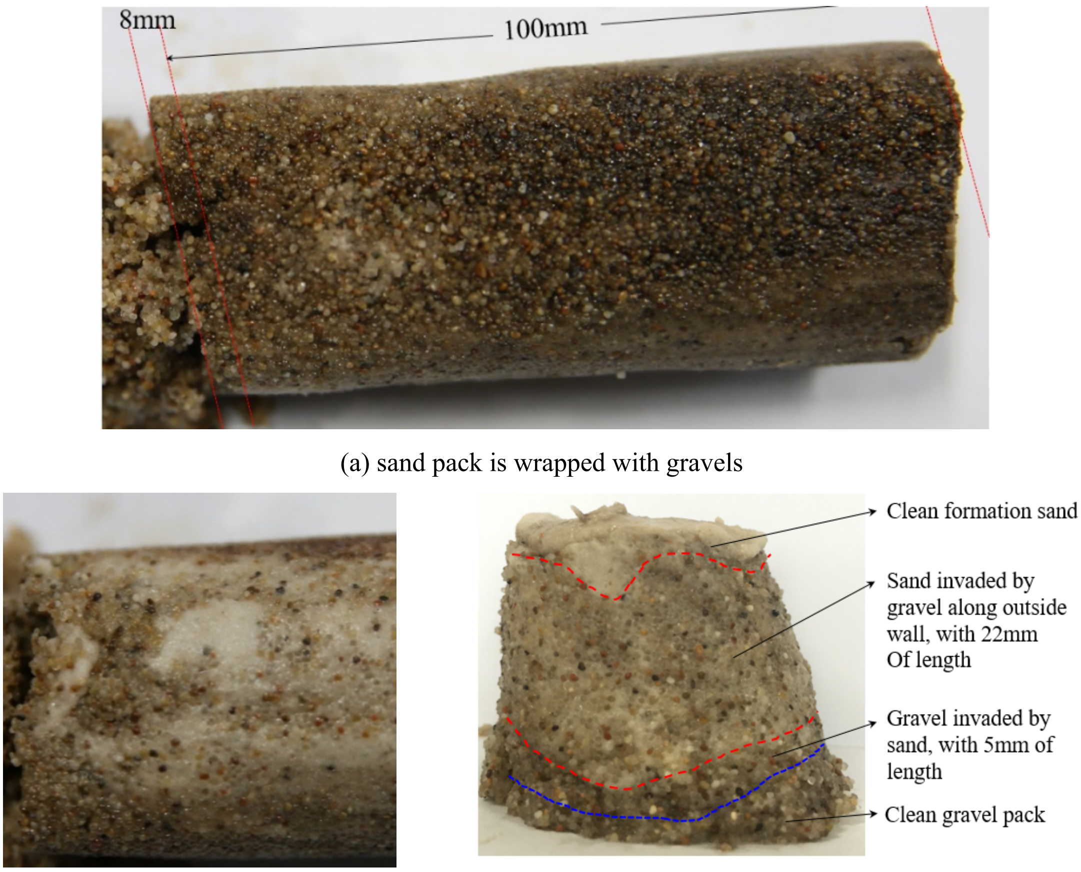


Fig. 9. Pressure drop and permeability varying with time under single cycle steam-water displacement.



(a) sand pack is wrapped with gravels

(b) gravels intrusion in the sand layer

(c) movement of the interface between gravel packs and the sand layer

Fig. 10. Interchanging pattern of gravel interface after single cycle steam-water displacement.

Fig. 10 illustrates the characteristics of the gravel-pack and sand layer after single cyclic steam water displacement. The gravel was impulse by steam during the injection, and the sand layer is therefore wrapped with gravels. Besides this, intrusion depth in the sand layer by quartz sand is approximately 2.2 cm at the interface between sand and gravel pack under steam impulsion, whereas a depth of 0.5~0.8 cm was recorded under reverse alternating water displacement. The much larger intrusion depth of the gravels in the sand layer at the interface of the gravel and sand layer could indicate the high magnitude of the initial displacement due to the steam layer in comparison with water. The result indicates that steam-fluid alternating displacement makes the interface between sand and gravel pack so unstable that there is sand-to-gravel and gravel-to-sand invasion in steam-soaked wells.

3.2.2 Multi-cycle steam-water alternating displacement

Fig. 11 shows the relationship between the permeability of the gravel pack and displacing pressure difference under multi-cyclic steam-water alternating displacement. Symbol A denotes the stages for measuring the permeability of gravel pack by water. Symbol B and C denote steam displacement and water displacement, respectively. The subscripts (1, 2, 3) mean the different cycles of displacement. According to the results shown in Fig. 11, the decreasing percentage of permeability of the gravel pack after the first cycle is similar to that after single cyclic displacement, reaching 20~25%. Decreasing percentages of permeability of gravel pack after the second and third cycles are 22% and 27%, with no clear changes compared with those after the first cycle. The result demonstrates that the permeability of gravel pack dropped due to sand intrusion caused by steam-water alternating displacement at the first cycle. This resonates with the latest research (Roostaei et al., 2018), which argues that the resulting sand invasion could be attributed to initial instabilities of the gravel/sand interface during cyclic steam operations. Moreover, the interface of sand and gravel pack has become stable after the first displacing cycle without strong dissolution and reaction between water and quartz sand.

The strong intrusion phenomenon of the gravel layer is shown in Fig. 12 (a) and (b), and the reverse intrusion of the formation sand into the gravel layer is shown in Fig. 12 (c).

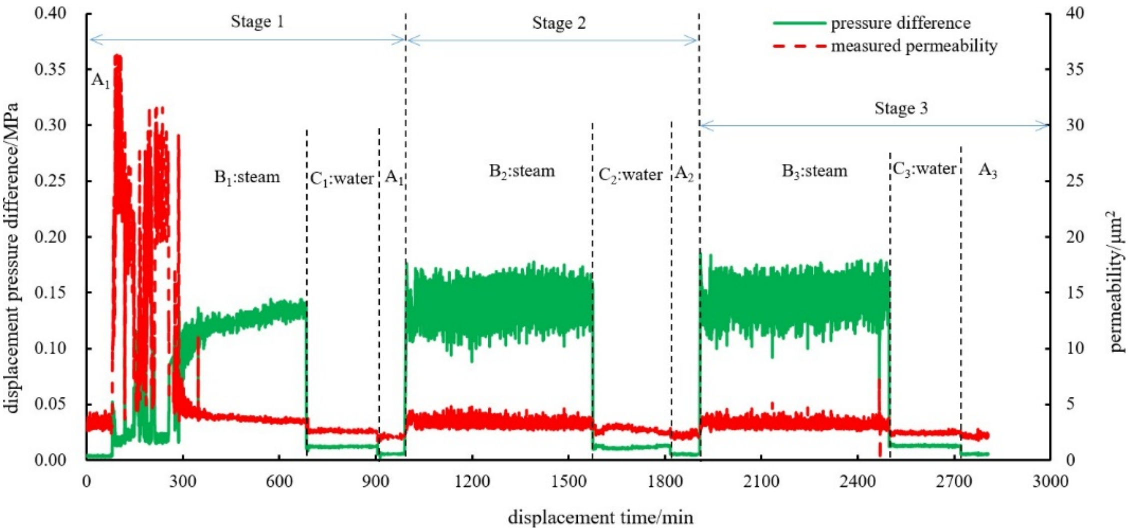
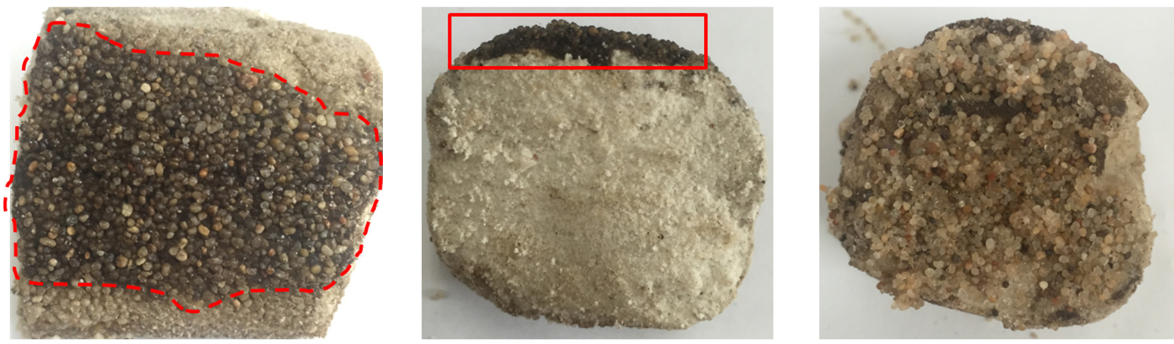


Fig. 11. Pressure drop and permeability varying with time under multi-cycle steam-water displacement.



(a) Gravel intrusion (b) Gravel intrusion (c) Formation sand intrusion

Fig. 12. The phenomenon of mutual intrusion between gravel layers and stratum sand.

Results from Fig. 12 confirm the increasing variation of pressure and permeability following successive multi-cyclic steam-water displacements. The injection cycle repetitions over the life of the well thus ensure that well permeability and flow pressure are revitalized by a continuous supply of steady steam-water cycles (Filimonov et al., 2018). Maintaining an adequate supply of steam after each cycle ensures that well permeability declines resulting from the plugging effect of both gravel and sand are reversibly minimized. However, the permeability of the well, despite the steady supply of steam-water displacement, still continuously falls over time.

3.3 Results for multi-cyclic steam-oil alternating displacement

To investigate further the impact of displacement on plug at gravel pack, multi-cyclic steam-oil alternating displacement is investigated. Initially, a sand-packed column is filled with compacted gravels to form a gravel pack with known permeability. The heating jacket is then adjusted to the experimental temperature and kept for 2 hours. Next, distilled water is injected into the sand-packed column as it comes to a stable state and measuring the initial permeability of the gravel pack. Displacement using 200 ℃

steam is continued for 10 hours. This is followed by displacing the oil with constant-flux pump for 4 hours, which is held at a stable pressure. Finally, the permeability of the gravel pack after every single cycle is measured. The steps above are repeated and continued for the next cycle of displacement. Fig. 13 and Fig. 14 illustrate pressure drop and gravel permeability variation with time under multi-cyclic steam-crude oil displacement.

In Fig. 13 and Fig. 14, symbol A denotes permeability measurement for gravel pack, symbol B denotes steam displacement step, and symbol C denotes reverse displacement, while subscripts (1, 2, 3) refer to different cycles for displacement. According to Fig. 14, the permeability of the gravel pack after finishing the first cycle of reverse displacement (15% of the initial permeability) is lower than that after steam-water reverse displacement (80% of the initial permeability), which means steam-oil displacement causes more severe damage to the permeability of the gravel pack than steam-water displacement. Whereas a number of researchers agree with the notion that gravel packing could significantly enhance sand control during thermal recovery of heavy oils, some contrasting views presented in underscore the fact that cyclic steam injection could synthesize oil wetness (Punase et al., 2014). Oil adsorption in the pore sites at the gravel pack could account for this experimental result. It concludes that due to inconsistencies in various research on wettability studies, and given the significance of wettability analysis within the context of cyclic steam simulation, perhaps our experimental investigation, as evidenced in Fig. 14 and 15, underscores a more practical view to explaining this notion. It is imperative to suggest that the fraction of oil lost within the gravel pores is evidently mobile, referred to as “dead oil”, and leads to a decline of the effective permeability of gravel packs. Fig. 15 compares pictures of prime clean gravel, oil-plugged gravel, and steam flashed gravel. Oil adsorbed at the surface and pore space of gravels can lead to oil reduction in practical production. And the effective permeability of gravels is far lower than that of cleaned gravels on the ground. According to the results shown in Fig. 13 and Fig. 14 in the second cycle, permeability recovery reaches 93% of the initial permeability after the second cycle of steam displacement. High temperature steam has a positive impact on oil mobility and therefore removes plugs in gravels caused by oil adsorption. Reversely displacing the oil again and then implementing the third cycle of steam displacement, permeability recovery is maintained at approximately 85% of the initial permeability. As a result, a conclusion can be drawn that high temperature steam has a positive effect on plug removal in gravels, while the efficiency drops with increasing number of displacing cycles. Latest research (Wu et al., 2019) investigating thermal recovery of the Jinlou oilfield in China remarks that after applying cyclic steam stimulation to the B125 Block of the Henan Oilfield, oilfield recovery became poor after some time, which prompted the alternative use of hot water flooding since 1996. The explanation for the decline in production was attributed to steam channeling and premature plugging caused during cyclic steam simulation with time (Wu et al., 2018). This resonates well with our current research pointing to the decline in permeability recovery of the reservoir over time.

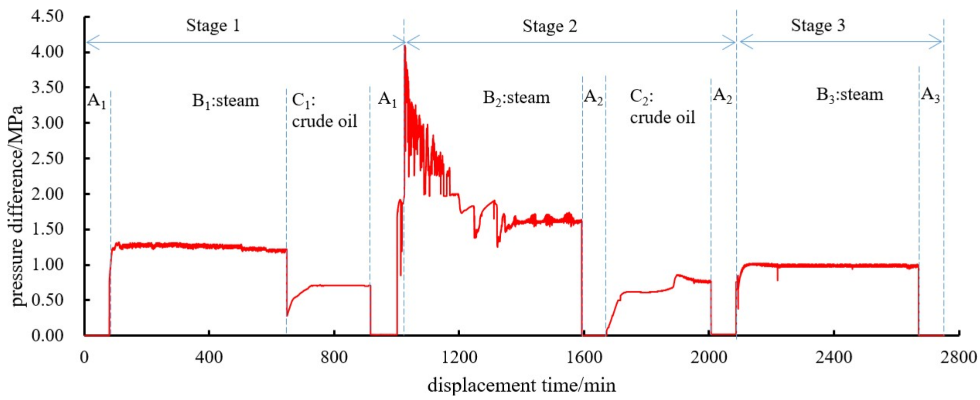


Fig. 13. Pressure drop varying with time under multi-cycle steam-crude oil displacement.

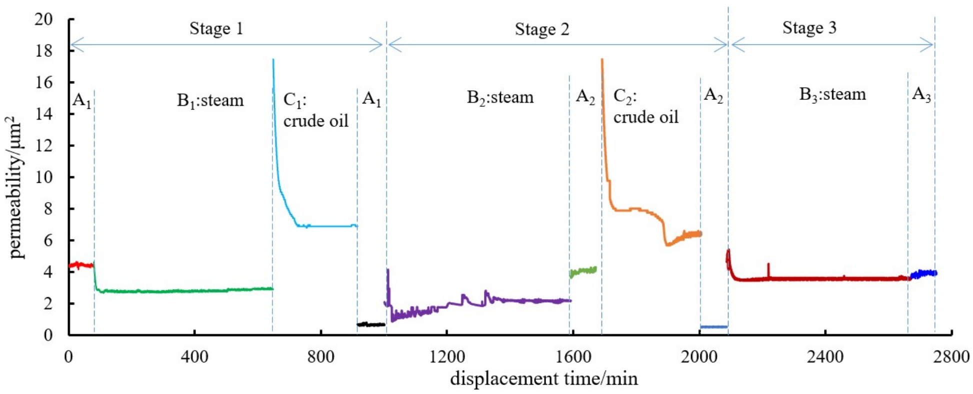
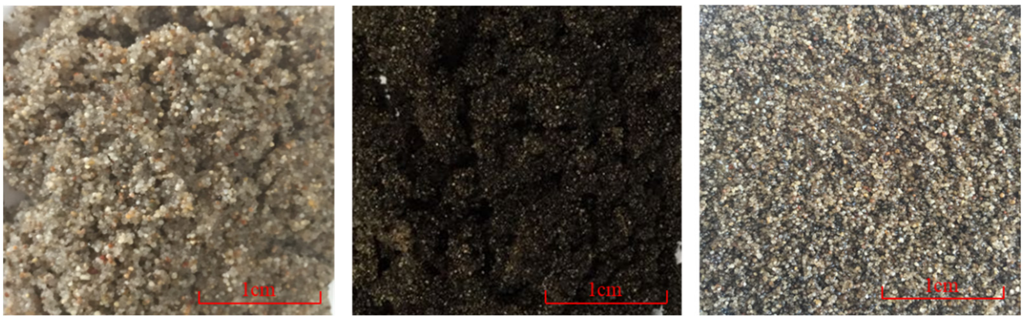


Fig. 14. Gravel permeability varying with time under multi-cycle steam-crude oil displacement.

Our research suggests that the declining permeability of gravel indicates an increase in the plugging effect, higher heat losses to the understrata, overburden, and lower viscosity of steam, as can be compared to water lowering the hydrocarbon yield. Besides, pressure-out in the local plug area of gravels causes dramatic fluctuations at the beginning of steam injection during plug removal operations. Later, the thermal effect displacing pressure remains gradually at a stable state. Therefore, we suggest a stepwise increase of the volume of gas injection and maintaining steam dryness during the second cycle of steam injection, as it makes the well bottom full of high temperature steam, and better for plug removal efficiency. Key industry data reveals the need to design appropriate steam-to-oil ratios that deliver economic viability of the production method adopted. Typical steam-to-oil ratios of 3:1-4:1 have been suggested to offer an economic value given the sensitivity of the multicyclic steam-assisted method (Alvarez et al., 2013). The sensitivity of the cyclic steam operation implies that operators strive to maintain the steam-to-oil ratio lower than the oil-to-steam ratio. According to the present study (Alvarez et al., 2013), developing an optimum steam injection rate is key to assuring high average oil production and, as such, postulates that a steam to oil ratio of about 1 would ascertain the recovery of the expected 20% of crude oil in low permeability reservoirs. We suggest that operators establish the adequate values for SOR/OSR for a given field context that assures that the displacement is neither too high to affect the gravel to sand interface nor too little to provide the required displacement, but rather high enough to ensure an economic recovery is attained.

Fig. 15 compares pictures of prime clean gravel, oil-plugged gravel, and steam flashed gravel. It is obvious that the surface of steam-plugged gravel is far less clean than flashed gravel with a small amount of absorbent. As a result, the plug removal effect is good if considering the size effect of the core barrel. However, steam channeling is common in practical plug removal operations, and therefore, the plug removal effect sometimes is better at the gravels surrounding the screen pipe and worse at the gravels in other positions.



(a) Prime cleaned gravel (b) Oil plugged gravel (c) Steam flashed gravel

Fig. 15. Comparison of prime cleaned gravel, oil-plugged gravel, and steam flashed gravel.

3.4 Result for high-temperature steam unblocking experiment

The experiment obtained the permeability variation curves of the blocked screen under different conditions by injecting distilled water at different temperatures and high-temperature steam, as shown in Fig. 16.

It was found through the permeability change curve that the unblocking capacity of 200 ℃ high-temperature steam was significantly higher than that of the other two fluids. Due to the existence of mechanical particle blockage, the permeability after unblocking is relatively low. The compactness of the gravel filling should be enhanced to prevent formation sand from invading the screen pipe and blocking it as much as possible. During the initial stage of steam injection, high temperature and high dryness should be maintained.

After the experiment, remove the sieve to observe the unclogging situation. The changes of the pre-blocking screen before the comparison experiment are shown in Fig. 17.

It was found through comparison that after the unblocking effect of the three fluids, the surface of the screen was significantly cleaner than before unblocking, but there was still a small amount of formation sand blockage. The unblocking capacity of 200 ℃ high-temperature steam is significantly higher than that of the other two fluids. However, high-temperature hot steam alone cannot completely unblock the blockage. Therefore, the compactness of gravel filling should be increased to avoid the phenomenon of formation sand invading the screen pipe and blocking it as much as possible.

4. Discussion and suggestion

Latest research suggests that other conditions, including non-uniform inflow of formation fluids into the gravel completions, could aggravate gravel dissolution and or erosion attributed to fluidization of the gravel (Bhowmick et al., 2018), among other reasons. It is worth noting that injection of highly pressured steam is associated with increased elevation of the flow velocity of the fluid across the gravel pack, creating weaker zones. Field applications of such a phenomenon imply the need to maintain the flow velocity below the critical values, which necessitates the application of computational fluid modelling to further analyze the effects of high velocity rates for certain gravel pack configurations. The sharper increase in the permeability gradient, particularly at 270 ℃ as compared to gradients at lower temperatures, could be indicative of an elevated increase in voids resulting from erosion of gravel widening pore throats. It is imperative that steam temperatures are maintained at sufficient levels during injection to mitigate not only dissolving the gravel but also the formation and reservoir sands, since very hot steam could potentially weaken the wellbore and surrounding formation integrity.

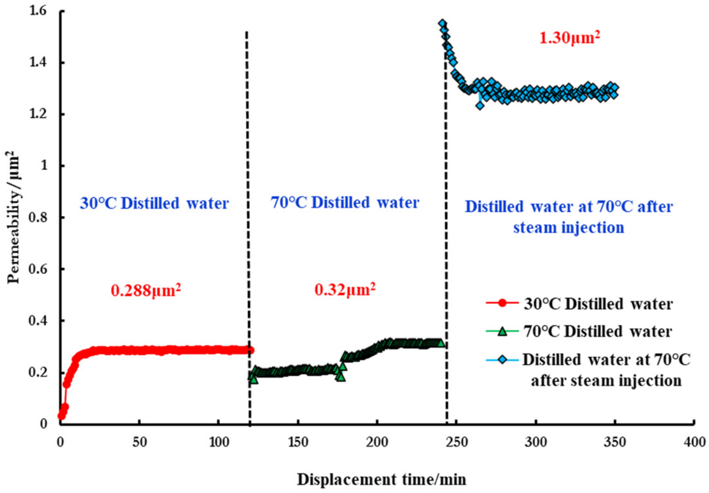
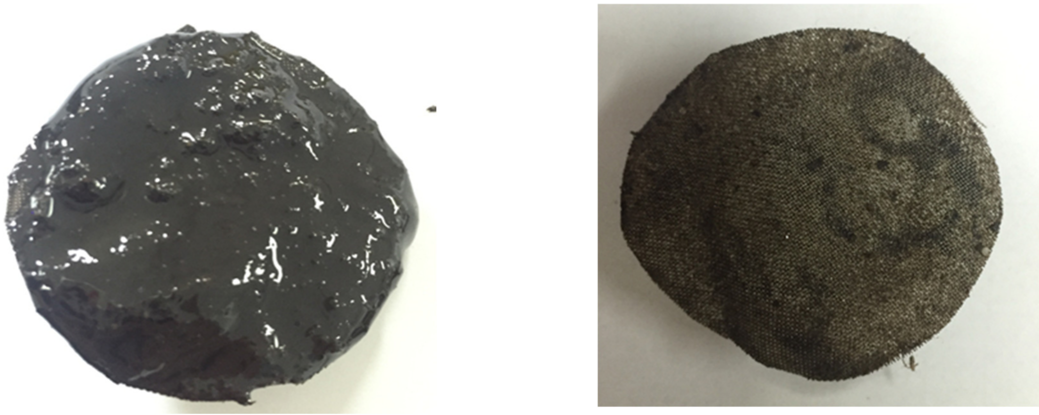


Fig. 16. The curve of permeability varying with displacement time.



(a) Pre-blocking the screen (b) Unblocking the screen

Fig. 17. The changes of the pre-blocking screen before the comparison experiment.

The research investigated the gravel filling performance in steam-driven operations and revealed the severe instability of the gravel-sand interface in steam-driven operations based on two-phase flow (Roostaei et al., 2018). Analysis of results following the study reveals that, whereas the pressure gradient across the 20/40 gravel was always less than that of the sand pack, results from a 20/40 gravel pack reveal a lower initial pressure gradient across the gravel/sand interface, with respect to the sand pack. Moreover, later phases witness a higher gravel/sand pressure gradient. Fines migration into the gravel pack was attributed to the abnormal increase of gravel/sand interface pressure gradient since the 20/40 gravel pack blocked effective sand migration. Thus, any changes in the stability of the gravel/sand interfaces have direct implications on the sand migration and pore plugging of the gravel pack, affecting permeability. Latest research suggests that modifying the gravel completions through a two-stage process could significantly limit sand blockage in gravel packs in highly silty reservoirs (Meng et al., 2019). This is especially true during the injection of steam, where loose parts of sand/gravel layers are more easily intruded by gravel/sand cyclically. Research argues that whereas the expected recovery from cyclic steam operations is between 20~25% of the original oil in place, this could perhaps suggest the preference of other thermal recovery methods, including steam flooding and SAGD (Alvarez et al., 2013).

Our research suggests that the stability of the gravel-sand boundary in the gravel pack significantly affects the efficiency of the sand pack to minimize sand production. By providing adequate control to parameters such as steam temperature, injection rate, among others, it is possible to maintain a stable operating gravel pack to achieve maximum crude production at the expected 20~25% recovery rate. Otherwise, the cyclic effects arising from multicyclic steam-oil and water injection proposed for the revitalization of permeability have the potential to not only facilitate the erosion of the gravel pack but also cause damage to the screen, which further undermines the sand control system. The application of multicyclic steam reduces the plugging effect that could be associated with plugging of gravel pores, both by the sand and dead oil.

Although the present experimental study provides valuable insights into the dynamic behavior of gravel-packed sand control wells under multi-cyclic steam-soaked operations, several limitations should be acknowledged. First, the experiments were conducted under controlled laboratory conditions with a single gravel–sand configuration and limited temperature and flow rate ranges, which may not fully represent the complex thermal–mechanical interactions in actual field environments. Second, the scale effect between laboratory cores and field gravel packs could introduce deviations in the permeability variation trends. Third, chemical and geomechanical effects such as thermal stress-induced fracturing and mineral alteration were not considered in the current setup.

To enhance the generalizability and applicability of the results, future research could focus on multi-case experimental validation under different reservoir characteristics and steam injection parameters. Furthermore, integrating numerical simulations (e.g., coupled thermal–hydraulic–mechanical models) could provide a deeper quantitative understanding of gravel-sand interface stability and permeability evolution. Such combined experimental–numerical approaches would allow the development of predictive tools for optimizing gravel pack design and steam injection strategies in diverse field scenarios.

5. Conclusions

In the production of steam-soaked wells, multi-cyclic reverse alternating displacement high temperature steam-formation fluid makes the interface between sand and gravel pack so unstable that there is invasion from both materials. This implies that gravel invades the weak parts of the sand, while sand, on the other hand, invades the gravel during alternating reverse cycles. The high temperature dissolution ratio of quartz sand was tested as 10.20% with a steam temperature of 300 °C, which is very small and almost has no influence on its sand retention effectiveness. Thus, oil producers ought to focus on establishing cyclic steam design parameters that ensure that the steam temperature is not too high to destabilize the gravel-sand interface but rather high enough to ensure economic production is realized.

The permeability of gravel packs slightly dropped to about 80% of its initial value after a single cyclic steam-water alternating displacement, as it leads to compaction and intrusion of sand grains in the gravels. Since the invasion of sand grains and the plugging effect of sand in the gravel pores compromise the efficiency of the gravel pack, proper design of the gravel pack could increase the sand control reliability to achieve high pack efficiency (Roostaei et al., 2018). However, the displacement of steam and crude oil damages the gravel permeability to 15%, the mechanism of which is mainly adsorption plugging of oil in gravel pores. This effect could even be elevated by the gravel pack design, where either a coarse or fine gravel pack may allow invasion and/or accumulation of formation sand into the gravel pack, resulting in more elevated plugging. It is worth asserting, therefore, that steam and crude oil displacement create far more disturbing damage to gravel permeability compared to steam and water displacement. This suggests that compaction could be less damaging in comparison with adsorption with respect to water or crude oil in a steam-heated operation.

High temperature steam has a positive impact on improving oil mobility and therefore removes plugs in gravels caused by oil adsorption, and the permeability recovery is about 93%. However, the damage removal effect decreases obviously as the displacement cycle increases. Besides, steam has a better plug removal effect than high temperature water, as evidenced. Our research postulates the significance of determining parameters and applicable factors for gravel pack sand control with its application in steam-soaked processes. Improving the compactness of the gravel pack could substantially facilitate the optimization of parameters during steam-soaked and sand control operations, as it maintains interface stability. We suggest that by stepwise increasing the volume of gas injection during practical production, keeping steam dryness during the second cycle of steam injection is vital. Dry steam maintains the well bottom full of high temperature steam and better for plug removal efficiency. Besides, gravel-packed steam-soaked sand control is also suggested to gradually increase production by avoiding intrusion of formation-produced sand during a blowout. Our research is limited to one experimental case study, and as such, additional future case studies applying this principle would facilitate further validation within similar field conditions.

Author Contributions

H.W.: conceptualization, methodology, software; D.X.: data curation, writing—original draft preparation; Z.Y.: visualization, investigation, supervision; C.D.: software, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study.

Use of AI and AI-assisted Technologies

No AI tools were utilized for this paper.

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References

Abdallah, W., Buckley, J. S. Fundamentals of wettability. Oilfield Review, 2007, 19(2):44-61.

Alvarez, J., Han, S. Current overview of cyclic steam injection process. Journal of Petroleum Science

Research, 2013, 2(3): 116-127.
Bhowmick, A., Amritkar, A., Ehlig-Economides, C. Determining Gravel Pack Fluidization Velocity. SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, September 2018.
Buckley, J. S. Wetting alteration of solid surfaces by crude oils and their asphaltenes. Revue de l'Institut Français du Pétrole, 1998, 53(3): 303-312.
Burger, J., Sourieau, P., Combarnous, M. Thermal methods of oil recovery. France, 1985.
Dong, C., Gao, K. C., Zhou, C., et al. Experimental Study on Quantitative Law of Sand Retaining Media plug and Prediction Model for plug Degree. Journal of Experimental Mechanics. 2017, 32 (3): 351-360.
Dong, C., Gao, K., Wang, J., et al. Experimental study on mechanical and chemical combined plug mechanism of sand control media in heavy oil reservoirs with polymer flooding. Journal of China University of Petroleum (Edition of Natural Science), 2016, 40 (5): 104-111.
Dong, C., Jia, B., Liu, C., et al. Blocking mechanism and blocking laws experiments of sand retention media in mechanical screens. Journal of China University of Petroleum(Edition of Natural Science), 2011, 35 (5): 82-88.
Dong, C., Liu, H., Han, Y., et al. Mechanisms of crude oil-sand synergistic plugging of sand control media in heavy oil and unconsolidated sand stone reservoirs. Journal of China University of Petroleum (Edition of Natural Science), 2024, 48 (1): 133-141.
Dong, C., Zhou, Y., Chen, Q., et al. Effects of fluid flow rate and viscosity on gravel-pack plugging and the optimization of sand-control wells production. Petroleum Exploration and Development, 2019, 46 (6): 1178-1186.
Elias, R., Powell, T., Medizade, M. An Analysis of Cyclic Steam Stimulation Projects in the California Opal A Diatomite. SPE Western Regional Meeting, Garden Grove, California, USA, April, 2015.
Filimonov, O. V., Galiullina, I. F. Area of reservoir heating during steam cyclic treatment of oil wells. Conference Series: Earth and Environmental Science. IOP Publishing, 2018, 194(8): 082010.
Gao K., Dong C., Gao J., et al. Regularity of permeability loss in gravel-packing layer for sand control during initial production. Oil Drilling & Production Technology, 2016, 38(6): 876–881.
Hu, Z., Zhan, X., Xiong, S., et al. Evaluation and optimization experiment of high-efficiency sand control methods in heavy oil reservoirs with with high clay and high asphaltene content. China Offshore Oil and Gas, 2022, 34 (5): 158-170.
Jia, L., Gong, Y., Xin, Y., et al. Study on sand production prediction method in Bohai steam huff and puff heavy oilfield. Petrochemical Industry Application, 2024, 43(8): 21-25.
Li, Y., Li, M., Qin, G., et al. Numerical simulation study on gravel-packing layer damage by integration of innovative experimental observations. SPE Canada Heavy Oil Conference, Calgary, Alberta, Canada, June, 2012.
Li, Y., Li, M., Yang, G., et al. Productivity Prediction of Horizontal Well by Integration of Formation Damage Model during Gravel-pack Completions. SPE European Formation Damage Conference and Exhibition, Noordwijk, The Netherlands, 5-7 June, 2013.
Meng, X., Qi, M., Meng, Z., et al. Visual experimental study on gradation optimization of two-stage gravel packing operation in unconventional reservoirs. Energies, 2019, 12(8): 1519.
Oyeneyin, M. B., Peden, J. M, Hosseini, A., et al. Factors to consider in the effective management and control of fines migration in high permeability sands. SPE European Formation Damage Conference and Exhibition, The Hague, Netherlands, May, 1995.
Pang, Z., Liu, H. The study on permeability reduction during steam injection in unconsolidated porous media. Journal of Petroleum Science and Engineering, 2013, 106: 77-84.
Ponelis, S. R. Using interpretive qualitative case studies for exploratory research in doctoral studies: A case of information systems research in small and medium enterprises. International journal of doctoral studies, 2015, 10: 535.
Punase, A., Zou, A., Elputranto, R. How do thermal recovery methods affect wettability alteration? Journal of Petroleum Engineering, 2014, 2014(1): 538021.
Roostaei, M., Kotb, O., Mahmoudi, M., et al. An Experimental Investigation into Gravel Pack Performance in Steam-Drive Operations. SPE Western Regional Meeting, Garden Grove, California, USA, April, 2018.
Sai, D., Dong, C., Li, Y., et al. Influence Law of Hybrid Plugging of Gravel-Packed Media on Productivity in Natural Gas Hydrate Reservoirs. Petroleum Drilling Techniques, 2022, 50(5): 94-101.
Si, L., Li, Z., Zhang, J., et al. Influence of gravel packing sand control on the productivity of heavy oil well. Journal of Southwest Petroleum University (Edition of Natural Science), 2013, 35(5): 135–140.
Wang, J., Liu, X., Niu, C., et al. A new productivity evaluation method of sand control completion for steam stimulation in heavy oil reservoirs. Acta Petrolei Sinica, 2020, 41(1): 80-87.
Wang, Z., Li, A., Zhang, G., et al. Experimental study on pore-blocking mechanism in gravel packs of sand control well. Journal of China University of Petroleum (Edition of Natural Science), 2000, 24(5): 49-51.
Wu, C. H., Sharma, M. M., Fuller, M. J., et al. Estimating sand production through gravel packs. SPE International Conference and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, February, 2018.
Wu, S., Yan, J., Zhao, F. Effect of adsorption and deposition of asphaltines in crude oil on wettability and permeability of reservoir rocks. Journal-University of Petroleum China (Natural Science Edition), 2004, 28(141): 36-40.
Wu, Z., Liu, H. Investigation of hot-water flooding after steam injection to improve oil recovery in thin heavy-oil reservoir. Journal of Petroleum Exploration and Production Technology, 2019, 9(2): 1547-1554.
Yan, M., Yuan, Z., Li, K., et al. Study on sand production

prediction of thermal recovery wells with multiple cycles of steam huff and puff. Natural Gas and Oil, 2025, 43 (3): 62-72.

Zhang, Y., Liao, H. L., Li, G. S., et al. Laboratory research on plugging mechanism in gravel packed well. Shiyou Daxue Xueban: Ziran Kexue Ban (Journal of the University of Petroleum, China: Natural Science Edition) (China), 2004, 28(3): 40-42.