Mechanisms and Influence Factors of Downhole Electrical Heating-Assisted Steam-Assisted Gravity Drainage Production

Yongbin Wu,* Bolin Lv, Tong Liu, Chao Wang, Youwei Jiang, and Songlin Li

ABSTRACT: Approximately 70% steam-assisted gravity drainage (SAGD) wellpairs have entered into the production phase in China, while due to the fluvial sedimentation environment with strong reservoir heterogeneity, only 53% of the horizontal well section develops a steam chamber. In order to massively recover the bypassed oil and expand the steam chamber along the horizontal section, downhole electrical heating was proposed, and its mechanisms of high temperature-induced rock mechanics change and influence factors are investigated in this study using laboratory experiments and electrical steam hybrid numerical simulation. It is found that the electrical heating-assisted SAGD has four key mechanisms, namely, localized temperature elevation, development of a fixed point steam chamber, localized oil gravity drainage, and petrophysical property improvement. The influence factors include the static and operational factors, in which the permeability ratio is the primary factor for choosing SAGD wellpairs, while the steam injection rate, steam chamber operational pressure, injector and producer pressure difference, adjacent SAGD steam chamber pressure differential, heater surface temperature, and electrical heating period integrally influence the incremental production performance. Through carefully modifying the parameters, the typical SAGD wellpair steam chamber could expand from 67 to 100% along the horizontal section, with an incremental oil rate of 3−5 m³/day, and the cumulative steam/oil ratio decreases from 6.67 to 4.17. The downhole electrical heating is particularly efficient in improving steam chamber conformance in heterogeneous reservoirs and also has significant potential in similar reservoirs developed by horizontal wells.

1. INTRODUCTION

Reservoir heterogeneity is one of the crucial factors for steam chamber evolution, swept volume, and final oil recovery factor of a steam-based SAGD (steam-assisted gravity drainage) process.1 Due to the fluvial sedimentation environment, the production performance of SAGD wellpairs in China is particularly challenged by the reservoir heterogeneity, which results in a low oil rate level and undesirable steam chamber expansion along the horizontal section. The statistics of SAGD recovery shows that only 53% of the horizontal length of the SAGD wellpairs develops a steam chamber in average, which means that approximately half of the horizontal section is bypassed by conventional steam injection.

In order to massively improve the utilization ratio of the SAGD horizontal section, literature studies have proposed and tested various techniques and strategies, both in the laboratory and field, with inconsistent results. The most common approach is to install two parallel tubings into the injector and producer and to modify the injection and production proportions between the long tubing and short tubing to achieve the re-distribution of steam.2−5 However, when the SAGD enters into the steam chamber expansion stage, it becomes increasingly difficult to achieve the expected performance only through modifying the combination of tubings, as the steam would converge in the wellbore under the low friction of the inner wellbore and a high injection pressure.

One of the other methods is FCD (flow-control-device), which is used in a downhole wellbore to allocate injected steam into different sections designed before the installation of the FCD instrument. As verified by extensive field tests, this technique could take effect when the low-permeability zones or barriers are far from the wellbore, as the steam needs to enter the payzone.6−10 For wellpairs that penetrate the low-permeability zones, it is difficult to inject steam into the payzone, and the injected steam would flow in the outer wellbore backward to the existing steam chamber.

Other strategies, including wedge well and vertical well assistance, involve drilling one of the several infilled wells in the interwell region.11−14 Meanwhile, the infilled horizontal well recovers the oil reserve along the horizontal length, which cannot deal with the problems of enhancing the horizontal

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utilization ratio. The evenly spaced infilling vertical wells in the interwell region have an effect on establishing added thermal communication and expanding the steam chamber, but the massive drilling cost and multiple-well management compromise the incremental production performance. Other researchers proposed downhole electric heating in the SAGD start-up process to achieve uniform communications of heat and fluid. A cost-effective way should consider incremental production performance, operation cost, and technical and economic availability. China has made a strategic plan to develop new and sustainable energy, in which solar power and wind power are the development directions with the most potential in the coming years. With electricity generated by solar and wind power, it is technically and economically feasible to carry out downhole electrical heating. Thus, the authors of this study proposed a downhole electric heating-assisted SAGD process. However, the mechanism in improving the SAGD horizontal utilization ratio is unclear and the influence factors that are crucial for SAGD production performance are not fully understood. Thus, this study is focused on these issues using experimentally combined numerical simulation approaches and obtained key learnings.

2. NUMERICAL SIMULATION

2.1. Model Description. In order to reveal the production mechanism of SAGD assisted by electric heating, a typical SAGD wellpair numerical model was established based on reservoir and fluid parameters in the Fengcheng Zhong 18 well area. The numbers of grids in the three directions of the model I, J, and K are 21, 25, and 15, respectively. In the direction of I, the grid size ranges from 1 to 2.5 m, in the direction of J, along the horizontal length, it is 21 m, and the grid thickness in the direction of K is 1–2.5 m. The thickness of the simulated oil layer is 21 m, the length of the horizontal section is 380 m, the distance between IP (injection well and production well) is 5.0 m, and the distance between adjacent wellpairs is 80.0 m. The porosity is 30%, the permeability is divided into high permeability and low permeability along the horizontal segment (50% of the horizontal segment individually), in which the permeability of the high permeability section is 1.5 Darcy and the permeability of the low-permeability section is 0.5 Darcy. The permeability ratio of the horizontal section is 3, and the oil saturation is 70% (Table 1).

For the purpose of accurately describing the characteristics of temperature elevation near the wellbore, development of the steam chamber, and oil drainage at the interface of the steam chamber during electric heating-assisted SAGD production, the numerical model of the typical SAGD wellpair was locally refined in plane and longitudinal directions. The closer it was to the wellbore, the smaller the grid size became. The size of the plane grid near the wellbore was reduced to 0.5 m (Figure 1a). The vertical grid size between the IP wells was refined to 1.0 m (Figure 1b), and the heating section of the electric heater was placed in the low-permeability horizontal section of the producer well (Figure 1b,c).

2.2. Rock Geomechanics. The HTHP (high-temperature-high-pressure)-induced changes in rock geomechanics is one of the main causes of expanding the steam chamber by electrical heating under borehole conditions. Thus, the rock geomechanics characteristics under different confining pressures, fluid injection pressures, and temperature levels were tested using a triaxial rock mechanics testing machine. The variation characteristics of Young’s modulus and Poisson’s ratio with temperature were obtained from the test results, which were crucial to run a more accurate simulation on the basis of conventional SAGD numerical simulation.

The real core samples of oil saturated sandstone were prepared for the triaxial test, and the conditions and geomechanic results of each test are listed in Table 1. It is shown that at a temperature of 250 °C, the compression strength varies from 20.3 to 33.9 MPa, the Young’s modulus increases from 2.9 to 10.6 GPa, and the Poisson’s ratio decreases from 0.37 to 0.24 when the confining pressure increases from 0 to 10 MPa (Table 2). The deduced friction angle is 29.47°, and the cohesion of the core sample is 5.95 MPa. All the geomechanic data of the core sandstone was added into the rock geomechanic module of a CMG-STARS simulator to characterize the changes in permeability and porosity induced by the changes in rock geomechanics during high-temperature electrical heating.

2.3. Relative Permeability Curves. During the steam-based SAGD recovery process, the injected steam and condensed water flow in the porous media and displace the heated oil through mass transfer and heat transfer, thus producing oil under the combined forces of gravity and displacement preferentials. The relative permeability of oil and water has a direct impact on the oil flow tendency and also influences the steam chamber formation, uprising, and expansion during the electrical heating period and in the heater section.

The relative permeability curves of oil and water at different temperature levels were obtained through one-dimensional relative permeability tests. The results are illustrated in Figures 2 and 3, which show that the oil relative permeability increases dramatically at the same water saturation value at elevated temperatures. Therefore, a high temperature is beneficial for the oil porous flow.

2.4. Oil Viscosity–Temperature Curve. A Haake Mars III rheometer was used to test the oil viscosity with temperature, in which the oil viscosity values at the reservoir temperature (22 °C) and 50 °C are 404,902 and 15,111 mPa·s, respectively (Figure 4). The sensitivity of oil viscosity with temperature indicates that the added high temperature of the electric heater is beneficial to the oil reserves in the steam-bypassed horizontal sections and to the cold oil mobilization to form new steam chambers.

3. RESULTS AND DISCUSSION

3.1. Mechanisms of Downhole Electrical Heating-Assisted SAGD Production. Figure 5 shows the simulated temperature field of electrical heating-assisted SAGD. From

Table 1. Parameters of the Typical SAGD Wellpair Model

| items                  | value        | items                  | value  |
|------------------------|--------------|------------------------|--------|
| grid size in the I direction, m | 1–5          | netpay thickness, m    | 21     |
| grid size in the J direction, m | 21           | porosity, %            | 30     |
| grid size in the K direction, m | 1–2.5        | permeability, mD       | 500–1500 |
| initial pressure, MPa | 2.3          | oil saturation, %      | 70     |
| initial temperature, °C | 22           | net/gross ratio        | 1      |
| horizontal section, m  | 380          | low-permeability section, m | 200 |
| I-P well distance, m   | 5            | adjacent wellpair distance, m | 80   |
the changes in temperature fields at different production periods, for the SAGD wellpair that has entered into the steam chamber later expansion phase, electrical heating has an effect of improving the steam chamber development along the horizontal section and enhancing the horizontal tapping ratio through the following three steps: (1) Porous flow field establishment between the injector and the producer (Figure 5a). Through steam injection in the injector and localized electrical heating in the producer, the steam and condensed water porous flow field establishes at the previously steam-bypassed horizontal section, which leads to the communication of heat and fluids. (2) Small steam chamber development (Figure 5b). Continual development of the porous flow field promotes hot oil drainage in this section, which forms cavitation, allows steam entering, and forms steam chamber consequently. (3) Uprising of the small steam chamber (Figure 5c,d). The overriding of steam promotes the steady uprising of the steam chamber, forming an increasingly stable steam chamber.

Moreover, in comparison with temperature fields of different electrical heating times, the first mechanism of electrical heating-assisted SAGD is localized temperature enhancement to establish the SAGD oil drainage temperature field.
Figure 6 shows the steam (gas) saturation fields of electrical heating-assisted SAGD at different production periods. From Figure 6a, the electric heating first realizes the development of low steam quality and a small steam chamber near the steam injection well, and the high quality steam mainly enters the existing steam chamber. In the continuous electric heating process, the scope and quality of the steam chamber in the electric heating section gradually increase and expand upward with the expansion of the steam chamber Figure 6b,c. Therefore, the second mechanism of downhole electric heating is the development of a fixed point steam chamber and the establishment of a drainage channel. After 3 years of electric heating (Figure 6d), the steam chamber of the electric heating section has expanded to the top of the oil layer.

Figure 7 shows the oil saturation field and the intensity comparison of oil flow lines at different cross sections along the horizontal section at the end of 2.5 years of SAGD production assisted by electric heating. It can be seen from the figure that SAGD production assisted by electric heating has the following characteristics of oil drainage. When the electric heating is implemented in the steam chamber expansion stage of SAGD, the vertical oil drainage directly above the existing steam chamber in the horizontal section has been finished, and the oil drainage enters the slope drainage stage. By contrast, the vertical drainage stage can be gradually entered by electric heating (Figure 7b) in the electric heating section, so the horizontal section is divided into two stages, namely, slope drainage + vertical drainage (Figure 7a,b). Meanwhile, it can be seen from the distribution changes of oil flow lines in SAGD assisted by electric heating (Figure 7b) that the third mechanism of electric heating is fixed-point oil drainage,
which recovers the reserves of the electric heating section and reduces the oil saturation of the electric heating section.

The numerical simulation embedded in the rock mechanics module can well simulate the characteristics of reservoir stress in the process of electric heating and steam heating. As can be seen from the simulation results of the stress field in Figure 8, with the establishment of the thermal field and fluid communication in the electric heating section by electric heating, the stress field changes significantly, and the principal stress increases and extends upward. Finally, a steam chamber with high conductivity and scale is formed. Therefore, the fourth mechanism of underground electric heating is to improve the effective permeability of the low-permeability electric heating section through high temperature stress that induced the changes of petrophysics.

3.2. Influence Factors of Electric Heating-Assisted SAGD Production.

In the process of downhole electric heating, for the SAGD wellpair that has entered the steam chamber expansion stage, the steam cavities between adjacent wells have partially merged with each other. Therefore, the

Figure 6. (a–d) Steam chamber changes at different periods of electrical heating-assisted SAGD.

Figure 7. (a, b) Oil saturation profiles at different periods of electrical heating-assisted SAGD (purple arrows: oil flow vector).

Figure 8. (a–c) Normal stress and permeability changes at different periods of EH-SAGD from conventional SAGD.
optimal design of operating parameters requires a comprehensive consideration of steam injection operations, production operations, joint operation of steam chambers in adjacent SAGD wells, and synergies of electric heating operations.

In this study, the influence factors including geologic parameters and the operation parameters (steam injection parameters, injection production parameters, and electric heating operation parameters) from a typical heterogeneous wellpair model in the Well Zhong 18 area are simulated and their sensitivities are quantified. The SAGD wellpair has been turned into SAGD production for 3 years, and the utilization degree of the horizontal section is 67%.

3.2.1. Petrophysical and Static Factors. There are many petrophysical parameters that affect the development effect of electric heating-assisted SAGD. Among them, the most critical parameters include the permeability difference along the horizontal section, oil viscosity, and spatial interwell space of the injector and producer. In order to quantify the influence degree of these factors, the orthogonal design method is used to evaluate each factor, and the values of the factors in the orthogonal simulation are listed in Table 3.

Table 3. Factors and Levels of the Orthogonal Simulation

| no. | factors                        | Level 1 | Level 2 | Level 3 | Level 4 |
|-----|--------------------------------|---------|---------|---------|---------|
| A   | permeability ratio             | 3       | 5       | 8       | 12      |
| B   | oil viscosity, mPa·s           | 10,000  | 15,000  | 30,000  | 50,000  |
| C   | netpay thickness, m            | 12      | 15      | 18      | 22      |
| D   | interwell spacing variation, m | 0.3     | 0.5     | 0.7     | 0.9     |

Table 4 lists the orthogonal simulation parameters and results. A range analysis is carried out to evaluate the influence degree of the four factors on simulation results. The average value $k_N$ and the influence degree $T$ are calculated using the following equations:

$$k_N = \frac{1}{m} \sum_{i=1}^{m} y_i$$

$$T = R_{\text{max}} - R_{\text{min}}$$

where $i$ is the test number; $y$ is the test result; $n = 4$; $m = 4$; $N$ is the level number; $R_{\text{max}} = \max\{k_1, k_2, k_3, k_4\}$; and $R_{\text{min}} = \min\{k_1, k_2, k_3, k_4\}$.

From the results, it is obvious that the permeability ratio along the horizontal section is the primary factor when choosing the target SAGD wellpairs (Table 5), while the netpay thickness and oil viscosity basically only affect the oil drainage rate and the CSOR, but not the oil recovery factor. The least important factor is the interwell spacing variation, as this variation is only related to the spatial fluctuation of horizontal wellbores, and when the fluctuation is within 1 m, it does not pose an issue to the steam chamber conformance.

3.2.2. Operational Factors. 3.2.2.1. Steam Injection Rate. The steam injection rate is related to the utilization ratio of the horizontal section and the development status of the steam chamber in the electric heating section. Therefore, under the conditions of 50, 60, 70, 80, and 90% development ratios of the horizontal section before electric heating, the peak steam injection rates at the three stages of the electric heating, namely, thermal communication, steam chamber rising, and steam chamber expanding, were simulated and the production performance was compared. According to the optimization results in Table 1, considering that the utilization ratio of the SAGD horizontal section in China is generally 50–70%, the steam injection rates are 84–106, 109–136, and 158–171 m³/day in the thermal communication stage, steam chamber rising stage, and expansion stage, respectively, under the assistance of electric heating (Table 6).

3.2.2.2. Steam Chamber Operational Pressure. In the electric heating stage, increasing the steam injection pressure is beneficial to improve the oil-steam mass transfer rate, oil drainage rate, and steam chamber development rate in the electric heating section, but it is easy for too high operating pressures to cause the steam chamber in the used section to break through the cap layer, resulting in steam leakage. Steam chamber operating pressures of 2.3, 3.3, 4.3, 4.9, 5.4, and 5.9 MPa during electric heating-assisted production were simulated. The results show that the optimal operating pressure of the steam chamber is 1.0–2.0 MPa higher than the reservoir pressure (2.3 MPa) and 0.5–1.0 MPa lower than the cap pressure (5.9 MPa), and 4.9–5.4 MPa is preferred.

3.2.2.3. Injector and Producer Pressure Difference. At the initial stage of electric heating, the risk of steam channeling increases, so the pressure difference between injection and production wells needs to be controlled reasonably. Therefore, the electric heating-assisted production was simulated when the pressure differences between injection and production wells were 0.2, 0.3, 0.4, 0.5, and 0.6 MPa. The results show that the pressure difference should be kept small in the initial stage of electric heating. When the steam chamber size increases, the pressure difference between injection and production wells can reach the level of conventional SAGD operation. The optimal pressure differences are 0.2–0.3 MPa in the steam chamber rising stage and 0.4–0.5 MPa in the steam chamber expanding stage.

3.2.2.4. Neighbored SAGD Steam Chamber Pressure Differential. When the well group has entered the steam chamber expansion stage, the operating pressure of the adjacent well group steam chamber directly affects the electric heating production effect. Therefore, the conditions of electric heating-assisted production with pressure differences of 0.4, 0.5, 0.6, and 0.7 MPa between adjacent well groups were simulated. As can be seen from the simulation results in Figure
When the pressure difference between adjacent well groups reaches 0.5 MPa, a large amount of steam in the high-pressure chamber enters the steam chamber of the low-pressure SAGD well group from the combined section, resulting in insufficient steam supply in the steam chamber of the electric heating section of the high-pressure well group, making it difficult for the electric heating assistance to take effect.

3.2.2.5. Heater Surface Temperature. Considering the field operation, the coking temperature of the crude oil in the F SAGD block was tested at different temperatures. It was found that the crude oil did not coke at 320 °C in the nitrogen environment, but the distillation process vaporized the light components, increased the viscosity of the crude oil, and significantly reduced the content of the crude oil. At 340 °C, the distillation effect increases obviously, the light components of crude oil vaporized by distillation, and the left crude oil tends to be solidified. When the temperature rises from 340 to 360 °C, coking begins and full coking occurs at 380 °C (Figure 10). According to the test results, the surface temperature of the designed heater should not exceed 340 °C, and the temperature control begins after the wellbore fluid temperature rises to 300–320 °C.

The purpose of electric heating is to rapidly replenish heat at a fixed section, and the power should not be too low to promote the development of the steam chamber by fixed point heating. At present, the power per meter of the electric heater for long-term underground work in China is generally less than 1500 W. Therefore, the electric heating-assisted production

| Table 5. Range Analysis of the Orthogonal Simulation Results |
|----------------------------------------------------------|
| Recovery factor | CSOR |
|-----------------|------|
| K               | A    | B    | C    | D    | A    | B    | C    | D    |
| K1              | 234.43 | 207.31 | 199.53 | 211.98 | 2.62 | 3.59 | 4.01 | 3.49 |
| K2              | 211.20 | 206.66 | 205.19 | 207.98 | 3.42 | 3.60 | 3.68 | 3.57 |
| K3              | 195.86 | 209.37 | 208.90 | 206.72 | 4.19 | 3.49 | 3.48 | 3.55 |
| K4              | 188.668 | 206.82 | 216.54 | 203.48 | 4.74 | 3.55 | 3.17 | 3.62 |
| K1(average)     | 58.61 | 51.83 | 49.88 | 52.99 | 2.62 | 3.59 | 4.01 | 3.49 |
| K2(average)     | 52.80 | 51.67 | 51.30 | 52.00 | 3.42 | 3.60 | 3.68 | 3.57 |
| K3(average)     | 48.97 | 52.34 | 52.22 | 51.68 | 4.19 | 3.49 | 3.48 | 3.55 |
| K4(average)     | 47.17 | 51.70 | 54.13 | 50.87 | 4.74 | 3.55 | 3.17 | 3.62 |
| T               | 11.44 | 0.68 | 4.25 | 2.13 | 2.13 | 0.10 | 0.85 | 0.13 |

| Table 6. Peak Steam Injection Rates for Different Stages of EH-SAGD |
|----------------------------------------------------------|
| Utilization ratio before electric heating (%) | Stages |
|----------------------------------------------|--------|
| Thermal communication (m³/day) | Steam chamber rising (m³/day) | Steam chamber expansion (m³/day) |
|-----------------|-----------|--------------------------|
| 50              | 84        | 109                      | 158                      |
| 60              | 91        | 119                      | 161                      |
| 70              | 106       | 136                      | 171                      |
| 80              | 133       | 160                      | 185                      |
| 90              | 173       | 186                      | 196                      |

Figure 9. Steam channeling route of adjacent steam chambers (black arrows: water (steam) flow vector).

Figure 10. (a–d) Coking evolution at different temperatures (nitrogen environment).
with 800, 1000, and 1200 W electric heating power per meter is simulated. The results show that when the electric heating power per meter is greater than 800 W/m, the oil increase amplitude decreases greatly.

Therefore, at the early stage, a constant power heating mode of 800 W/m was adopted to elevate the fluid temperature in the wellbore annulus to a predetermined temperature of 300 °C. When the wellbore temperature reaches 300–320 °C, constant heater-surface-temperature heating mode was adopted to vaporize the annulus fluid into saturated steam. With the increase in temperature near the wellbore, the temperature difference between the wellbore vicinity and heater gradually decreased, and the heater power gradually decreased correspondingly. Therefore, the electric heating control adopts the dual control mode of constant power at the early stage and constant heater-surface temperature later on.

3.2.2.6. Electrical Heating Period. The preliminary field test shows that if the electric heating time is too short, the subsequent steam cannot continue to enter the newly formed steam chamber, and this steam chamber will even gradually disappear. Therefore, the production with electric heating times of 1, 2, 3, 4, and 5 years was simulated (Figure 11). The simulation results show that continuous electric heating has the dual effects of promoting the steam chamber development and accelerating the oil drainage rate, and the steam chamber development in the electric heating section slows down after the electric heating is stopped. Therefore, the electric heating time is required to ensure that the newly developed steam chamber reaches the top of the reservoir to form a large enough steam chamber volume. According to the simulation results, the optimal electric heating time is determined to be 2–3 years.

4. FIELD PERFORMANCE PREDICTION

Using these optimized parameters above, a comparison is made between conventional steam SAGD production and electric heating-assisted SAGD production for a typical SAGD well group in this field. As can be seen from Table 7, after 3 years of downhole electric heating in the SAGD steam chamber expansion stage, the utilization ratio of the horizontal section increases from 67 to 100% and the daily oil production rate increases by 3–5 m³/day. By converting to conventional SAGD, the cumulative SOR (gas/oil ratio) decreases from 6.67 to 4.17, and the final recovery factor increases from 43.2% to 51.3% on the basis of conventional SAGD. The results show that the application of downhole electric heating-assisted SAGD production can effectively improve the utilization ratio of the horizontal section, oil production rate, and oil/gas ratio in the middle and late stage of SAGD development and greatly improve oil recovery.

5. CONCLUSIONS

For SAGD wellpairs that have entered the steam chamber expansion stage, the downhole electric heating-assisted steam production is proposed in this study, on the detailed review of suitability and potential of current conventional operation strategies.

Experiments including oil–water relative permeability, oil-temperature viscosity, and high temperature-induced changes in rock geomechanics were systematically tested and analyzed to build the typical electric heating-assisted SAGD wellpair model.

Mechanisms of downhole electrical heating-assisted SAGD production include localized temperature enhancement to establish the SAGD oil drainage temperature field, development of fixed point steam chamber, and the establishment of drainage channel, fixed-point oil drainage, and improvement of the effective permeability of the low-permeability electric heating section.

Static influence factor analysis of orthogonal simulation results show that the permeability ratio along the horizontal section has the largest influence on the incremental performance of EH-SAGD, and the largest permeability ratio should be less than 8.

Dynamic influence factors, including the steam injection rate, steam chamber operational pressure, etc., were simulated, their influences were quantified, and the appropriate values were determined.

The EH-SAGD performance was forecasted, which indicated that after 3 years of electric heating, the utilization ratio of the horizontal section increases from 67 to 100%, and the daily oil production rate increases by 3–5 m³/day. By converting to conventional SAGD, the cumulative SOR (gas/oil ratio) decreases from 6.67 to 4.17, and the final recovery factor increases from 43.2% to 51.3% on the basis of conventional SAGD.

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Table 7. Production Performance Comparison for Conventional SAGD and EH-SAGD

| SAGD mode     | production time (year) | Cum. oil (10⁴ m³) | peak oil rate (m³/day) | CSOR (m³/m³) | utilization ratio (%) | recovery factor (%) |
|---------------|------------------------|-------------------|------------------------|--------------|----------------------|-------------------|
| SAGD          | 13.5                   | 6.72              | 21.7                   | 6.67         | 67                   | 43.2              |
| EH-SAGD       | 13.5 (electric heating: 3 years) | 7.98              | 24.7–26.7              | 4.17         | 100                  | 51.3              |
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Notes
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■ NOMENCLATURE

SAGD: steam-assisted gravity drainage
EH-SAGD: electric heating-assisted SAGD
K\text{rw}: water relative permeability
K\text{ro}: oil relative permeability
K\text{rog}: oil relative permeability in the steam (gas) environment
K\text{rg}: gas relative permeability
CSOR: cumulative steam/oil ratio

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