Study on Thermal Efficiency Analysis and Improvement Strategies in the Development of Super-Heavy Oil Reservoirs

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Abstract. In view of the problems of large heat consumption and low heat utilization rate in SAGD (Steam Assisted Gravity Drainage) development in mid-deep super-heavy oil reservoirs, the causes and influencing factors of heat loss in each phase of SAGD development were analyzed by referring to the actual production data of SAGD in Guan Tao reservoir, Du Block 84, Liao he Oilfield, and the heat loss in each phase of the whole development process was calculated. Measures to improve thermal efficiency are also proposed. The results show that the heat loss in the whole process of SAGD development includes 6 parts: steam boiler heat loss, steam separator heat loss, steam injection pipeline heat loss, steam injection wellbore heat loss, formation heat absorption and production wellbore heat loss. The heat loss is mainly concentrated in steam injection boiler, steam separator, steam injection pipeline and steam injection wellbore, the heat loss ratio reaches 34.8%, and the formation heat absorption ratio is only 36.0%. In view of the main heat loss phase, the strategies to improve the thermal efficiency were proposed, and the comprehensive thermal efficiency was increased by 17.0 percentage points after field implementation. This study can provide technical reference for improving SAGD development efficiency and economy in mid-deep super-heavy oil reservoirs.

Keywords: Steam assisted gravity drainage, super-heavy oil, thermal efficiency, Liaohe Oilfield.

1 Introduction

SAGD (Steam Assisted Gravity Drainage) is one of the most technically and economically successful super heavy oil reservoir development mode conversion technologies. It has been implemented in Liao he and Xinjiang oil fields in China and Canada. At present, the annual oil production of Liao he oils field has reached more than

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100×10^4t/a, which is an efficient thermal recovery and development method for super heavy oil [1-2]. However, due to the imperfect surface technology and the influence of internal factors in the reservoir, most of the heat in the SAGD development process is not effectively used, and the heat utilization and economy of the reservoir cannot be guaranteed. At present, the research on heat utilization in SAGD development of super-heavy oil reservoirs is mainly aimed at shallow super-heavy oil reservoirs. The research focuses on improving the heat utilization rate of steam inside the reservoir, ignoring the heat loss of surface process part and produced liquid, and failing to quantify the heat loss at each phase of the whole development process, which is disadvantage to the improvement of thermal efficiency [3-10]. Therefore, according to the geological characteristics of super-heavy oil reservoirs in Liao he Oilfield, the causes and influencing factors of heat loss in the whole process of SAGD development are analyzed, and the heat loss in each phase is quantitatively calculated with reference to the actual production data of Guan Tao reservoir in Block Du 84 of Liao he Oilfield. On this basis, the strategies of improving thermal efficiency are put forward to improve the thermal utilization rate of the system and improve the development performance and economy of SAGD [1].

2 Heat Loss Analysis in SAGD Development Process

In the SAGD development process, a large amount of high quality steam needs to be injected into the formation, and the whole process (steam injection, artificial lift, gathering and transportation, oil and water treatment) is in a high temperature state, and each part of the heat loss is large. Heat loss mainly includes six aspects: steam boiler heat loss, steam separator heat loss, steam injection pipeline heat loss, steam injection wellbore heat loss, formation heat loss, production wellbore heat loss (Figure 1).

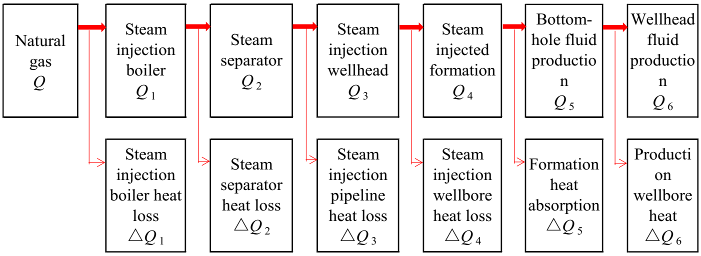

Fig. 1. Schematic diagram of heat loss at each phase of the SAGD development process

3 Heat Loss Calculation

The SAGD development of Guan Tao reservoir in Block Du 84, Liao he Oilfield is taken as an example. The Guan Tao reservoir in Block Du 84 is an ultra-heavy oil reservoir with extremely thick edge-top and bottom-water. The effective thickness of the reservoir is 106m, the porosity is 36%, the permeability is 5.5D, and the oil saturation is 70%.Based on the SAGD development field test data of Guan Tao reservoir in Block Du 84 (Table 1), taking heating 1000kg water as an example, according to the field test, the amount of natural gas required to be burned is $69m^3$, and according to the combustion value of natural gas $39820kj/m^3$, the total heat Q generated is 2.749×10^6kj. Then, according to the enthalpy values of saturated water and steam under different pressures in Table 2, the heat loss at each phase is calculated [2].

Table 1. Steam monitoring data at all phases of the SAGD development process

Production process	Pressure /MPa	Temperature /°C	Steam quality /%
Boiler outlet	12.00	330	75
Steam separator	11.40	318	99
Injector wellhead	9.00	281	90
Steam chamber	5.50	270	75
Producer downhole	2.40	220	0
Producer wellhead	1.15	185	0

Table 2. Enthalpy values of saturated water and steam at different pressures

Pressure/MPa	Sensible heat of saturated water/(kj·kg^{-1})	Latent heat of steam/(kj·kg^{-1})	Total enthalpy/(kj·kg^{-1})
12.00	1490.70	1193.80	2684.50
11.40	1466.20	1231.00	2697.20
9.00	1363.10	1378.90	2742.00
5.50	1184.50	1604.50	2789.00
2.40	943.36	1849.80	2793.16
1.15	790.14	1992.70	2782.80

3.1 Steam Boiler Heat Loss

The thermal efficiency of steam boiler is little affected by the outlet pressure and steam quality of steam injection boiler, which is mainly related to the material and fuel of the boiler itself [3-4]. At present, the outlet pressure of the steam boiler on site is 12.0MPa, and it is calculated that the heat carried by 1000kg steam with 75% quality is 2.386×106kj. The heat loss of steam boiler mainly includes smoke exhaust heat loss and heat dissipation loss of steam injection boiler, the heat loss is 0.363×106kj, and the thermal efficiency of the boiler is 86.8%.

$$Q_1 = M_1 h' + M_1 D r = 1000\times1490.7 + 1000\times75\%\times1193.8 = 2.386\times10^6 kj \quad (1)$$

$$\triangle Q_1 = Q - Q_1 = 2.749\times10^6 - 2.386\times10^6 = 0.363\times10^6 kj \quad (2)$$

In the equation: Q_1 The total heat of steam at the outlet of steam injection boiler, kj; $\triangle Q_1$ Steam boiler heat loss, kj; D Steam boiler outlet steam quality; M_1 Amount of steam at the outlet of steam injection boiler, kg; h', r Refers to the sensible heat of saturated water and latent heat of steam when the steam boiler outlet pressure is 12MPa, kj/kg.

3.2 Steam Separator Heat Loss

The steam separator increases the quality of the steam produced by the steam boiler to 99%, meeting the needs of SAGD development. According to the following formula, the heat loss amount and heat loss ratio of the steam separator under different pressures can be calculated (The proportion of heat loss to the total heat of the phase, %).

$$Q_2 = M_2 h \tag{3}$$

$$\triangle Q_2 = Q_1 - Q_2 \tag{4}$$

In the equation: Q2 Total heat of high quality steam, kj;△Q2 Steam separator heat loss, kj;M2 Amount of steam from steam separator outlet, kg; h The total enthalpy of steam at different pressures, kj/kg.

At present, the outlet pressure of the steam separator in use on site is 11.40MPa, then 750kg of high quality steam is produced (250kg of water is separated), the heat of high quality steam is 2.022×10^6kj, the heat loss of the steam separator is 0.363×106kj, and the heat loss ratio is 13.21% (Table 3).

Table 3. Heat loss of steam separator under different pressure conditions

Pressure/MPa	Total enthalpy/(kj·kg^{-1})	Heat loss/10^6kj	Heat loss ratio/%
11.00	2705.34	0.357	12.99
11.20	2701.31	0.360	13.10
11.40	2697.21	0.363	13.21
11.60	2693.05	0.366	13.32
11.80	2688.81	0.369	13.44
12.00	2684.50	0.373	13.55

3.3 Steam Injection Pipeline Heat Loss

The high quality steam is transported to the steam injection well through the steam injection pipeline, and the heat loss of the steam injection pipeline under different wellhead steam injection pressure can be calculated according to formula (5) and (6).

$$Q_3 = M_2 h_1' + M_2 D_1 r_1 \tag{5}$$

$$\triangle Q_3 = Q_2 - Q_3 \tag{6}$$

In the equation: Q3 Heat from steam injection wellhead, kj;D1 Quality of steam injection wellhead;h1′,r1 Sensible heat of saturated water and latent heat of steam under different wellhead injection pressure, kj/kg.

Field measurement shows that steam injection wellhead pressure is 9.00MPa, steam quality is 90%, heat is 1.953×106kj, then steam injection pipeline heat loss is 0.069×106kj, heat loss ratio is 2.51% (Table 4).

Table 4. Steam pipeline heat loss under different wellhead injection pressure

Pressure /MPa	Sensible heat of saturated water/(kj·kg^{-1})	Latent heat of steam/(kj·kg^{-1})	Total enthalpy/(kj·kg^{-1})	Heat loss/ 10^6kj	Heat loss/ ratio/%
8.50	1340.10	1409.90	2750.02	0.065	2.37
9.00	1363.10	1378.90	*2741.92*	0.069	2.51
9.50	1385.40	1348.00	2733.40	0.073	2.66
10.00	1407.20	1317.20	2724.46	0.077	2.82

3.4 Steam Injection Wellbore Heat Loss

High quality steam is injected into the oil reservoir through steam injection well. Under the current steam injection wellbore technology conditions, the steam quality at the bottom of the wellbore is different according to the heat loss model of the wellbore under different reservoir depths and different formation pressures, and the heat loss of the steam in the wellbore is different [5-6]. The deeper the reservoir is, the higher the pressure is, and the greater the proportion of heat loss in the wellbore is (Figure 2). At present, the pressure of steam chamber of Guan Tao reservoir is 5.5MPa, and the quality of steam of the downhole is 75%, so the heat of steam injected into the formation is 1.791×10^6kj, and the heat loss of steam injection wellbore is 0.162×10^6kj, and the heat loss ratio is 5.9%.

$$Q_4 = M_2 h_2' + M_2 D_2 r_2 \tag{7}$$

$$\triangle Q_4 = Q_3 - Q_4 \tag{8}$$

In the equation: Q_4 The total heat injected into the formation, kj; $\triangle Q_4$ Steam injection well heat loss, kj;D_2 steam quality of the downhole;h_2',r_2 Sensible heat of saturated water and latent heat of steam under different formation pressures, kj/kg.

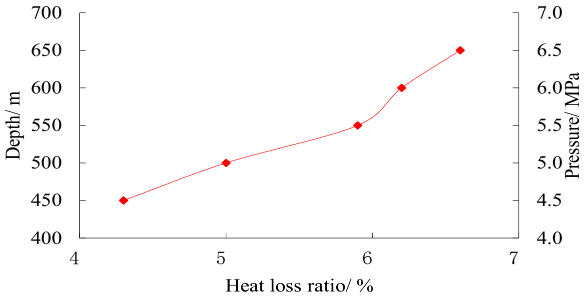

Fig. 2. The proportion of heat loss of injector at different depths and under different formation pressures

3.5 Formation Heat Absorption

The heat absorbed by the formation in the SAGD development phase is mainly determined by the formation conditions [7-8]. The proportion of heat absorbed by the formation varies with different oil saturation and porosity. The lower the oil saturation, the greater the porosity and the more heat absorbed by the formation [9-11] (Figure 3). Based on oil saturation of 70% and porosity of 36%, the heat absorption of Du84 Guan Tao reservoir is 0.990×106kj, accounting for 36.00% of the total heat.

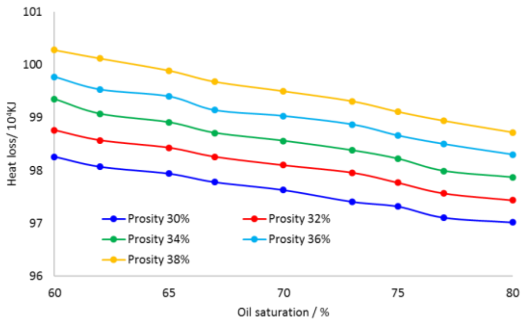

Fig. 3. Heat loss in strata with different porosity and oil saturation

3.6 Producer Wellbore Heat Loss

When the emulsion rate, water cut and temperature of the wellhead produced liquid are the same, and the temperature of the wellhead produced liquid is different under the condition of different reservoir depth, the wellbore heat loss of the production well can be calculated according to equations (9) and (10).

$$Q_6 = M_3 h_4{}' + M_o r_o (T_1 - 34) \tag{9}$$

$$\triangle Q_6 = Q_5 - Q_6 \tag{10}$$

In the equation: Q6 Emulsion heat, kj; △ Q6 Heat loss of production wellbore,kj;M3,Mo The amount of water and oil in the emulsion,kg;h4′ Sensible heat of saturated water under different pressures, kj/kg;T1 Emulsion temperature,℃.

Six different depths were selected to calculate the heat loss of production wellbore (Table 5). It can be seen from Table 5 that the greater the reservoir depth, the greater the heat loss of the wellbore; Finally, the residual heat is carried to the surface by the downhole production fluid, and the buried depth of Guan Tao reservoir is 600m, so the wellhead generated heat is 0.670×106kj, and the wellbore heat loss of the production well is 0.130×106kj, and the loss ratio is 4.71%.

Table 5. Heat loss of production wellbore under different reservoir depth conditions

Depth/ m	Sensible heat of S_w/ (kj·kg^{-1})	Water/ kg	Oil/ kg	WHT/ ℃	Heat loss/ 10^6kj	Heat loss ratio/ %
600	790.14	712.5	237.5	185	0.13	4.71
700	772.26	712.5	237.5	181	0.15	5.28
800	755.05	712.5	237.5	178	0.16	5.80
1000	719.25	712.5	237.5	170	0.19	6.93
1200	693.03	712.5	237.5	164	0.21	7.77
1400	649.58	712.5	237.5	156	0.25	9.10

According to the above analysis, the heat loss of steam before injected into the formation is mainly concentrated on steam injection boiler, steam separator, steam injection pipeline and steam injection wellbore, and the proportion of heat loss reaches 34.8%. The production well heat loss and heat carried by high temperature production fluid accounted for 29.2%, and the formation heat absorption ratio was only 36.0%. Therefore, in order to improve the development effect of SAGD, measures should be taken to reduce the steam heat loss in each phase and increase the proportion of formation heat absorption.

4 Measures to Improve Thermal Efficiency

4.1 Improve Boiler Thermal Efficiency

The main factors of heat loss of steam boiler are smoke exhaust heat loss and heat dissipation loss of steam injection boiler. To solve this problem, a series of optimization were carried out: by stopping the heat exchanger in front of boiler, setting the air preheater at the rear of the heating smoke tube, and using the heat tube air preheater to heat the air, the flue gas temperature of the heating furnace was reduced from 230℃

to about 170°C, and the effect of reducing the exhaust heat loss was achieved. Adjust the damper to match the supply air volume with the fuel volume, improve the combustion effect, and increase the thermal efficiency of steam boiler from 82.8% to 92.8% after implementation. Replace part of the combination of OTSG and steam separator with the combination of drum boiler and MVC water treatment to reduce heat loss in the steam separator, and use MVC water treatment to treat SAGD produced water into distilled water that can be used by drum boiler through vertical film evaporation technology, improve steam quality and steam production rate, and reduce waste water production rate. Improve the thermal efficiency of steam boilers and water supply systems [12].

4.2 Reduce Heat Loss of Steam Injection Pipeline and Wellbore

The main factor affecting the thermal efficiency of steam injection pipeline is the insulation quality of the pipeline. In order to improve the thermal efficiency of the steam injection pipeline, three layers of 10mm aerogel aluminum foil + color steel plate were adopted to keep heat, after using the Φ114mm pipeline heat flux decreased from 280W/m2 before the modification to 134W/m2, the pipeline heat loss decreased from 278.0W/m to 74.1W/m, and the proportion of pipeline heat loss decreased from 2.50% to 0.62% by 1.88 percentage points. In terms of the amount of heat loss in the wellbore, the heat insulation method of nitrogen injection was optimized, a reasonable working system was formulated, and the heat insulation method was upgraded and modified, and vacuum heat insulation pipe was adopted to reduce the heat loss of steam in the wellbore. After the implementation, the proportion of heat loss in the wellbore was reduced from 4.70% to 1.70%, a reduction of 3.00 percentage points.

4.3 SAGD High Temperature Separation Water and Produced Emulsion Heat Utilization

The daily rate of SAGD high temperature separated water is 2500t/d, and the temperature is as high as 300°C. By transferring heat between high temperature separated water and boiler feed water, heat recovery is realized, saving gas 4.5×104m3 per year, saving cost 3220×104 yuan, equivalent to increasing thermal efficiency by 6.2 percentage points. The heat carried by the wellhead produced emulsion accounted for 24.4% of the total heat. At present, the daily rate of SAGD high temperature production emulsion is 9300t/d, and the temperature is 135°C. Through the method of heat exchange with the CPF exporting crude oil, the daily heat energy is recovered by 1602MJ, equivalent to 3.9×104m3 of natural gas equivalent, and the annual gas cost is saved by 2790×104. In this way, the heat of SAGD high temperature separation of water and production emulsion can be efficiently utilized, and the temperature of produced emulsion can be lowered to the temperature suitable for oil and water separation (90°C) [13].

4.4 Improve the Thermal Efficiency of Steam in the Reservoir

By reducing the operation pressure to improve the thermal efficiency of steam, only the latent heat of steam vaporization can be used to heat the oil reservoir in SAGD development, and the effective heat enthalpy and specific volume of steam increases while the pressure decreases. When the operation pressure is reduced from 5.5MPa to 4.0MPa, the steam thermal efficiency can be increased by 6.6 percentage points. And the operation pressure is reduced, the temperature of the steam chamber is reduced from 270°C to 251°C, and the heat stored in the rock framework is released outward. Taking the Du 84 Guan Tao reservoir as an example, the heat released by the rock framework is equivalent to 55.3×104t steam. To address this problem of decreasing thermal efficiency after the steam chamber reaches the overburden, gas-assisted SAGD is implemented to form a thermal insulation layer at the upper part of the steam chamber, which reduces the heat transfer rate of steam to the overburden, maintains the pressure of the steam chamber, reduces the steam consumption, and improves thermal efficiency.

5 Implementation Effect

Comprehensive measures are taken to reduce the heat loss of steam boiler exhaust gas and heat loss of boiler body, and the thermal efficiency of steam boiler system is increased from 86.8% to 92.8%. The application of new insulation materials in steam injection pipelines reduces the heat loss ratio by 1.88 percentage points, and by strengthening the application of new wellbore insulation technology, the wellbore heat loss ratio is reduced by 3.00 percentage points, ensuring the quality of steam injection into the well downhole and the heat carried by it. In terms of production adjustment, the steam consumption was reduced by reasonably reducing the operation pressure and implementing gas-assisted SAGD measures, the thermal efficiency of steam was increased by 6.6 percentage points, and the heat absorption ratio of formation was increased by nearly 20.0 percentage points. The heat of high temperature separated water and produced emulsion is rationally utilized, and the production cost is reduced. After adopting the above method, the comprehensive heat utilization rate in SAGD development has been increased from the original 65.0% to 82.0%, and the improvement effect is significant.

6 Conclusion

1) The heat loss in the whole process of SAGD development includes 6 parts: heat loss of steam boiler, heat loss of steam separator, heat loss of steam injection pipeline, heat loss of injector wellbore, heat loss of formation absorption and heat loss of producer wellbore.

2)In the process of SAGD development, the steam heat loss is mainly concentrated on the surface equipment and pipelines, and the formation heat absorption only accounts for 36% of the total heat.

3)Through the analysis of the factors affecting the heat utilization rate of SAGD steam injection system, the comprehensive heat utilization rate is increased by 17.0 percentage points by relying on the technical progress and the optimization of steam injection process, which ensures the SAGD development performance, but there is still room for further improvement.

4)Continuous improvement of steam heat utilization is still an effective measure to ensure the SAGD development performance in the later phase, which requires continuous upgrading of steam injection, artificial lift and surface gathering systems.

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