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Smart completion design in cyclic steam stimulation process: an alternative for accelerating heavy oil recovery

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Abstract: Cyclic steam stimulation (CSS) has succeeded in recovering bitumen and heavy oil. However, after the fifth cycle, the process is no longer effective as indicated by the increasing cumulative steam-oil ratio (cSOR). This paper proposes an improvement to the CSS performance by modifying the completion design. The perforation interval is divided into two parts: upper section (for injection) and lower section (for production). In such design, the injected steam would condense due to heat loss. The steam would then flow to the lower section because of gravity force and the oil starts to produce. The injection-production cycle is managed by an interval control valve (ICV). Simulation results show that the proposed design would reduce the cSOR up to 30% and increase the cumulative oil production by 3.5 times. It is also revealed that the longer the distance between the injection and production sections, the better the steam efficiency. [Received: July 11, 2014; Accepted: March 22, 2015]

Keywords: cyclic steam stimulation; CSS; heavy oil; smart completion; heat efficiency; recovery factor.

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1 Introduction

Total estimate of the world's heavy oil reserve is approximately 3,396 billion barrels, of which 30 billion barrels are identified as prospective undiscovered reserve (Meyer et al., 2007). To produce those resources, several methods have been successfully applied such as cyclic steam stimulation (CSS), steam flooding, steam-assisted gravity drainage (SAGD) process, and non-thermal recovery methods.

CSS is a well stimulation method in which the heat is transferred to the reservoir by injecting steam periodically into the production well. This method was first applied in the late 1950s to recover bitumen from the tar sands of Venezuela. Following the successful field trial, CSS has been applied worldwide to recover heavy oil and bitumen. This process can achieve a recovery factor of 3% to 10% of the remaining oil in place (Hong, 1994).

In some cases, the ultimate recovery factor could be greater than 20% as reported by Esso, or it could be much lower than 20% as experienced by some projects in Cold Lake, Canada. In some other cases such as those in Duri Field, Indonesia, it can be switched into steam flooding recovery mechanism after the CSS period is over. However, it also might not be feasible as demonstrated in several cases in Cold Lake (Ali, 1994). This is because of the complexity of geological structure, such as shale barriers, sealing faults, and disconnected formations, that makes the continuous steam flooding very difficult. In such cases, the CSS is the only method that seems feasible to recover heavy oil and bitumen.

In conventional CSS processes, the initial oil production rate is usually high due to the condition where the reservoir pressure is increased, the initial oil saturation is still high, and the oil viscosity is reduced (Sheng, 2013). The well may be produced for several months. After several cycles, the oil saturation will gradually decrease in the surrounding area near the borehole. This area should not be the target of heating, but the area further away from the borehole instead. To reach such target, the steam volume will obviously increase. Consequently, the cumulative steam-oil ratio (cSOR) will increase indicating that the process is no longer efficient.

In order to improve the flaws of the conventional CSS process, several techniques have been applied and reported to be successful. Injecting nitrogen prior to CSS seems to assist the process and provide better results. Since nitrogen has a low heat conductivity coefficient and large compressibility coefficient, its insulation effect and great expansion energy can improve the recovery (Wang et al., 2013). In addition, the optimisation of the operating conditions including steam injection rate, steam quality and soaking time can also increase the oil production and reduce the cSOR (Ho and Morgan, 1990; Azad et al., 2013). It has been shown that improving heat efficiency in the wellbore using a vacuum insulated tubing (VIT) is better than conventional thermal insulation techniques (Yue et al., 2013). Furthermore, improving the ultimate recovery factor using gravity drainage effect has proved to be successful in the Xing VI Formation. In this method, adding horizontal wells up in the bottom of vertical well during CSS process will improve the recovery (Liu et al., 2003). Therefore, smart completion design in CSS process by utilising gravity drainage effect is proposed and investigated in this research.

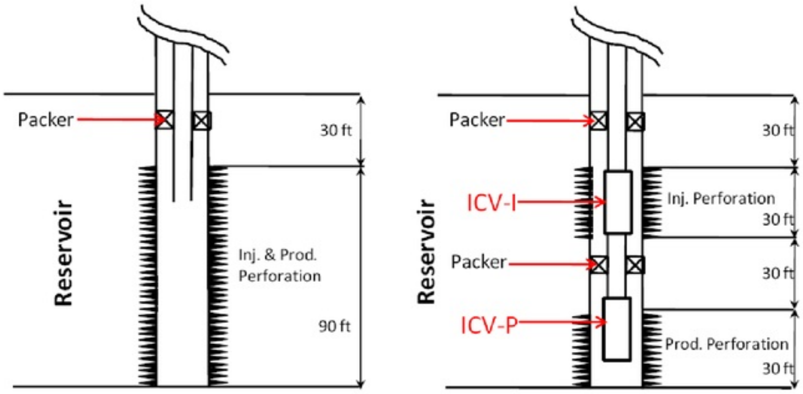
The novel method to improving CSS process proposed in this research is based on the modification of the perforation interval. This smart completion design consists of two perforation sections, the first section is at the top and the second section is at the bottom of the reservoir. In this process, after the steam is injected into the top perforation section, the steam would condense because of heat loss to the reservoir, and then it would flow to the lower section because of gravity force. Hereafter, the oil is produced through the production section (i.e., lower section). The injection and production cycles are managed by an interval control valve (ICV). The process is repeated until the end of the project.

The advantage of this process is that the injection of steam and the production of oil are conducted in different path ways so that the steam will stay in the reservoir for longer time and the reservoir pressure can be maintained properly. Consequently, the effectiveness of steam in the smart completion design is better than that of the conventional CSS.

2 Smart well completion principle in CSS process

The first smart well completion was installed in August 1997 at Saga's Snorre Tension Leg Platform in the North Sea (Gao et al., 2007). The principle of the smart completion is to optimise the operation of the well by closing and opening of the perforations and, hence, to maximise its production. This can be achieved by using ICVs. Some equipment can be installed in a typical ICV system such as pressure gauge and temperature sensor to determine the wellbore conditions. Specific equipment is attached allowing the operator to optimise the operation of the valves (Mohaghegh, 2008). For example, when the pressures between the two perforation sections are different, undesirable cross-flow may occur. To prevent such a problem, the bottom valve is closed from the surface via a hydraulic or electronic line. In addition, the temperature sensor provides real-time monitoring of the temperature at the installed location. When a valve is closed, it only isolates the path between the annulus and the tubing. It still allows the fluid to go through the area inside of the tubing, thus the production of the fluid can be continuous.

Figure 1 The schematic diagram of CSS perforation, (a) conventional CSS (b) smart CSS (see online version for colours)



(a) (b)

As mentioned, a novel method for improving the CSS process is proposed in the present study by applying the smart well completion principle. The method is based on modification of the perforation interval. In this case, the perforation interval is divided into two sections where the first section is at the top and the second section is at the bottom. This may also be called as commingled perforation. A packer is installed between the injection and the production sections. An ICV is installed in the tubing as a connector between the annulus and the inside of the tubing. While the steam is injected, the injection section is opened by opening the ICV, but the production section is closed. During the soaking period, both sections are closed. Then, during the production period, the injection section is closed and the production section is opened correspondingly. The next cycle is repeated similarly. Figure 1 shows a comparative schematic diagram of the conventional perforation (a) and the smart completion (b) in the CSS process. The performance of both types of CSS (conventional and smart completion) is evaluated and compared in the present study. Furthermore, a sensitivity analysis of the section lengths is also conducted to find the optimum operational conditions.

3 Description of reservoir model

The thermal reservoir simulator, STARS Version 2011 by Computer Modeling Group (CMG, 2011), was used to construct the reservoir model and to investigate the performance of conventional and smart CSS processes. A reservoir model representing generic Pertamina and Kedua Formations in Duri Field, Indonesia, was selected for this investigation. It consists of one vertical well in the center of a radial system. Table 1 shows the pertinent reservoir properties that were used in this research.

There were no gas cap and bottom water driving mechanisms. The boundary condition was no-flow. The geo-mechanicals effects such as dilation related to pressure or temperature were also ignored. Due to limited data, the rock and fluid properties were assumed to be homogeneous in the whole reservoir. The oil column thickness was constant for all layers. The ratio of the horizontal permeability to the vertical permeability is 0.5.

Table 1 Pertama/Kedua reservoir properties

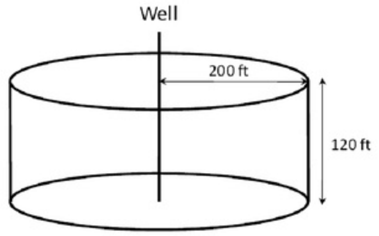
Reservoir properties	*Value*
Depth, ft	500
Initial reservoir temperature, °F	100
Initial reservoir pressure, psi	100
Net thickness, ft	120
Reservoir radius, ft	200
Porosity, %	0.34
Permeability, mD	1,500
kv/kh, fraction	0.5
Rock compressibility, 1/psi	5.7e-6
Oil density, °API	20
Oil viscosity at reservoir condition, cP	330
Oil viscosity at 432 °F, cP	8.2
Oil formation volume factor at reservoir condition, RB/STB	1.02
Solution gas-oil ratio, SCF/STB	14
Residual oil saturation to water, fraction	0.25
Residual oil saturation to steam, fraction	0.1
Irreducible water saturation, fraction	0.40
Reservoir, underburden/overburden volumetric heat capacity, BTU/ft^3-°F	33.2
Reservoir, underburden/overburden thermal conductivity, BTU/ft-day-°F	27.4

Source: Gael et al. (1995)

The number of grid was 22 × 4 × 40 (i, θ, k). The near-wellbore grid size was 3 ft and gradually increased toward the reservoir boundary to reach the value of 90 ft while the vertical grid size was kept constant at 3 ft. The injection steam quality was equal to 0.8 and the steam temperature was 432 °F. Figure 2 shows the idealisation of the model. The conventional and smart CSS processes were simulated using this reservoir model. In those processes, the steam injection pressure at the sand face was kept constant at 350 psi and the maximum steam injection rate (equivalent water) was 2,000 stb/day. During the production period, the minimum bottom-hole pressure (BHP) was set to be 70 psi which is generally reasonable for pump operations.

In the conventional CSS case, there was no ICV installed in the perforation interval as shown in the left-hand side diagram of Figure 1. The length of perforation was 90 ft starting from the bottom of the reservoir. In this investigation, the steam was injected for 21 days. The well was soaked for 5 days and produced for 4 months afterwards. The durations of steam injection, soaking times and production periods were the same in both conventional and smart CSS cases. The top of the perforation interval was 30 ft apart from the top of the reservoir to reduce the heat loss in overburden and the gravity override effects.

Figure 2 Idealisation of the 3D model



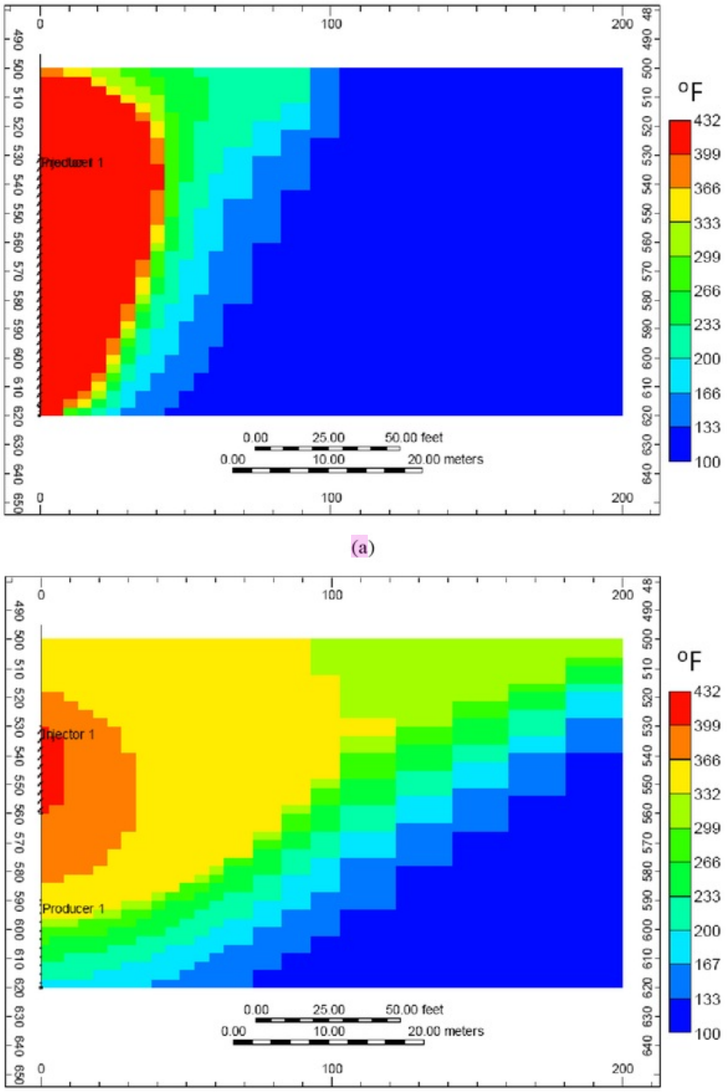
The perforation interval in the smart CSS case is divided into two sections, one section was at the top and the other was at the bottom as shown in the right-hand side diagram of Figure 1. In the base case, the lengths of both sections were approximately 30 ft, respectively, and the distance separating them was 30 ft. When the ICV in one section was closed then the corresponding perforation interval is closed or isolated.

4 Results and discussions

4.1 Comparison of the two methods

Figure 3 shows the temperature distribution in the reservoir in both conventional and smart CSS cases. In the conventional case [Figure 3(a)], the steam was injected into the reservoir through all perforation length. The area around the wellbore was soaked before the well was produced. In this process, only the steam in the front can contact with the oil while the steam behind might not. Thus, its effectiveness will decrease as characterised by an increase in cSOR as shown in Figure 5. As previously mentioned, the steam was injected and then was produced via the same perforation interval. It will be difficult for the steam to penetrate further into the reservoir due to the fact that a large volume of condensate was formed near the wellbore. This will require a larger volume of steam that leads to a larger cSOR.

Figure 3 Temperature distribution at the end of the project life during the steam injection period, (a) conventional CSS (b) smart CSS (see online version for colours)

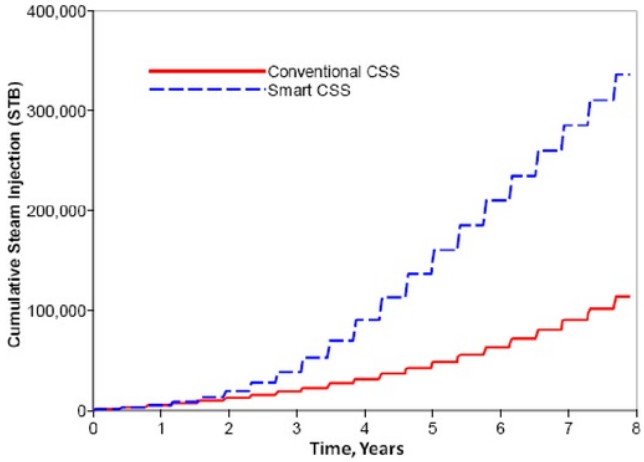


(a)

(b)

On the other hand, the temperature distribution resulted from the smart CSS is quite different to that of conventional CSS as shown in Figure 3(b). During the beginning of injection period, the steam would grow out radially from the injection section. After that, it went up due to its low density. During the soaking period, the steam would condense into liquid. This fluid then went down because of gravity force while it swept the oil. Because of the injection and production sections were separated, most volume of the injected steam could contact with the oil due to different path ways of fluid entering and exiting the wellbore. The heat would stay longer in the reservoir and consequently most of the heat would be adsorbed and therefore the effectiveness of steam would be increased. In addition, the injected fluid would not immediately be drained from the reservoir; hence, it would enhance significant pressure maintenance benefits.

Figure 4 Cumulative steam injection vs. time of the two methods (see online version for colours)

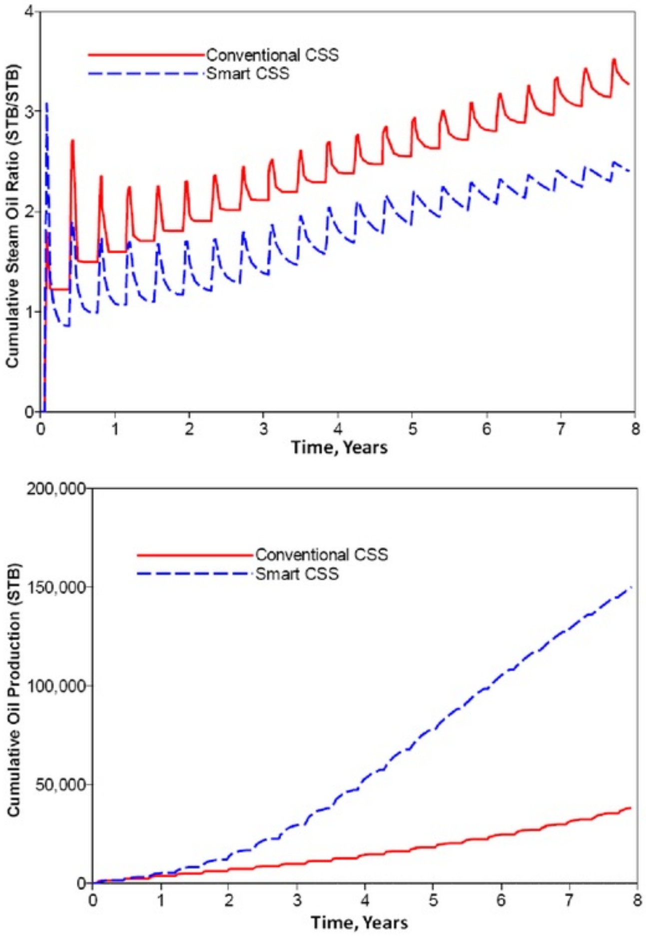


During the injection period in the smart CSS case, the steam volume would increase because the steam could flow continuously and it could propagate easily into the reservoir. On other hand, in the conventional CSS case, after the injection period was completed, the injected fluid would be flowed back via the same path. Hence, in the next injection cycle, the steam would have to 'start over'. It obviously needed more energy and the steam rate would be lower than that of the smart CSS case, even though both processes have used the same injection pressure. Furthermore, the cSOR reduces by 30% compared to conventional CSS in the end of project.

Although the operating conditions were the same in the two processes, the drainage radius were quite different, approximately 100 ft in the conventional CSS and 200 ft in the smart CSS (Figure 3), resulting from the effect of the steam volume. Figure 4 shows the cumulative steam injection in the conventional and the smart CSS cases. In the conventional CSS, after one cycle was completed, the steam would follow the similar path to penetrate into the reservoir. In this process, the energy needed would be slightly the same as the first cycle so that the cumulative steam injection curve would have a straightline characteristic. On the other hand, the cumulative steam injection of the smart

CSS would rapidly increase after 3 years, as a result of different path ways of steam injection and oil production. In this process, the steam would continue to penetrate further into the reservoir after the first production period and it would not follow the same pattern as in the case of the conventional CSS. Because of that, the oil cumulative production would be higher compared to that of the conventional CSS. Figure 5 shows the cumulative oil production vs. time and, as can be seen, the cumulative oil production of the smart CSS case could be 3.5 times higher than that of the conventional CSS case. In this circumstance, the increasing oil production rate and the decreasing cSOR were due to the ICV installation and perforation effects.

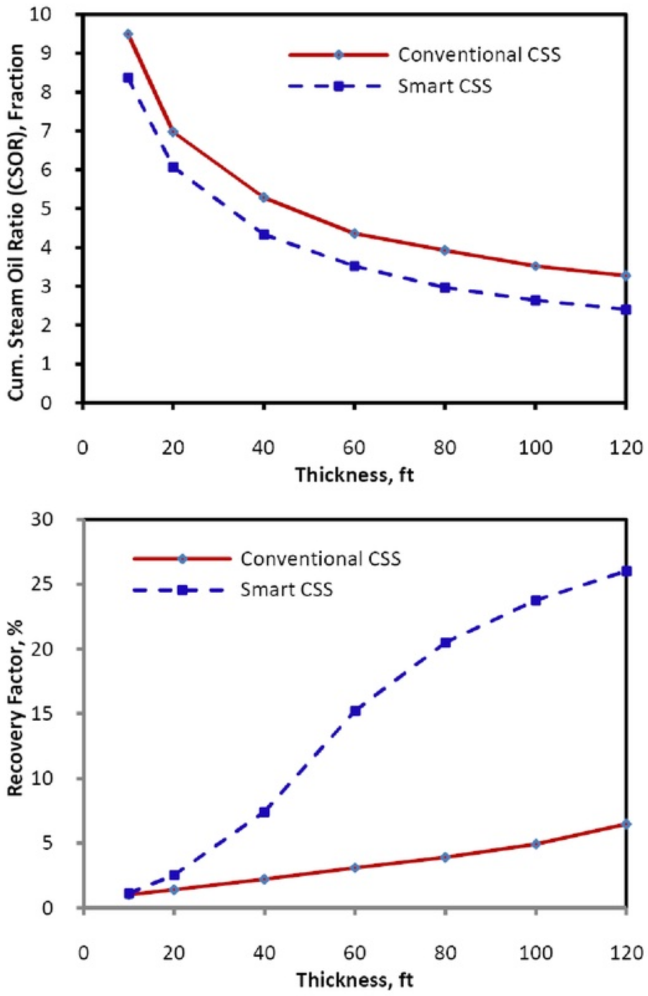
Figure 5 cSOR and cumulative oil production of the two methods (see online version for colours)



4.2 *Effect of reservoir thickness on the processes*

Figure 6 shows the relationship between reservoir thickness, cSOR, and recovery factor after 8 years of production. In both CSS processes, the cSOR increased with the reduction of reservoir thickness. As a result, the recovery factor of oil decreased as well. The effectiveness of steam also decreased because the heat was loss to overburden and underburden areas easily.

Figure 6 cSOR and cumulative oil production of the two methods with different reservoir thicknesses (see online version for colours)



In thin reservoirs, the distance between the perforation of injection and production sections was close to each other. Hence, the effect of gravity drainage in oil recovery was not significant compared to that in thick reservoirs. After the steam was injected, the condensed steam would slightly move to the lower section and it might be produced directly. Consequently, the reservoir pressure would be rapidly dropped. During the injection period, the steam rate would be lower due to the reduction of the injection interval length. As a result, the performances of smart and conventional CSS would likely be the same.

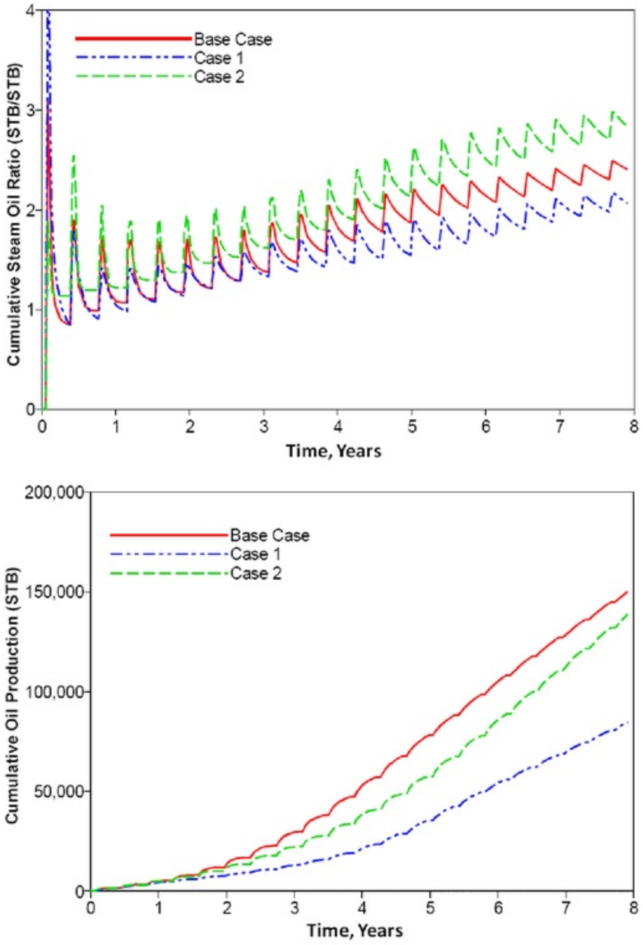
As can be seen in Figure 6, the cSOR of both methods increases in parallel with each other when the thickness of the reservoir was reduced. When the thickness is lower than 40 ft, the cSOR dramatically increases. In addition, when the thickness is below 20 ft, the recovery factor of both methods is almost similar. On the other hand, when the thickness is greater than 20 ft, it has a significant effect on the recovery factor.

4.3 Effect of perforation interval on the smart CSS process

The perforation interval is very important to the CSS process that its examination is necessary for the proposed design. The investigated scenario consisted of three cases, which were base case, case 1 and case 2. These cases were grouped based on the lengths of the injection and production perforation sections. Base case, case 1, and case 2 have the length of the perforation interval of 30 ft, 15 ft, and 45 ft, respectively. If the injection perforation interval was long, the steam would be easier to penetrate into the reservoir. However, as a consequence, the distance between the injection and the production sections would be small. Hence, the cSOR would increase because the steam was relaxed to move directly toward the production perforation. On the other hand, if the injection perforation interval was short, the steam would stay longer in the reservoir. That led to the decrease of cSOR, but the steam injection rate would also decrease. Thus, the cumulative oil production would not be satisfying. Figure 7 shows a sensitivity study of different lengths of the injection and production sections. As can be seen, the most effective lengths of injection and production sections are 15 ft and 15 ft, respectively (case 1). In this combination, the cSOR would be the lowest.

In contrast, it will be different in the scenario of lengthy perforation sections. If both of the injection and production sections were 45 ft (case 2), not only the steam that would easily penetrate into the reservoir, but also the condensed water that was very easy to move into the production intervals. Consequently, the pressure rapidly dropped while the cSOR increased. At the end of the production period, the steam injection increased because the oil had been swept out further away from the borehole. The area between the oil saturated zone and the borehole was filled with the steam. Thus, it made the steam easier to move into the reservoir. Technically, the optimum length was the one that led to a low cSOR and favorable production. In this investigation, the base case result was better than those of the other two scenarios. Economic criteria would be obviously very important to make decisions but it was not included in this research.

Figure 7 cSOR and cumulative oil production of the two methods with different lengths of perforation (see online version for colours)



5 Conclusions

Simulation results indicated that the steam effectiveness and cumulative oil production of the smart CSS would increase up to 30% and 3.5 times, respectively, compared to that of the conventional CSS. When the reservoir is very thick, applying the smart completion in CSS will be advantageous. For thin reservoirs, its performance is quite similar to that of the conventional CSS. Furthermore, the smart CSS method has limitation for reservoirs of which the thickness is less than 20 ft. When the lengths of the injection and production sections are equal and there is a big gap separating them, the smart CSS process is even more efficient.

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Nomenclature

CSS	Cyclic steam stimulation
SAGD	Steam-assisted gravity drainage
ICV	Interval control valve
cSOR	Cumulative steam-oil ratio
BHP	Bottom-hole pressure

SI metric conversion factors

bbl × 1.5899 = m^3
cP × 1.0 = Pa.s
ft × 3.048 = m
(°F–32)/1.8 = °C
psi × 6.8947 = kPa

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