Advantages of In-situ combustion

In-situ combustion has been proved to possess the high energy efficiency during heavy oil production process.1–6 In in-situ combustion process, air is injected through a central vertical well, which is surrounded by a number of production wells, and combustion initiated at the injector well then sweeps the oil in the formation toward the production wells.7 In China, in-situ combustion is widely used in heavy oil reservoirs, located in Shengli, Liaohe and Xinjiang oil regions.8 While steam stimulation and steam flooding have also been tested in these heavy oil reservoirs, they are not regarded as the suitable technologies, because energy efficiency of steam stimulation and steam flooding are much lower, due to the heat lose in steam generator, gas pipeline and wellbore.9 Meanwhile, the requirement of high temperature in the range between bottom of well and steam condensation front also results in the low energy efficiency. By utilizing in-situ combustion method, although the compressed air consumes energy, there is no heat loss from the air compressor to gas pipeline, and further to the bottom of wellbore. Heat loss does not occur until oxygen from injected gas reacts with the fuel in the oil layer to generate heat in the combustion front.10 During the process of injected gas flowing towards combustion front, a part of heat that remains in the rock can be recovered. This kind of heat recovery is more obvious during wet forward combustion process.11

Compared to other thermal oil production methods, in-situ combustion is more environmentally friendly. Due to its high thermal efficiency, less fuel is consumed.12,13 Meanwhile, most of the exhaust gas remains in the reservoir, leading to much less discharged exhaust gas in the atmosphere than that produced by steam flooding method. Even the small amount of exhaust gas from in-situ combustion can be re-injected into the reservoir after being replenished with oxygen, therefore, environment influence can be decreased to the minimum by in-situ combustion method.14

In in-situ combustion process, air, as combustion aid, is injected continuously through the vertical injection well, while residual oil in the reservoir works as a “fuel” (Figure 1).
After combustion starts, the oil layer will burn and a moving combustion front will form. The heat generated by the combustion reactions at combustion front is transported toward the cold oil by the generated steam and combustion gases, and this causes viscosity reduction of crude oil, allowing the oil to be displaced toward the production well. Meanwhile, more coke forms as a result of thermal cracking, providing more fuel for further combustion. According to the reservoir temperature and oil saturation distribution, the reservoir can be divided into six zones: post-combustion zone, combustion zone, coking zone, steam zone, light oil zone and crude oil zone. Physical and chemical reactions mainly occur in combustion zone, coking zone and steam zone.

**Adaptability of In-situ combustion**

Due to the obvious advantages of in-situ combustion, field tests have been conducted widely on heavy oil reservoirs in China. The results proved that in-situ combustion worked well in thin-bed heavy oil reservoir, deep heavy oil reservoir and bottom water reservoir.

For thin-bed heavy oil reservoir with oil layer thickness less than 10m, in-situ combustion has been proved as a more suitable method than steam flooding. Because of small unit reserve in thin-bed reservoir, large well distance is usually used for mining due to economic efficiency.\textsuperscript{15,16}

While steam flooding requires high temperature for the entire reservoir area in order to ensure propagation of steam condensing front, this feature limits the application of steam flooding in thin-bed heavy oil reservoir. Fortunately, by using in-situ combustion, combustion front can propagate normally as long as combustion front temperature is not lower than burning point and sufficient oxygen is supplied.\textsuperscript{1} The reservoir area temperature after combustion front is allowed to be lower during oil production process.\textsuperscript{3,8} Therefore, in-situ combustion is a favorable method for thin-bed heavy oil reservoir with large well distance. In-situ combustion pilot test was conducted on Du-66 reservoir in Liaohe oil region from 2006. Du-66 reservoir consists of medium deepthin-bed oil layers, and it had single well average daily production of 0.5t/d before conduction of in-situ combustion. After transferring thermal production method from steam flooding to in-situ combustion, the single well average daily production has increased to 3.8t/d, and total reservoir daily production has reached 619t/d (2017). Meanwhile, production costs are greatly reduced.

In-situ combustion is also regarded as a suitable method for deep heavy oil reservoirs, whose reserve burial depths are more than 1500m.\textsuperscript{3} For these deep heavy oil reservoirs, which commonly distribute in Liaohe and Xinjiang oil region, steam flooding has been tested. However, the great reservoir depth causes the huge amount of heat loss in the wellbore and the low stream dryness at the bottom of well. As a result, there is not enough amount of heat for oil production, leading to negative influence on economic benefit. Different from steam flooding, in-situ combustion is not limited by reservoir depth, because air flow is hardly influenced by reservoir depth and combustion heat is generated inside the oil layer. Besides, in these deep heavy oil reservoirs, crude oil viscosity is lower, usually in the range of medium viscosity, under formation condition since these deep heavy oil reservoirs have high temperatures. The fluidity of crude oil in the initial condition, which is resulted from lower viscosity, is also favorable for application of in-situ combustion. Gao3-6-18 reservoir in Liaohe Oil field is a typical deep heavy oil reservoir, whose reserve burial depth is 1540–1890m. Its reservoir properties, such as reservoir thickness 96.8m, porosity 20.6%, and permeability 1014.1md, make it suitable for in-situ combustion. In-situ combustion pilot test on this reservoir started from 2008, and a single well daily average production was 1.8t/d, while daily average production of this reservoir was 184t/d. The oil recovery was improved by 8.4% compared to that from steam flooding.

For bottom water reservoirs, in-situ combustion is also used as an effective production method.\textsuperscript{17} In bottom water reservoirs, at the initial stage of in-situ combustion, the gas flow propagation is difficult caused by the high viscosity of crude oil above water-oil interface. While air as a non-wetting phase compared to water may cause fluid channeling in the water area close to water-oil interface, fluid channeling does not occur in other area of bottom water. Even though fluid channeling causes air loss at the initial stage, the amount of air flowing into reservoir increases with propagation of combustion front towards the oil layer, and oil layer burning process can be carried out smoothly.

According to pilot tests and lab experimental results of in-situ combustion in China, the main application criteria of in-situ combustion are as follows: oil reservoir thickness in the range of 4–20m, reservoir burial depth>150m, porosity>0.2, permeability>100x10\textsuperscript{-14} \text{m}\textsuperscript{2}, permeability coefficient>0.7, oil saturation>0.5, and crude oil viscosity<10000mPa.s in reservoir condition. For thin bed heavy oil reservoir, deep heavy oil reservoir and bottom water reservoir possessing these properties, in-situ combustion has been proved as a high effective production method with significant economic benefit.

**Development of In-situ combustion technology**

Even though in-situ combustion has obvious advantages and wide adaptability, it still has some limitations. Due to gravity override of the injected gases, the combustion front may not advance uniformly in the vertical direction. Hence, the sweep efficiency may be reduced by the preferential flow of the gases to one or more wells of the pattern.\textsuperscript{7} Since in-situ combustion process requires the mobilized oil flows ahead of combustion front into the colder immobile oil, this can cause mobility reduction and lower injectivity.\textsuperscript{7,14} Therefore, more attention has been paid to improve in-situ combustion technology.

**In-situ Toe-to-Heel Air Injection (THAI)**

Toe-to-heel air injection (THAI) has been proved as an effective improvement for in-situ combustion.\textsuperscript{19-21} THAI is a variant of conventional in-situ combustion that uses a horizontal production well to recover mobilized partially upgraded heavy oil.\textsuperscript{22} The combustion front in THAI spreads along the horizontal well from the tip to the heel, rapidly forming a flowable oil zone, where the high temperature inside not only provides an effective heat displacement source for oil layer, but also creates an ideal condition for thermal cracking of heavy oil. Meanwhile, the heated crude oil flows rapidly due to gravity, and reaches the horizontal production well through a short distance, which avoids the long-distance displacement by using conventional in-situ combustion.\textsuperscript{23} Besides, by adding movable inner sleeve, the length of perforation section on production well can be maintained by simply adjusting the inner sleeve.

Due to the characterizations of THAI, it improves the volume sweep efficiency, and provides a more homogeneous and effective combustion front condition at the initial stage of burning, compared
to conventional in-situ combustion. Meanwhile, quality of crude oil is improved in THAI, and this is regarded as the result of increased drainage capacity of downstream movable oil, which stays close to the high temperature zone formed around horizontal well. Besides the obvious improvement on oil recovery, because of the small production pressure difference when oil flows in the horizontal production well, THAI also avoids the problems during production of straight wells, such as sand production and emulsion treatment.

**Combustion Override Split Production Horizontal Well (COSH)**

Combustion override split production horizontal well (COSH) improved the conventional in-situ combustion by using a novel well arrangement. Lateral wells are used to vent flow gases out of the reservoir, and a horizontal well is used as a production well. The horizontal production well has a similar function as that in THAI, providing a larger contact area between formation and the combustion front. Meanwhile, gravity drainage stabilizes the combustion front development along the production well.

Compared to conventional in-situ combustion, distance between combustion front and the production well is smaller in COSH, resulting in higher heat transfer efficiency. During COSH process, in the heat-affected zone below the combustion front, crude oil viscosity is decreased. Due to gravity drainage, oil is drained without passing through cold oil area, and the flow resistance is small. Meanwhile, the combustion fingering has little negative influence on COSH. In the early stage of COSH, the combustion fingering facilitates the connections between the gas injection well and the gas recovery well. At the later stage, the low sweep efficiency caused by the combustion fingering can be reduced by reducing gas production through the gas recovery well. In addition, in COSH process, gas-liquid gravity separation and combustion override also make gas-liquid separation possible, reducing production problems associated with gas-liquid synchronous production.

**Combustion Assisted Gravity Drainage (CAGD)**

Most recently, combustion assisted gravity drainage (CAGD) has been proposed as a promising alternative to in-situ combustion method. CAGD improves conventional in-situ combustion by utilizing a horizontal injector at the top of the formation with a horizontal producer located near the bottom of the reservoir. In CAGD process, because of the horizontal injector, combustion front develops towards the heel-end of the injector and extends laterally after initiation of combustion along the length of the injector, then the heated oil flows downward towards the underlying horizontal production well due to gravity drainage.

Even though CAGD has not been applied for pilot test in China, laboratory test results show that a stable combustion front propagation can be created under gravity drainage, and injected oxygen is consumed efficiently in combustion reactions.

**Conclusions**

Because of the obvious advantages of in-situ combustion, many researches have been done on in-situ combustion in China. In-situ combustion has been widely used in heavy oil reservoirs. THAI, COSH and CAGD, as improved in-situ combustion methods, utilize a horizontal well as a production well, overcoming the limitations of conventional in-situ combustion, such as low sweep efficiency, low mobility and low injectivity. Therefore, heavy oil recovery has been improved significantly in China.

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