OPEN ACCESS

Ology Press

Mini Review

Journal of Oil, Gas and Petrochemical Sciences

Application of In-situ combustion for heavy oil production in China: A Review

Jia Yao[1], Guihe Li[2], Jinjin Wu[1]

[1]Department of Petroleum Engineering, University of Wyoming, USA

[2]Department of Chemical Engineering, University of Wyoming, USA

Correspondence: Jia Yao, Department of Petroleum Engineering, University of Wyoming, 1000E University Ave. Laramie, WY 82071, USA, Email jyaouwyo@gmail.com

Received: June 16, 2018 | **Published:** June 26, 2018

Abstract

In China, heavy oil reservoirs face several production challenges: most of the heavy oil reservoirs have already been in the middle or last stage of steam stimulation, and the throughput effect has deteriorated significantly; even though steam flooding has been widely applied in shallow reservoir, steam flooding technology suitable for medium-deep reservoir is still in the experimental stage; meanwhile, for ultra-heavy oil reservoir, a rapid decline in production is observed by utilizing conventional steam injection. Therefore, it is necessary to develop new technologies to replace steam floodingin order to enhance oil recovery of heavy oil reservoirs. In-situ combustion has been proved as a relatively effective technology for heavy oil production. In recent years, several field tests have been conducted in Shengli, Liaohe and Xinjiang oil regions, and the results proved that the feasibility of in-situ combustion technology for heavy oil reservoirs in China. This review paper introducesadvantages, adaptability, and developments of in-situ combustion technology for heavy oil reservoirs in China.

Keywords: heavy oil reservoir, in-situ combustion, in-situ Toe-to-Heel Air Injection (THAI), Combustion Override Split Production Horizontal Well (COSH), Combustion Assisted Gravity Drainage (CAGD)

Advantages of In-situ combustion

In-situ combustion has been proved to possess the high energy efficiency during heavy oil productionprocess.[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).

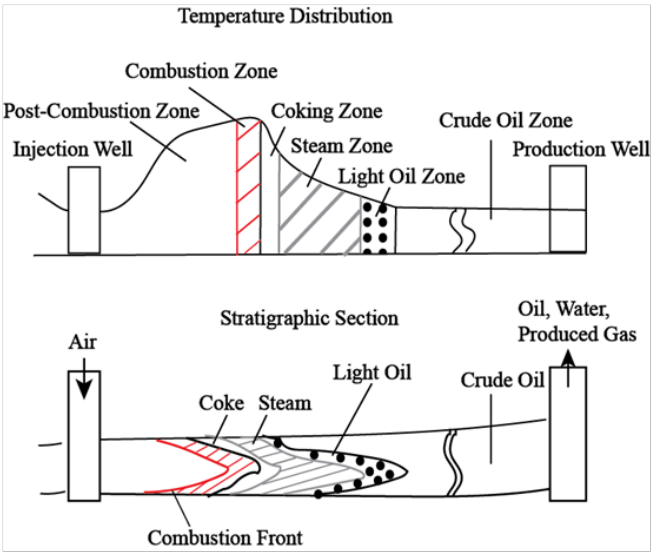

Figure 1 Schematic of temperature and phase distribution during in-situ combustion process.

Citation: Yao J, Li G, Wu J. Application of In-situ combustion for heavy oil production in China: A Review. *J Oil Gas Petrochem Sci.* (2018);1(3): 69–72. DOI: 10.30881/jogps.00014

After combustion starts, the oil layer will burnand 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.[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.[8] The reservoir area temperature after combustion front is allowed to be lower during oil production process.[5,8] 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.[8] 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 thesedeep 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.[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^{-3}μm^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.[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.[7,18] 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.[19–21] THAI is a variant of conventional in-situ combustion that uses a horizontal production well to recover mobilized partially upgraded heavy oil.[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.[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

Citation: Yao J, Li G, Wu J. Application of In-situ combustion for heavy oil production in China: A Review. *J Oil Gas Petrochem Sci.* (2018);1(3): 69–72. DOI: 10.30881/jogps.00014

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.[24,25] 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[7].[7]

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.[26] 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.[27,28]

Combustion Assisted Gravity Drainage (CAGD)

Most recently, combustion assisted gravity drainage (CAGD) has been proposed as a promising alternative to in-situ combustion method.[29,30] 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.[7] 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.[7,31]

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.[7]

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 of Chinese oilfields, and oil recovery enhancement has been observed, especially in thin bed heavy oil reservoirs, deep heavy oil reservoirs and bottom water 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.

References

1. Cinar Y, Marquez S, Orr FM. Effect of IFT variation and wettability on three-phase relative permeability. *SPE Reserv Eval Eng*. 2007;10(03):211–220.
2. Bazargan M, Chen B, Cinar M, et al. A combined experimental and simulation workflow to improve predictability of in situ combustion. In: *SPE Western North American Region Meeting*. Society of Petroleum Engineers. 2011.
3. Gutierrez D, Moore RG, Ursenbach MG, Mehta SA. The ABCs of in-situ-combustion simulations: from laboratory experiments to field scale. *J Can Pet Technol*. 2012;51(04):256–267.
4. Prats M. A current appraisal of thermal recovery. *J Pet Technol*. 1978;30(08):1–129.
5. Ramey HJ. In Situ Combustion. In: *8th World Petroleum Congress*. World Petroleum Congress; 1971.
6. Zhao R, Chen Y, Huan R, Castanier LM, Kovscek AR. An experimental investigation of the in-situ combustion behavior of Karamay crude oil. *J Pet Sci Eng*. 2015;127:82–92.
7. Rahnema H, Barrufet M, Mamora DD. Combustion assisted gravity drainage–Experimental and simulation results of a promising in-situ combustion technology to recover extra-heavy oil. *J Pet Sci Eng*. 2017;154:513–520.
8. Zhong F. A Review on In-situ Combustion. *Spec Oil Gas Reserv*. 2011;(6):1–5.
9. Green DW, Willhite P. *Enhanced Oil Recovery*. 1998.
10. Thomas S. Enhanced oil recovery-an overview. *Oil Gas Sci Technol-Rev IFP*. 2008;63(1):9–19.
11. Bagci S, Kok MV. In-situ combustion laboratory studies of Turkish heavy oil reservoirs. *Fuel Process Technol*. 2001;74(2):65–79.
12. Cinar M, Castanier LM, Kovscek AR. Combustion kinetics of heavy oils in porous media. *Energy Fuels*. 2011;25(10):4438–4451.
13. Ambalae A, Mahinpey N, Freitag N. Thermogravimetric studies on pyrolysis and combustion behavior of a heavy oil and its asphaltenes. *Energy Fuels*. 2006;20(2):560–565.
14. Parker HW. In situ combustion method. May 1962.
15. Schmitt DR. Seismic attributes for monitoring of a shallow heated heavy oil reservoir: A case study. *Geophysics*. 1999;64(2):368–377.
16. Vedanti N, Sen MK. Seismic inversion tracks in situ combustion: A case study from Balol oil field, India. *Geophysics*. 2009;74(4):B103–B112.
17. Moore RG, Laureshen CJ, Belgrave JD, Ursenbach MG, Mehta SR. In situ combustion in Canadian heavy oil reservoirs. *Fuel*. 1995;74(8):1169–1175.
18. Coates R, Lorimer S, Ivory J. Experimental and numerical simulations of a novel top down in-situ combustion process. In: *SPE International Heavy Oil Symposium*. Society of Petroleum Engineers; 1995.
19. Greaves M. Upgrading athabasca tar sand using toe-to-heel air injection. In: *SPE/CIM International Conference on Horizontal Well Technology*. Society of Petroleum Engineers; 2000.

Citation: Yao J, Li G, Wu J. Application of In-situ combustion for heavy oil production in China: A Review. *J Oil Gas Petrochem Sci*. (2018);1(3): 69–72. DOI: 10.30881/jogps.00014

20. Greaves M, Xia TX, Ayasse C. Underground upgrading of heavy oil using THAI-'toe-to-heel air injection'. In: *SPE International Thermal Operations and Heavy Oil Symposium*. Society of Petroleum Engineers; 2005.

21. Xia TX, Greaves M. Upgrading Athabasca tar sand using toe-to-heel air injection. *J Can Pet Technol*. 2002;41(08).

22. Rabiu Ado M, Greaves M, Rigby SP. Dynamic simulation of the toe-to-heel air injection heavy oil recovery process. *Energy Fuels*. 2017;31(02):1276–1284.

23. Ado MR, Greaves M, Rigby SP. Effect of pre-ignition heating cycle method, air injection flux, and reservoir viscosity on the THAI heavy oil recovery process. *J Pet Sci Eng*. 2018;166:94–103.

24. Kisman KE, Lau EC. A new combustion process utilizing horizontal wells and gravity drainage. *J Can Pet Technol*. 1994;33(03).

25. Lau EC, Kisman KE. Attractive control features of the Combustion Override Split-Production Horizontal Well process in a heavy oil reservoir. In: *Annual Technical Meeting*. Petroleum Society of Canada. 1994.

26. Shen C. Limitations and potentials of in-situ combustion processes for heavy oil reservoirs. In: *Canadian International Petroleum Conference*. Petroleum Society of Canada. 2002.

27. Bagci S, Aybak T. A Laboratory Study of Combustion Override Split-Production Horizontal Well (COSH) Process. In: *Annual Technical Meeting*. Petroleum Society of Canada. 1998.

28. Liu S, Bao L, MA D. New Technology Study for the Development of a Super-Heavy Oil Reservoir in Liaohe Oil Field. *Pet Explor Dev*. 1999;26:80–81.

29. Rahnema H, Mamora DD. Combustion Assisted Gravity Drainage (CAGD) Appears Promising. In: Society of Petroleum Engineers. 2010.

30. Liang J, Guan W, Jiang Y, Xi C, Wang B, Li X. Propagation and control of fire front in the combustion assisted gravity drainage using horizontal wells. *Pet Explor Dev*. 2012;39(6):764–772.

31. Heidary S, Dehghan AA, Mahdavi S. Feasibility study on application of the recent enhanced heavy oil recovery methods (VAPEX, SAGD, CAGD and THAI) in an Iranian heavy oil reservoir. *Pet Sci Technol*. 2017;35(21):2059–2065.

Citation: Yao J, Li G, Wu J. Application of In-situ combustion for heavy oil production in China: A Review. *J Oil Gas Petrochem Sci*. (2018);1(3): 69–72. DOI: 10.30881/jogps.00014