1. Introduction

In-situ combustion is a process in which, by injecting air (enriched air), small fraction (usually 10-15%) of heavy components of oil combust and combustion front propagates through the reservoir and the rest of oil get warm and upgrade to be produced easily. Because of complexity of in-situ combustion (ISC) processes, their design must be preceded by extensive laboratory investigations to ascertain the burning characteristics of the crude, fuel availability and air requirements. Numerous laboratory and fields observations show upgrading of 2 to 6° API for heavy oils \(^1\). ISC is generally classified as a technique that is applicable for heavy oils because of the dramatic reduction in oil viscosity with temperature. \(^2\) It also promotes production through flue-gas drive, thermal expansion and vaporization of lighter fractions of heavy oil. \(^2\) This thermal recovery method is not only applicable for recovery of heavy oils but that of light oils as well. \(^1\) So it provides a steam drive and intense gas drive for the recovery of oil. \(^4\) In order to successfully exploit the vast potential of processes based on air injection for the recovery of conventional and heavy oils, it is necessary to ensure the combustion zone sustainably propagates in the reservoir. \(^5\) For heavy oils and bitumen it is vital to constantly maintain the combustion front at high reaction temperature (\(>653\) K) in order to mobilize and produce these hydrocarbons under condition of dry in-situ combustion. \(^5\) It has been found further that the heavy residue (coke), which gets occurred in the reservoir core during the cracking of crude oil, provides itself as the main fuel source for combustion and thereby sustains the combustion front. \(^6\) Generally, the higher the combustion temperature, the lower is the amount of unburned fuel remained. The presence of this organic residue is not necessarily obvious from visual examination. The color of burned zone is typically off-white, with light hues in grays, browns, yellows and reds. This is the zone that has been subjected to the highest temperatures for the longest period and exhibits mineral

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According to difficulties of producing heavy oil reservoirs, in-situ combustion (ISC) as one of the high efficient methods leads to reduce oil viscosity by increasing temperature. Since there are remarkable amounts of heavy oil reservoirs in the world and lots of experimental works have been carried out on sandstones, shale or oil sands, the research on carbonate rocks seems to be rare. The experimental tests were performed with the oil of 17.5° API and 8° API mixed with the crushed carbonate rocks of Asmari and Sarvak formations respectively to investigate the feasibility of ISC and calculate its parameters. According to experiments, combustion tube conducted vertically to use gravity as a force to minimize gravity segregation effects. Results show that combustion is technically applicable to both rock-fluid systems. Additionally the percentages of CO\(_2\), O\(_2\) and CO have been measured by gas analyzer. Moreover, the effect of grain size on combustion temperature, connate water on oil recovery and front characteristics are investigated. Finally, fractured model of combustion tube is simulated and the effects of air injection rate, permeability, initial oil saturation and grid size are investigated. The obtained basic parameters of experiments are suitable for ISC implementation to fields efficiently.

Keywords

In-situ combustion, Combustion front, Fractured porous media, Carbonate reservoir, Enhanced oil recovery

1. Introduction

In-situ combustion is a process in which by injecting air (enriched air), small fraction (usually 10-15%) of heavy components of oil combust and combustion front propagates through the reservoir and the rest of oil get warm and upgrade to be produced easily. Because of complexity of in-situ combustion (ISC) processes, their design must be preceded by extensive laboratory investigations to ascertain the burning characteristics of the crude, fuel availability and air requirements. Numerous laboratory and fields observations show upgrading of 2 to 6° API for heavy oils. \(^1\) ISC is generally classified as a technique that is applicable for heavy oils because of the dramatic reduction in oil viscosity with temperature. \(^2\) It also promotes production through flue-gas drive, thermal expansion and vaporization of lighter fractions of heavy oil. \(^3\) This thermal recovery method is not only applicable for recovery of heavy oils but that of light oils as well. In the case of light oils, the production is stimulated (eventual) vaporization of lighter fractions, which then move downstream and mix with the original crude. \(^2\) So it provides a steam drive and intense gas drive for the recovery of oil. \(^4\) In order to successfully exploit the vast potential of processes based on air injection for the recovery of conventional and heavy oils, it is necessary to ensure the combustion zone sustainably propagates in the reservoir. For heavy oils and bitumen it is vital to constantly maintain the combustion front at high reaction temperature (\(>653\) K) in order to mobilize and produce these hydrocarbons under condition of dry in-situ combustion. \(^5\) It has been found further that the heavy residue (coke), which gets occurred in the reservoir core during the cracking of crude oil, provides itself as the main fuel source for combustion and thereby sustains the combustion front. \(^6\) Generally, the higher the combustion temperature, the lower is the amount of unburned fuel remained. The presence of this organic residue is not necessarily obvious from visual examination. The color of burned zone is typically off-white, with light hues in grays, browns, yellows and reds. This is the zone that has been subjected to the highest temperatures for the longest period and exhibits mineral
alteration upon detailed analysis \(^7\). Running *in-situ* combustion process in carbonate reservoirs might be risky due to the probability of decomposition of the rock and production of carbon dioxide at high temperature \(^8\). So majority of laboratory and field researches are done on sandstone formations and research on carbonate formations seems to be less. It is necessary to mention that this study is unique due to use carbonate formations in both experiments.

Water is sometimes injected simultaneously or alternately with air, creating steam, which contributes to better heat utilization and reduced air requirements and also it can lessen the detrimental overriding of combustion gases \(^4\). The use of wet combustion began at the moment in which it was recognized that much of the heat stored in the rock during the dry, forward combustion behind the combustion front was being lost to the adjacent formations \(^3\).

Several dry and wet combustion tests were carried out on different API gravities of oils. Results show that front temperature does not depend on Water Air Ratio (WAR), while front velocity is appreciably dependant on WAR \(^9\). According to the process, schematics of forward *in-situ* combustion is illustrated in Fig. 1; which shows that crude oil gets ignited at the wellbore and the combustion front, which is otherwise slow moving in nature, gets propagated by the continuous injection of air. The injected air reacts with residual hydrocarbons, thus causing thermal cracking and vaporization of the hydrocarbon at high temperature and generates carbon oxides and water. Additionally it can be observed that the steam, which is formed by vaporization of water during combustion, condenses with drop in temperature to form a hot water bank. The formation of this hot water bank is one of the factors that contributes towards an increased mobility of oil, resulted by extra thrust induced on the upstream of the water bank \(^10\). Even for those areas of reservoir which are not in direct contact with the hot water bank, a rise in temperature could be observed because of thermal conduction-leading to increase in the mobility of heavy oil and thereby enhancing recovery \(^11\). The effect of fractures could be sometimes very dramatic. Since fractures may lead to oxygen breakthrough and failure of the process \(^9,12\). Thus, ISC in fracture reservoirs is strongly rate dependant.

Several experiments of ISC in porous medium showed that the burning process is governed by diffusion of oxygen from the fracture in to the matrix. The main oil production mechanisms were found to be thermal expansion and evaporation with subsequent condensation of the oil from the matrix \(^13\). Toe to Heel Air Injection (THAI) is a process in which integrates ISC and advanced horizontal well concept \(^14\). It uses a horizontal producer well instead of vertical producer well. The combustion front propagates along the horizontal well, from the toe to the heel position. It is able to achieve very high recoveries from heavy oil and tar sand bitumen reservoirs \(^15,16\). Due to the efficient sweep of the reservoirs by the combustion and hot gas fronts. One of the most important benefit of THAI application for heavy oil and tar sand bitumen reser-

![Fig. 1 Schematic of Combustion Setup](image-url)
voirs is that it produces and preserves upgraded oil\(^{17}\). In this study, combustion tube conducted vertically (top-down ISC) to use gravity as a force in which used in THAI, so as to minimize gravity segregation effects. The conceptual strategy of the top-down ISC process involves the stable propagation of a high temperature combustion front from the top to the bottom of a heavy oil or oil sand reservoir\(^{18}\). Since, in this study the tube is operated vertically, it is documented that in vertically operated tubes at high pressures, distortion of the test results may arise due to thermal convection of gas in the annular region between the tube and the pressure jacket\(^{19},20\). It should be mentioned, although applying top-down combustion tube and running ISC for carbonate formations are used separately in others researches so far, this study is unique and novel due to apply top-down and use carbonate formations simultaneously for the first time.

An experimental work was carried out with light crude oil and it was found that as the oxygen concentration increased, the CO\(_2\) content and combustion front velocity increased\(^{21}\). Several combustion tube experiments were conducted with different enrichment of air. The injected air of 94.33 % mole O\(_2\) and 21 % mole O\(_2\), obtained combustion front temperature of 788 K and 755 K, respectively\(^{22}\). Usually, long term investigations and studies are conducted before choosing a reservoir for this process. One of the most important parts of these studies is the feasibility study. Feasibility studies are carried out in order to understand whether the process is possible on the rock and oil of the field. Combustion tube test and other thermometric tests like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are usually used to test the feasibility of the process\(^{21},23,24\).

1.1. Experimental Setup

**In-situ** combustion apparatus consists of combustion tube, band heaters, separator, mass flow controller, back pressure regulators, igniter, gas analyzer, thermowell, data acquisition, helium and air gases. Ten thermocouples are designed in every five centimeter inside the thermowell which is passed through the center of tube to record the temperature of front and its location throughout the tube. Since combustion temperature depends on pressure and propensity of crushed rock-oil mixture, an igniter is placed at the top of the tube which its temperature increase gradually to initiate combustion. Several band heaters are conducted on the tube’s body to establish temperature of reservoir in advance. According to the literature, initiating combustion depends on following factors:
(a) Heat; which is supported by igniter.
(b) Fuel; which is packed in the tube as heavy components of oil.
(c) Oxygen (enriched air); which is continuously injected with an efficient rate of injection during the test.

![Fig. 2 Top-down ISC Apparatus](image)

The top-down combustion apparatus is presented in Fig. 2.

1.2. Experimental Process

The carbonate rocks of both of the formations which were collected from their outcrops, crushed in three steps in different mesh sizes in the laboratory and washed up to remove impurities. According to the literature, there is an equation to specify the amount of crude oil and crushed rock for mixing. Crude oil-sand weight ratio can be estimated by Eq. (1).

\[
\frac{m_o}{m_s} = \frac{\rho_o \phi S_o}{\rho_s (1 - \phi)}
\]

Mixtures were packed in the tube in which a thermowell passed through the center. Crush carbonate rock with large mesh sizes packed at the end of the tube in order not to plug the production well. At the top of the tube, near the igniter, a little amount of linseed oil was added to mixture of 1st run sample in two different distances to decrease combustion temperature. At the beginning of the test, pure helium injected to the tube to maintain reservoir pressure during heating period and make path (permeability) through the mixture. Band heaters started heating to establish the reservoir temperature which was 333 K for both of reservoir samples. As the temperature stabilized at the desired value, igniter was set at the 623 K and injecting helium switched to enriched air (60 % O\(_2\)-40 % N\(_2\) and 50 % O\(_2\)-50 % N\(_2\) for 1st and 2nd run, respectively) simultaneously to combust and upgrade oil due to propagate combustion front downwards. Combustion in both samples initiated at the range of 573-673 K. At last, process was shut
by injecting helium to the tube. The properties of the runs are indicated in Table 1. Meanwhile, both of runs have been reproduced and rechecked twice and it is found that the error range is less than 2%.

1.3. Simulation Model—base case

Simulation model was built by using CMG-STARS. In this section combustion tube is simulated as a top-down cylindrical fractured model. The model consists of 15 grid blocks in $r$ direction, 10 grid blocks in $\theta$ direction and 20 grid blocks in $z$ direction. Figure 3 shows simulated model in different axis which black part shows the fracture that is drawn along $z$ direction. The gas injection rate is 4 L/min and the other parameters and rock properties are given in Table 2. In this model six components and pseudo components such as water, heavy oil, light oil, oxygen, inert gas and coke are considered. All non-condensable gases such as CO$_2$, CO, N$_2$, etc. were lumped to a single inert gas. Crude oil is divided into the light and heavy pseudo components with 156.7 and 675 molecular weights and 0.25 and 0.75 initial mole fraction, respectively.

Molecular diffusion of oxygen from fracture to matrix is one of the main controlling process variables for the air injection in fractured reservoir. In this study a value of 1.1E-05 is considered for oxygen molecular diffusion.

After preheating the top of the model, air is injected from the injector at the top. Because of higher permeability of fracture, air mostly goes through the fracture. Ignition occurs immediately in fractures and front goes toward the production well while generated heat conducted to the matrix blocks and ignition also occurred in matrix blocks but in lower quantity because of lower amount of oxygen available.

2. Result and Discussion

2.1. Carbon Dioxide in Effluent Gas

Figure 4 demonstrates a comparison in amount of CO$_2$ in the effluent gas for both of samples. The percentage of CO$_2$ at the beginning of the test is about zero due to primary reactions before initiating combustion like low temperature oxidation (LTO) and suddenly a drastic increase is observed due to complete high temperature combustion reactions (HTC).

| Table 1 | Sand Packs Properties of 1st and 2nd Runs |
|---------|------------------------------------------|
| No. of run | 1st run | 2nd run |
| Type of rock | Sarvak (carbonate) | Asmari (carbonate) |
| Oil API degree | 8 | 17.76 |
| Sand density [kg/m$^3$] | 2800 | 2500 |
| Initial temperature [K] | 333.15 | 333.15 |
| Air injection rate [m$^3$/s] | 5E-5 | 5.1667E-5 |
| Injecting pressure [Pa] | 31.71588E + 5 | 31.71588E + 5 |
| Type of injected gas | 60 % O$_2$, 40 % N$_2$ | 50 % O$_2$, 50 % N$_2$ |
| Oil/sand weight ratio | 0.18 | 0.2 |
| Sand weight [kg] | 6 | 6 |
| Oil weight [kg] | 1.080 | 1.200 |
| Oil specific gravity [60 $^\circ$F/60 $^\circ$F] | 0.975 | 0.948 |
| Oil saturation [%] | 80 | 100 |
| Water saturation [%] | 20 | 0 |
| Porosity [%] | 40 | 35 |
| Permeability [md] | 12500 | 10000 |

| Table 2 | Initial Condition and Carbonated Rock Properties Used in Simulation |
|---------|---------------------------------------------------------------|
| Temperature [°C] | 60 |
| Pressure [Pa] | 3171.5 |
| Air injection rate [L/min] | 6.7E-5 |
| Oil saturation [%] | 80 |
| Water saturation [%] | 20 |
| Porosity [%] | 35 |
| Matrix permeability [md] | 1000 |
| Rock thermal conductivity [J/(m s K)] | 4.33 |
| Rock compressibility [Pa$^{-1}$] | 1.45E-10 |
| Rock thermal expansion coefficient [K$^{-1}$] | 7.2E-5 |
| Rock heat capacity [kJ/(kg K)] | 148.2 |
2.2 Carbon Monoxide in Effluent Gas

Figure 5 shows a comparison in amount of CO in the effluent gas for both of samples. Since CO evaluation is one of the signs of combustion quality, the average percentage of CO in 2nd run is more than 1st run, which means combustion quality for 1st run is better than 2nd.

2.3 Cumulative Recovery of Combustion Tube Test

Figures 6 and 7 demonstrate the cumulative oil recovery of combustion. It should be noticed that the recovery in laboratory condition is more than reservoir due to reservoir heterogeneity. Recoveries of 1st and 2nd runs are 71.4 % and 52.16 %, respectively.

2.4 Effect of Grain Size

The effect of grain size has been investigated and demonstrated in Fig. 8. In the first part of combustion tube where smaller grains have been applied, higher combustion temperatures were observed.

2.5 Front Characteristics

2.5.1 Front Temperature vs. Tube Length

Figure 9 demonstrates front temperature versus location. As mentioned before, the tube is 0.5 m long and has 10 thermocouples in every 0.05 m.

2.5.2 Front Velocity vs. Time

Average front velocities for 1st and 2nd run are 3.31E-5 (m/s) and 4.58E-5 (m/s), respectively. Figure 10 shows a comparison in front velocity versus time for both of runs.

2.6 Parameter Calculation

Based on obtained data, combustion parameters have been calculated and presented in Table 3.

2.7 Simulation

2.7.1 Effect of Air Injection Rate

One of the important parameters of ISC process is air injection rate. Efficient amount of rate should be determined in order to exist sufficient amount of oxygen to sustain combustion front during process. Two additional runs with 20 ft³/h and 11 ft³/h have been
compared with the 8.4 ft³/h of base case model to investigate the effect of rate. It is obvious that, as the air injection rate increases, average temperature of process increases and it causes higher cumulative oil recovery as shown in Figs. 11 and 12.

2.7.2 Effect of Permeability

To investigate the effect of permeability, base case model with 1000 md of permeability have been compared with two additional models with 50 md and 500 md and the other parameters are the same. Oil in high permeable formations will be mobilized and drained to the production well as soon as the temperature increases due to ISC process. However, in tight reservoirs upgraded oil will not be mobilized due to low permeability. So, not only heavy components of oil burns during process but also some parts of intermediate components burns and that is why in tight reservoirs, average temperature is higher and cumulative oil recovery decreases as shown in Figs. 13 and 14.

2.7.3 Effect of Initial Oil Saturation

As initial oil saturation increases, average combustion temperature and cumulative oil recovery increases as demonstrated in Figs. 15 and 16. Since oil viscosity depends on temperature intensively, it decreases dramatically during combustion. Thus in the case of higher oil saturation, large amount of heavy oil can be mobilized and cumulative oil recovery increases.

2.7.4 Effect of Grid Block Size

Grid block size has a great effect on combustion simulation. Figure 17 shows average combustion temperature for the base case model with 3000 grid blocks compared with two additional models with 280 grid and 8000 grid blocks. As grid block size increases, amount of sediment coke on the grid surface for combusting increases. Thus, in the case of larger grid block size, average combustion temperature increases and combustion front propagation become slower.

Table 3 Calculated Parameters of 1st and 2nd Runs

| No. of run | 1st run | 2nd run |
|------------|---------|---------|
| H/C ratio  | 0.4274  | 0.6054  |
| O₂/fuel ratio | 1.92359 | 2.05513 |
| Air/fuel ratio | 3.19319 | 3.43416 |
| Injected O₂ to Cox’s [%] | 83.8 | 68.5 |
| Reacted O₂ utilization [%] | 87.46 | 83.23 |
| O₂ utilization [%] | 95.8 | 82.3 |
| Excess air [%] | 4.38 | 21.506 |
| (CO₂ + CO)/CO ratio | 3.3722 | 2.0114 |
| (CO₂ + CO)/N₂ ratio | 1.4905 | 1.3606 |
| Oil recovery [%] | 71.7 | 52.16 |
| Oil recovered [kg] | 0.774 | 0.626 |
| Total air injected [m³] | 1.022 | 1.1548 |
| Average front velocity [m/s] | 3.3167E-5 | 4.5833E-5 |
2.7.5. Matching Simulation Results with Experimental Results

Simulated fractured model is converted to the conventional model by removing fracture zone in simulation software in order to match simulation results with experimental results. Average temperature, CO$_2$ concentration and cumulative oil recovery had been chosen for matching with experimental data. The average temperature of system during combustion process for matching experimental and simulation results is presented in Fig. 18. The error range between experimental and simulation results is 10.322. Matching curves of carbon dioxide concentration for both simulation and experimental results have been compared and demonstrated in Fig. 19 which its error range is 7.852 %. Figure 20 shows matching curve of cumulative oil recovery for both simulation and experimental results indicating good predicting of experimental data with the error range of 11.21 %.

3. Conclusion

(1) In-situ combustion process is feasible for both
Sarvak and Asmari formations at laboratory conditions. Although combustion in Sarvak sample initiated later, the recovery factor was higher than Asmari sample. (2) Smaller grain size causes higher combustion temperature. This phenomenon is due to more specific area available for coke deposition and more complete combustion. (3) Since it was observed previously by TGA test that both of Carbonite rocks used in this experiment generally decompose at the temperature above 873 K \(^{25}\), there is no risk of decomposition for the both of carbonate formations due to high temperatures of the process. (4) Although oil saturation in 1st and 2nd run was 80 % and 100 % respectively and no water was added to 2nd run, the recovery factor of 1st run was much more than the 2nd. This shows the effect of connate water due to vaporization with subsequent condensation of water. (5) Injecting rate was a dominate parameter in the tests. When the rate was changed to lower values, all the output data, such as carbon oxides percentages and temperatures were affected. (6) Increasing oxygen partial pressure results in more fire flood temperatures, more rapid HTC reactions, more complete reactions, more possibility of ignition and faster ignition. (7) Simulation shows that as air injection rate, permeability and initial oil saturation increases, cumulative oil recovery increases.

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Nomenclatures

| Symbol | Description | Unit |
|--------|-------------|------|
| \( m_s \) | mass of sand | [kg] |
| \( s_o \) | oil saturation | [-] |
| \( \rho_o \) | oil density | [kg/m\(^3\)] |
| \( \rho_s \) | sand density | [kg/m\(^3\)] |
| \( \phi \) | porosity | [-] |

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