P201 A NEW HORIZONTAL WELL CONCEPT FOR IOR FROM LIGHT OIL RESERVOIRS USING AIR INJECTION

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ABSTRACT

There is growing interest in the application of air injection in deep light oil reservoirs, especially in remote locations and offshore. Air represents a cheap source of injection gas, and with low temperature oxidation (LTO) the oxygen is generating an *in situ* source of N_2 or 'flue gas' to carry out immiscible or miscible displacement processes. If the oil and reservoir matrix are sufficiently reactive, high temperature oxidation (HTO) can be implemented to sustain fully-propagating *in situ* combustion, with excellent improved oil recovery (IOR).

One problem observed with light oil reservoirs is the tendency to desaturate the oil layer downstream of the moving front, particularly for a thermal IOR process because of the additional vaporisation which occurs. A low pressure test was carried out in a 3-D cell equipped with an extensive thermocouple array. In order to restrict desaturation of the oil layer, a modified horizontal producer well, incorporating a 'sleeve-back' principle, was used. The idea was to mimic the process occurring during heavy oil recovery wherein the downstream oil is essentially immobile, due to its high viscosity. The 'sleeve-back' of the well was achieved using a co-aligned, two-well assembly, so that the upstream section of the horizontal producer well is active, and adjusted during propagation of the combustion front.

Sufficient improvement in overall stability of the process was observed using the 'sleeve-back' modification, as witnessed by sustained propagation of the combustion front and high levels of CO_2 in the produced gas.

INTRODUCTION

The introduction of horizontal wells has been responsible for tremendous advances in oil field development. Horizontal and multi-lateral wells are being introduced in ever-increasing numbers to achieve further gains in reservoir productivity. Two hundred horizontal wells were drilled a decade ago. Now, one company has reported drilling more than 2,100 horizontal wells in North America^[1]. Advances have also been achieved in the depths drilled, reaching 8,761m^[2], and also the length, reaching up to 8km. Multi-lateral wells, with four or more side-tracks, are not uncommon now and offer further optimisation gains. Moreover, this technology will accommodate reservoir faults and problems of structural geology as regular design factors so that strategic placement of the well path is achieved. More recently, a new technique to control gas and water production rates by varying the fluid entry points along the well length has been successfully tested^[3].

The most important advantage of horizontal wells is the increase in reservoir contact area, which is limited to the reservoir thickness for a vertical well. This property has also created new possibilities for the implementation of advanced EOR methods, especially in thermal recovery. A horizontal well can increase both injectivity and productivity.

In situ combustion (ISC) has been studied and piloted extensively for several decades and has been widely considered for production of viscous and heavy oils. Although many successful field projects have been reported, overall field experience has shown a number of problems, such as slow production response, severe sanding, gas locking of down hole pumps, corrosion, and scaling. For light oil reservoirs, despite a small number of successful field projects, the apparent lack of fuel to sustain the process is viewed as a major difficulty. A main concern with light oils is whether the residual oil saturation available to the combustion front and the oxidation kinetics behaviour is sufficient in terms of fuel to make the process self-sustaining.

Generally speaking, the low rate of coke deposition observed for light oils can be attributed to two main causes. Firstly, insufficient heavy fractions are available in the oil to be deposited as fuel, and secondly, the more volatile components are vaporised ahead of the front, further displacing more oil downstream.

In this study, the effect of oil desaturation downstream of the combustion front, due to vaporisation and gas stripping, was subjected to a 'practical test', in order to evaluate the effect on the displacement mechanisms. The basic idea was to 'mimic' the process occurring during heavy oil recovery, wherein the downstream oil is essentially immobile at reservoir temperature, due to its high viscosity. It is considered that the effect of the hot gases produced by combustion will be very limited, due to the poor gas permeability when the chosen well placement does not create connectivity in the oil zone.

To achieve this, the horizontal well was separated into two sections. The upstream section was initially open, and the downstream closed. When the combustion front reached the mid point of the sandpack, the reverse procedure was adopted. To achieve this condition, the horizontal well was placed in line drive, so as to provide the main communication path/fracture in the reservoir. In this way, connective gas displacement should be restricted to the active mobile zone immediately ahead of the combustion front, so long as it behaves like its heavy oil reservoir counterpart.

EXPERIMENTAL

The rectangular stainless steel combustion cell measuring 0.4m square by 0.1m deep, which was used to carry out the *in situ* combustion experiments, is shown in Figure 1. The cell was fitted with an array of 61 thermocouples arranged on three levels: TOP, MIDDLE and BOTTOM. These were placed respectively 0.02, 0.05 and 0.08m from the top surface of the cell. One thermocouple was inserted inside the production tubing to closely monitor the combustion front and also for the purpose of adjusting the production tubing length.

The 3-D cell system, shown in Figure 2, includes injection lines and mass flowmeters D11 and D12, to supply nitrogen and oxygen to the combustion cell. At the outlet of the production side of the cell, the produced fluids are passed through the 1st stage separator (V2) and then a 2nd stage separator (V3) before the gases are sent to the gas analysers and wet test meter (D3), via a three-way valve. A sample side stream is also taken via 3WV for GC analysis.

Temperature regulation of the combustion cell surface cell is achieved by means of three tape heaters, wound around the cell, to compensate for heat losses and to maintain the cell temperature at approximately adiabatic condition. This was controlled manually on demand, in response to the observed combustion peak temperature and adjacent wall temperature. All measurement and control was achieved by National Instruments 'Labview' software, run under Windows 95 on a Pentium PC 90MHz platform. Further details of the equipment and procedures are given by Mahgoub^[4].

In order to physically simulate or 'mimic' the process behaviour in a heavy oil reservoir (see, for example, Tuwil^[5]), the line drive configuration was chosen because of its unique flexibility in controlling the fluid entry points along the horizontal producer well, as it is traversed by the combustion front. This was achieved by using the co-aligned, two-well assembly shown in Figure 3. This arrangement enables: (1)

prevention of the hot gases from displacing into the downstream sections of the sandpack, and (2) the division of the sandpack into two segments which are perpendicular to the well so that the flow in each section can be treated independently.

The upstream section of the well (specifications are given in Table 1) has an adjustable internal production tube of OD 6.4mm, which is inserted inside a perforated casing having an ID of 6.4mm (*i.e.* essentially no clearance between the tubing and exterior casing). It was connected to the production header assembly via a flexible stainless steel hose, which incorporated a shut-off valve. The downstream section of the well has an ID of 10mm and is connected to the production header via a ball valve. Both sections were constructed from stainless steel tubing and perforated on the drainage side with a series of 1.5mm diameter holes placed 180°opposed on a 4mm pitch. Both upstream and downstream sections were covered with a 200 gauge mesh to prevent sand entering the wells.

The adjustment of tubing opening perforations along the upstream production section, during the experiment, was accomplished using a screw-bracket assembly mounted on the side of the cell (Figure 3). This was achieved with reference to the temperature measured by a thermocouple located at the far end of the open part of the upstream section. The specifications are given in Table 1. The upstream section of the horizontal well was continually adjusted as the combustion front propagated through the first half of the sandpack, while the downstream section was shut in. When the combustion front reached the toe of the downstream well section, it was opened and the upstream section closed. Along the length of the upstream section, at any segment of the bed, hot fluids were drained through the open perforations into the inner tubing, while the downstream perforations were closed. This mode of operation prevented the hot fluids displacing into the downstream sections of the sand matrix. Therefore, the oil saturation at any point downstream of the mobile oil zone ahead of the combustion front should, ideally, remain unaffected. However, oil in the downstream zones will be heated continually by conduction of heat from the combustion front (through the sand matrix) and through the production tubing and casing.

The production tubing of the upstream section of the horizontal producer well passed through the production casing of the downstream well section. This configuration allows heat transfer from the hot produced fluids flowing through the annular space. Therefore, oil in the downstream zones was heated continuously from the start of the experiment. However, the oil saturation in this downstream zone remains unchanged until the well is opened.

The properties of the oil and sandpack material used for the experiments are given in Table 2. The conditions for the experiments are given in Table 3.

RESULTS AND DISCUSSION

Produced Gas Composition (upstream well section)

From the flue gas composition in Figure 4, ignition was achieved at 330°C. This was followed by a steep increase in temperature to 440°C. During the same period, there was a rapid fall-off in oxygen concentration, mirrored by a rise in CO₂ and CO levels. The levels of CO₂, CO and O₂ during the ignition phase were 11.3%, 4.3% and 0.75%, respectively. Low oxygen levels during the ignition phase indicate very high oxygen utilisation (96%), *i.e.* most of the oxygen is consumed by combustion reactions. Soon after the ignitor was turned off, the CO₂ and CO levels fell sharply, stabilising at steady values of 8.4% and 3.0%, respectively. However, the O₂ levels increased rapidly to 5%, reducing the oxygen utilisation to 76%. As the experiment proceeded, the produced gas composition became more stable during combustion in the upstream well section of the sandpack and the effect of tubing adjustment disappeared 3.5 hours from ignition. At 431 minutes combustion time, the combustion front reached the end of the upstream production well section.

Produced Gas Composition (downstream well section)

The combustion front temperature was 375°C (Figure 4) and the average bed temperature in the downstream oil zone was 219°C. The upstream well section was then shut-in and the downstream well section opened. Immediately, the CO₂ level increased to 10.35%, and the CO and O₂ values dropped to 1.3% and 3.6%, respectively. Soon after, the CO₂ value started to gradually decrease and within 37 minutes stabilised at 9.3%. Similarly, the CO and O₂ levels also gradually increased and stabilised at 3.6% and 4.7%, respectively. The CO₂ and CO values in this second phase were 11% and 20% higher than in the first stage (upstream), while O₂ values were correspondingly 5% lower.

Temperature Profiles

The measured temperature profiles in the sandpack, at the TOP, MIDDLE and BOTTOM planes, respectively located 2, 5 and 8cm from the top surface of the cell, are shown in Figure 6. The leading edge of the highest temperature zone provides a good indication of the combustion front position. The stability of the combustion front is clearly indicated by the vertical section temperature profile at the central position of the cell (in line with the horizontal producer well). There is no evidence of any gas override effect during the period of the experiment.

Combustion Behaviour

The main results from the *in situ* combustion experiment are summarised in Table 4. The apparent atomic H/C ratio of the fuel consumed during the first stage of combustion (upstream well section) was 2.32, whereas during the second stage (downstream well section) it was 1.9. (Note that the H/C for the original crude oil is approximately 2.0.) Therefore the fuel burnt in the downstream section (second half of the sandpack) is of heavier composition. Significantly, the higher H/C value indicates that significant low temperature is most likely to have occurred. This was substantiated by a post mortem analysis of the sandpack taken after the experiment, which showed appreciable residual 'coke' downstream of the ignitor region and a much more substantial 'coke' loading near the heel of the upstream well section. Table 4 (see also Figure 5) also shows that the oxygen utilisation is relatively low in both cases, at around 75%. It is quite clear, therefore, that substantial oxygen bypassed the combustion front into the downstream regions of the sandpack, giving rise to low temperature oxidation of the unproduced crude oil. Either the oxygen flux for the experiment was too low to efficiently burn this 'coke', or the pre-oxidised coke was more difficult to burn under these conditions. It is interesting that, for this reasonably light crude oil, the amount of fuel consumed is not unduly low, at around 5% of OOIP, and that the potential fuel availability could, therefore, possibly be increased, so long as the injected air flux can be optimised to burn it.

The most significant result of the experiment concerns the oil recovery in the downstream zone. Here the recovery is highest at 57.1%, but it is much lower, at 36.4%, in the upstream section. This is not entirely the expected result, since using the 'sleeve-back' principle for the upstream well section to limit the extent of downstream oil desaturation ('mimicking' heavy oil behaviour) to maximise fuel availability and improve combustion front stability, one would have expected better performance in the upstream zone. However, it should be noted that the total oil recovery from the upstream and downstream sections is 93.5% OOIP. This is a very high value, and serves to demonstrate that the 'sleeve-back' well principle has indeed controlled the desaturation effect in the downstream section of the sandpack.

CONCLUSIONS

- 1 The new horizontal producer well concept in line drive, incorporating a 'sleeve-back' design of the upstream section of the well, successfully reduced the level of desaturation occurring in the downstream oil layer. This was confirmed by the very high level of oil recovery achieved, equivalent to 93.5% OOIP.
 - 2 Self-sustained combustion was achieved with light 'Forties Mix' oil, but the combustion front temperature was not sufficiently high to burn the additional fuel produced by low temperature oxidation.
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- 3 The levels of CO₂ and CO in the produced gas were higher than those observed in conventional horizontal well line drive experiments. The produced oxygen level was also much lower.

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References

- 1 Koen, AD, 'Horizontal drilling retains steady share of US activity', Oil & Gas Journal, August 1992, 34-41
- 2 Blikar, H, Drevdal, KE and Aarestad, TV, 'Extended reach, horizontal and complex design wells: Challenges, achievements and cost-benefits', SPE Centennial Petroleum Engineering Symposium, Tulsa, OK, 29-31 August 1994, 505-517
- 3 McIntyre, F, Grenon, JP and See, D, 'Horizontal well gas shut-off - field results', Paper 96-63, 47th Annual Technical Meeting of the Petroleum Society, Calgary, Canada, 10-12 June 1996
- 4 Mahgoub, M, 'Improved recovery of light oil by air injection using horizontal wells', MPhil Thesis, University of Bath, 1995
- 5 Greaves, M, Tuwil, AH and Bagci AS, 'Horizontal producer wells in *in situ* combustion (ISC) processes', Journal of Canadian Petroleum Technology, 32(4), 1993, 58-67

TABLE 1-PRODUCTION WELL SPECIFICATIONS

Well Section	UPSTREAM	DOWNSTREAM
Total length (mm)	375	205
Perforated interval length (mm)	170	170
O.D (mm)	8.5	12.5
I.D (mm)	6.4	10
Perforation diameter (mm)	1.5	1.5
Phase angle (deg)	180°	180°
Distance from injector (mm)	40	210

TABLE 2- OIL AND SANDPACK PROPERTIES

Sand type	Silica
Sand wt%	90
Clay wt%	10
Porosity %	42.53
Permeability (md)	616
Soi %	60
Swi %	35
Sgi %	5
Crude type	Forties Mix
Density (kg/m ³)	872
API gravity	30.8
Viscosity @ 18° C (cp)	9.57

TABLE 3-TEST CONDITIONS

Injection gas	Air
Gas flux (Sm ³ /m ² .hr)	4.5
Injection rate (l/min)	3
Operating pressure (kPa)	270
Initial temperature (deg.C)	55
Combustion mode	Dry

TABLE 4-SUMMARY OF TEST RESULTS

Well Section	UPSTREAM	DOWNSTREAM
CO ₂ %	8.4	9.3
CO %	3	3.6
O ₂ %	5	4.7
CO/(CO+CO ₂)	0.26	0.21
H/C Ratio	2.32	1.9
Air to fuel requirement (Sm ³ /kg)	10.9	11.6
Fuel burnt (kg)	0.154	0.167
Fuel burnt (% of OOIP)	4.7	5.1
Oxygen utilisation %	75.6	77.5
Average front velocity (m/hr)	0.028	0.025
Stabilised temperature (deg.C)	375	375
Oil recovery (% of OOIP)	36.4	57.1
Water recovery (% of OWIP)	31.8	54
Operating period (hrs)	7.18	7.52

Figure 3-Horizontal well arrangement

Figure 1-3D combustion cell

Figure 2- Flow diagram of 3D insitu combustion system

Figure 4- Produced gas composition

Figure 5-Oxygen utilisation

Figure 6- Temperature profiles