Recovery of Residual Light Oil from Waterflooded Reservoirs Using Horizontal Wells - Insitu Combustion Process

Greaves M., Ben Rahil M.

University of Bath, U. K.

Copyright 1995, Steering Committee of the European IOR - Symposium.

This paper was presented at the 8th. European IOR - Symposium in Vienna, Austria, May 15 - 17, 1995

This paper was selected for presentation by the Steering Committee, following review of information contained in an abstract submitted by the author(s). The paper, as presented has not been reviewed by the Steering Committee.

ABSTRACT

Preliminary 3D tests have been performed to physically simulate light oil *in situ* combustion (ISC) under waterflooded conditions. The experiments were carried out in a rectangular combustion cell using light Forties crude oil. A VIHP: vertical injector-horizontal producer well arrangement was used in line drive and also pattern drive. Two levels of residual oil-water saturation were investigated, 60-35% and 50-45%, using air and oxygen injection under dry forward combustion.

Generally high combustion zone temperatures and reasonably high combustion front velocities were sustained using line drive. The horizontal producer well in line drive generally conferred a good level of stability on the combustion front propagation, with only a small tendency overall towards gas override. This effect appeared to be controlled to a certain extent by the draw-down action of the horizontal well, nearer to the production end of the cell. In pattern drive, the propagation and extent of the combustion front was much less vigorous. Maximum oil recovery using line drive (67% OOIP) coincided with the highest initial residual oil saturation ($S_{oi} = 60\%$), reducing to 51% at $S_{oi} = 50\%$. Oxygen injection gave the lowest oil recovery at 46% OOIP.

Although oxygen utilisation generally remained in a low range and produced oxygen levels were

commensurately fairly high, low temperature oxidation (LTO) reaction was apparently only significant during the pattern drive and oxygen (line drive) tests. Measured horizontal and vertical temperature profiles in the sandpack indicate there is a substantial steam-combustion drive mechanism occurring, under otherwise dry combustion conditions. The volumetric sweep efficiency of this zone appears to reach up to nearly 100 per cent for all cases.

INTRODUCTION

A recent review of improved oil recovery (IOR) strategy for the UKCS [1] identified gas injection and horizontal and extended reach well technology as having the highest IOR potential, estimated at 3800 MMBOE. Hot water, steam and *in situ* combustion processes were aligned with the recovery of so-called 'viscous' oil, or medium heavy crude oil of API gravity around 20 to 25. The incremental oil from all IOR techniques was estimated to be 6% (probable) and up to 11% (probable plus potential) at an oil price of \$18 per barrel. A further 46 % of the oil was categorised as unrecoverable. Experience over the last decade has shown that assumptions underlying such an analysis tend to be vulnerable to radical shifts in oil price factors and political exigency. There is, however, some opinion that the current surplus in oil supply is being eroded by increasing demand in the markets.

The key technological element in IOR strategy, over the medium to long term, will be AEORP's, or advanced EOR processes, with the potential to maximise investment by recovering a high fraction of the trapped residual oil. Air injection has been proposed as a process for the recovery of residual light oil from deep, high pressure reservoirs [2]. Energy generated by the *in situ* combustion reactions is translated into a series of successive-interacting sub-processes, involving convective gas, distillation, steam and hot water drives, plus miscible drive *via* CO₂ and condensation of light ends. Thermal transport is a primary process mechanism, especially *via* the steam produced *in situ*, at a partial pressure perhaps one-half the total reservoir pressure. The conductive heat transfer mechanism is absent in all other non-thermal recovery processes, yet at sufficiently high temperatures it can mobilise otherwise non-contactable oil. The IOR or EOR efficiency of air injection is, therefore, potentially very high.

Although there have been a significant number of combustion tube studies conducted on light oil [3-4], which have identified a number of the main characteristics of the process, none has investigated behaviour in a three-dimensional geometry. This paper presents some preliminary results of an air injection/*in situ* combustion process which utilises a horizontal production well to recover residual light oil.

EXPERIMENTAL

The three-dimensional (3D) combustion cell was a rectangular, thin-walled stainless steel box, designed for a maximum operating pressure of 500kPa. In practice, the operating pressure was limited to 270 kPa. The rectangular cell, which was constructed of 316 stainless steel, 4mm thick, was 0.4m square by 0.10m deep. A VIHP (vertical injector-horizontal producer) well configuration was used, arranged with the horizontal producer either in direct line drive (at right angles to the vertical injector), or in pattern drive (parallel to the production end of the cell, opposite to the vertical injector-inlet end). Both injection and production wells were constructed from 6.4mm O.D. stainless steel tubing, with the horizontal section perforated with 1.6mm holes on a 0.6cm spacing. A 100 B.S. gauge stainless steel mesh was welded onto the tubing to prevent fine sand or clay particles from blocking the tube.

The principal means of observing the internal state of the process was by means of sixty

thermocouples arranged on three horizontal levels - TOP, MIDDLE and BOTTOM. These were located, respectively, 0.03m, 0.06m and 0.09m from the top surface of the combustion cell. All temperature measurements were logged automatically by an Analog Devices Macsym II computer. Figure 1 shows a flowsheet schematic of the combustion cell system.

Figure 1
3-D Combustion Cell System

The initial sandpack conditions for each test and the injected oxidant gas condition are listed in Table 1. Further details of the equipment and experimental procedures are given in the thesis by Ben Rahil [6].

Table 1
Sandpack Properties and Initial Combustion Test Conditions

Run No.	1	2	3	4
Porosity (%)	35	35	35	35
S _{wi} (%)	60	50	60	50
S _{ow} (%)	35	45	35	45
Injected gas	air	air	air	99% oxygen
Injected oxygen flux (m ³ /h m ²)	3.15	3.15	3.15	6

RESULTS AND DISCUSSION

A summary of the overall results for the four light oil *in situ* combustion tests is given in Table 2.

The maximum combustion peak temperatures vary from a low of 460°C (pattern drive) up to 550°C (line drive), indicating that there was a fairly vigorous burn condition in each of the tests. However, the temperature trend was typical of dry combustion experiments, in that the combustion peak temperature tended to decline as combustion time increased. The difference in maximum combustion peak temperature is only 40°C for the line drive arrangement and the highest temperature was achieved with 99% oxygen, at almost twice the oxygen flux used in the other

tests. This latter test also gave the highest combustion front velocity of 0.11 m/h, before the CO₂ concentration in the production gas declined sharply.

Table 2
***In situ* Combustion Test Results**

Run No.	1 (line drive)	2 (line drive)	3 (pattern drive)	4 (line drive)
Maximum combustion peak temperature °C	510	530	460	550
Combustion front velocity (m/h) [†]	0.067	0.072	0.02	0.11
Produced gas composition (% average (maximum))				
CO ₂	7 (10)	5.75 (8.2)	4.4 (6.8)	44 (65)
CO	1.55 (2.2)	1.5 (2)	1.5 (2)	8.5 (12)
O ₂	8 (9.8)	11.45 (11.8)	11.5 (13)	33 (50)
Atomic H/C ratio stabilised period	1.3	1.14	4.0	4.2
Oxygen utilisation (%) overall	61.5	50	46	71
Fuel consumption kg/m ³ , overall	15.4	13	16.2	14.1
% OOIP, overall	3.5	3.7	4.4	4.5
Air to fuel ratio (m ³ /kg) overall	12.1	9.6	14.5	22.6
Air to oil ratio (m ³ /m ³) overall	1436	1573	1709	3323
Oil recovery, % OOIP	67	51	55	46
Water production, % S _w	52	62	47	58

[†] excluding period of falling CO₂ concentration

The atomic H/C ratio values calculated from the combustion gas analyses are in the low range for the two air tests using line drive (H/C = 2.0 for Forties crude oil), but much higher values occurred for both the air-pattern drive and the oxygen-line drive tests. For the latter two cases, H/C = 4.0 and 4.2, respectively. These relatively high values imply that significant low temperature oxidation (LTO) occurred during the tests. Relatively low oxygen utilisation was achieved during all of the tests, particularly with pattern drive, although it was substantially increased, up to 71%, in the oxygen test. The relatively high levels of oxygen in the produced gases are also of concern, reflecting the generally low CO₂ levels achieved. Some of these important fuel-related factors will be discussed in more detail later in the paper. Discussion will now be focussed on the detailed combustion temperature contours, relating to sweep efficiency and oil production. These results provide basic insight into the overall stability and propagation of the light oil *in situ* combustion process and its potential for economic productivity.

Temperature Profiles

Ignition State

Figure 2a shows a typical temperature distribution in the sandpack, for Run 1 at the horizontal mid-plane, five minutes after ignition. The vertical temperature contours below this are at the inlet face of the sandpack, and illustrate the extent of combustion occurring during the initial start-up period. Figure 2b (air injection, line drive) shows a well-established high temperature combustion zone (500-600°C) extending across the middle third of the sandpack, and also a broader combustion zone (400-500°C) covering almost one-half of the inlet face. The situation is similar in Figure 2c for Run 2, at a slightly later time, in which the S_{oi} was lower at 50%. The highest temperature zone (500-600°C) is more displaced, either side of the central region of the sandpack. Figure 2d shows the post-ignition state for the pattern drive of Run 3. Here, the highest temperature zone (400-500°C) exhibits a quite different overall contour, residing mainly in the bottom half of the sandpack, covering about one-third of the inlet face. Run 4, using oxygen, has clearly established a good initial burn condition, as shown in Figure 2e. This is not too different from the air test in Run 1.

Overall, the initial combustion state for the four light oil *in situ* combustion tests is remarkably good in view of the relatively low initial oil saturations and correspondingly high water saturations. The use of oxygen injection does not appear to create any superior effect.

Figure 2

Temperature Profiles:

Horizontal mid-plane: (a) Run 2 (+5 min);
Vertical sections at inlet of sandpack: (b) Run 1 (+5 min); (c) Run 2 (+20 min); (d) Run 3 (+10 min); (e) Run 4 (+10 min)

(Note: The vertical profiles shown need to be reversed, vertically)

Horizontal Temperature Profiles

Figure 3a shows the sequence of temperature contours obtained during Run 1 at the horizontal mid-plane position. At $t = 15$ min, the combustion front is well-established across the inlet region of the sandpack, with the steam-gas zone ($100\text{--}200^\circ\text{C}$) extending uniformly to one-third the distance along the cell. After a further 55 minutes of combustion time ($t = 70$ min) the very high temperature zone has disappeared, and is replaced by an expanded combustion zone ($300\text{--}400^\circ\text{C}$). The leading edge of this combustion front has reached almost one-third of the distance through the sandpack, with the steam-gas front having now displaced through to two-thirds the distance. At $t = 130$ min, the expanded combustion zone ($300\text{--}400^\circ\text{C}$) has moved into the main reservoir body, with the steam-gas region now having extended up to the cell exit.

Figure 3b shows the temperature contour sequence for Run 2, occurring at the TOP, MIDDLE and BOTTOM horizontal planes of the sandpack.

At $t = 85$ minutes (Fig 3b) the combustion front has developed fairly uniformly in the central and top regions of the sandpack. However, the main combustion zone ($400\text{--}500^\circ\text{C}$) in the bottom region of the sandpack is displaced about the central axis. Clearly, the high temperature zone ($300\text{--}400^\circ\text{C}$) and also the steam-gas front ($100\text{--}200^\circ\text{C}$) are more advanced in the top part of the sandpack. This indicates a level of gas override, but which nevertheless appears to be controlled. At the later time of $t = 145$ min (Fig 3c), combustion is most vigorous in the central and top regions of the sandpack, but now exhibits a more asymmetric condition. There is virtually a 100 per cent sweep by the steam-gas front, reinforced by a strong thermal front ($200\text{--}300^\circ\text{C}$) in the middle and bottom layers of the sandpack.

For a light oil, the strong distillation effect due to the high sweep efficiency of the steam-gas front should augur well for high oil recovery. On the other hand, it will have a negative effect regarding residual fuel for the process.

The horizontal temperature profiles at the mid-plane for Run 3 (pattern drive) and Run 4 (line drive with oxygen injection) are shown in Figure 4. By comparison also with Figure 3, it is apparent that the combustion condition in Run 3 is very much less vigorous, judging by the extent of the high temperature region, especially at the later times, $t = 85$ and 160 min. The horizontal sweep of the steam-gas zone in Run 3 is also less advanced in the bottom region of the sandpack. The oxygen test in Run 4 (Fig 4b), in contrast, develops a very vigorous combustion region ($t = 75$ min) but the rate of advance of the combustion front, defined by the 300 to 400° contour, is reduced during the next 25 minutes.

Figure 3
Temperature Profiles at TOP (T), MIDDLE (M) and BOTTOM (B) Horizontal Planes:
(a) Run 1; (b) Run 2

Figure 4
Temperature Profiles at Horizontal Mid-Plane:
(a) Run 3; (b) Run 4

Vertical Temperature Profiles and Combustion Front Stability

One of the major concerns with any gas injection recovery process, in this case air (oxygen) injection, is the tendency for gravity gas override of the frontal displacement to occur, since this will ultimately lead to early gas breakthrough. The vertical temperature profiles for all four runs are shown in Figure 5. These vertical profiles provide a useful indication of the stability of the combustion front and hence any development of gas override, *i.e.* tendency for the combustion front to follow an overriding oxygen path and consequently burn only in the upper sections of the reservoir.

Figure 5a (Run 1) shows that the leading edge of the high temperature zone, at $t = 70$ min, has stabilised to an almost vertical condition over the bottom and middle regions, with a tilted profile in the top third of the sandpack. This gravity gas override effect is responsible for the leading position of the steam-gas zone downstream. At $t =$

130 min, however, the combustion zone has expanded in size and now exhibits a vertical leading edge profile in the top half of the sandpack with a trailing profile in the bottom half. Clearly, the combustion zone ($300\text{--}400^\circ\text{C}$) is much more stable than previously. Interestingly, there appears to be some counterbalancing measure acting on the steam-gas front. This effect may be due to the influence of the horizontal producer well, creating a gravity-assisted flow downwards towards the well.

Figure 5
Temperature Profiles along Vertical Mid-Plane:
(a) Run 1; (b) Run 2; (c) Run 3; (d) Run 4
(Note: The profiles shown need to be reversed, vertically)

After 85 minutes, the leading high temperature zone ($300\text{--}400^\circ\text{C}$) in Run 2 (Fig 5b) has advanced to a similar position to that in Run 1, at $t = 70$ min. Although the initial oil saturation is lower in Run 2 ($S_{oi} = 50\%$), there is still a substantial high temperature region ($400\text{--}500^\circ\text{C}$) extending out from the inlet end, mainly in the lower half of the sandpack. At $t = 145$ min, the combustion zone ($300\text{--}400^\circ\text{C}$) is similar in overall extent to that in

Run 1, with a basically stable profile. However, the combustion front is less advanced, probably due to lower fuel availability resulting from the lower initial S_{oi} .

The pattern drive arrangement used in Run 3 (Fig 5c) produces a distinctly different combustion profile compared to the line drive experiments. Although the combustion front temperature profile at $t = 25$ min is very similar to Run 1, thereafter, at $t = 85$ min, the combustion zone ($300-400^{\circ}\text{C}$) is greatly reduced in size and is confined to the top half of the sandpack. Gas override can be clearly seen at this stage. However, at $t = 160$ min, the combustion zone ($300-400^{\circ}\text{C}$) has further reduced considerably in size, and has also moved to the bottom of the sandpack. The leading edge of the high temperature front ($200-300^{\circ}\text{C}$) appears moderately stable, but there is nevertheless significant gas override occurring in the top of the sandpack.

A very vigorous combustion zone ($400-600^{\circ}\text{C}$) develops throughout the combustion period for Run 4 (Fig 5d), aided by oxygen injection. The high temperature region exhibits a more complex shape at $t = 100$ mins, propagating mainly in the top regions of the sandpack. Gas gravity override is occurring, but since the extent of this is reduced compared to $t = 75$ min, some controlling factor is now influencing the process. It is possible that an increasing 'draw-down' effect occurs nearer the producing end of the horizontal well.

Produced Gas (CO_2 , Apparent H/C, % Oxygen Utilisation)

During *in situ* combustion, the combustion intensity is measured partly by the combustion peak temperature, but also the level of CO_2 produced in the combustion gases. The CO_2 values for Run 1 in Figure 6 are typical of the overall trend observed. Initially an increasing level, up to the highest value (10%), then stabilising at a reduced level (8.5%) and, in the final period, gradually reducing with combustion time. The declining phase, below a CO_2 concentration of about 8%, is due to a reduction of the combustion intensity, resulting in lower combustion temperature and diminished size of the combustion region.

Figure 6
Produced Gas Composition, Run 1

In Table 2, it can be seen that low CO_2 levels were achieved in each of the three air tests, due either to lack of fuel, or difficulty of combustion. The CO_2 produced in the oxygen test (Run 4) is at a much higher level (up to a maximum of 65%), albeit at nearly twice the oxygen flux of the air tests. Apparent H/C ratios are low for Runs 1 and 2, at 1.3 and 1.14, respectively, indicating little LTO effect ($\text{H/C} = 2.0$ for Forties crude), even though produced oxygen levels are high. Figure 7 shows the trend of H/C during Run 2. The much higher H/C values for Runs 3 and 4 (respectively, 4.0 and 4.2) indicate that significant LTO reaction probably occurred in these tests.

Figure 7
Apparent H/C and CO/CO_2 , Run 2

The dominant factor governing the sustainability of *in situ* combustion in a light oil reservoir is the amount of fuel available for combustion. Table 2 shows that fuel consumption values are relatively low for the light oil (as expected), varying from 3.5 to 4.5% OOIP. This is about one-third the level observed for heavy oil *in situ* combustion. Generally, the early combustion state in all tests is good, and, with the exception of Run 3 (pattern drive), the combustion front velocities (front propagation) are at reasonable levels for the oxygen fluxes used, ranging from 0.067 to 0.11 m/h. Diminishing combustion intensity and front propagation, during the falling CO_2 concentration period later in the tests, must therefore have been

strongly affected by the degree of vaporisation occurring downstream of the combustion front. In view of the high initial water saturations ($S_{wi} = 35$ and 45%) and the extent of the steam-gas front development (100-200°C temperature contour in Figs 3 and 4), the residual heavy end fraction of the crude left to be thermally cracked to fuel in the process will be reduced below the initial, already limiting, reservoir value.

In an actual light oil reservoir, the pressure may be high enough to sustain a second fuel mechanism, *i.e.* auto-ignition, as proposed by Yannimaras *et al.* [2]. At higher pressure, vaporisation will be suppressed, creating a higher residual oil availability for fuel formation. The success of light oil *in situ* combustion, or air injection process, in waterflooded reservoirs will require further understanding of the fuel formation-fuel combustion mechanisms, as well as the interplay between combustion front propagation and steam-gas front advance. The results have demonstrated that the steam front-combustion gas zone during dry *in situ* combustion can achieve virtually 100 per cent sweep of the downstream oil.

Oil Recovery

The cumulative oil recovery (Fig. 8) increases continuously with combustion time, whereas the production rate is non-uniform. This trend occurred in all of the tests. Significantly, there is some measure of correspondence, albeit complex, between the rate of oil and water production, especially for Run 2. This suggests that the advance of the steam-gas region has a very significant effect on oil displacement.

Prior to ignition, when only nitrogen is flowing through the sandpack, some oil is produced. This initial oil production was highest in Run 1 at about 23% OOIP, and lowest in Run 4 at 11% OOIP, for which the total gas flux was also the lowest. The oil recoveries in Table 2 could be adjusted to take account of this initial oil production, but the trend between tests would remain the same. For the same test conditions, the oil recovery of 67% OOIP achieved by line drive (Run 1) is superior to that obtained by pattern drive (Run 2), which was 55% OOIP. Oil recovery is also significantly influenced by the residual waterflood state and hence residual oil saturation. Increasing the initial water saturation to $S_{wi} = 45\%$ in Run 2 results in a lower oil recovery of 51% OOIP compared to 67% OOIP in Run 1, for which $S_{wi} = 35\%$. The lowest oil recovery at 46% OOIP was achieved in Run 4, using oxygen. This is mainly the effect of increased fuel consumption, being nearly one-third

higher than in the air tests. The much higher air-to-oil ratio for Run 4, at 3323 m³/m³, reflects no economic advantage for using oxygen, although the amount of gas to be compressed will, of course, be only one-fifth this figure.

We have given water production values as a percentage of the initial water in place (% S_{wi}) in Table 2. The trend is essentially what would be expected, in that Run 2, with $S_{wi} = 45\%$, is highest at 62% compared to 52% for Run 1, with $S_{wi} = 35\%$. Run 4 is similar to Run 2 for the same S_{wi} . Water production in Run 3 (pattern drive) was, however, delayed considerably by more than two hours after ignition, compared to the other tests. This reflects the water-banking effect in the downstream condensation zone, but also the more advanced transport-displacement of the vaporised light oil moving ahead of the water zone. This behaviour is minimised with the line drive horizontal well configuration, since mobile oil and gases are drawn into the well earlier. Oil and gas flow into the horizontal well is complex and further study is required to understand the detailed multiphase flow behaviour near the well bore, and also its horizontal flow.

Figure 8
Oil Production, Run 1

CONCLUSIONS

- 1 Preliminary 3D tests carried out to physically simulate light oil *in situ* combustion, under waterflooded conditions, have shown that, when a horizontal producer well in line drive is used, high combustion zone temperatures are sustained at reasonably high combustion front velocities. This type of well configuration also confers a good measure of stability on the combustion front propagation, so that any tendency towards gas override is controlled, particularly further downstream towards the producing end of the cell.

- 2 The oil recovery achieved was significantly influenced by the water saturation in the sandpack initially, *i.e.* the residual oil saturation, and also convective gas drive displacement prior to ignition. However, the main trend was to higher oil recovery with line drive compared to pattern drive, up to 67% OOIP in total. Oxygen *in situ* combustion also gave lower oil recovery compared to the air tests.
- 3 CO₂ levels in the produced gases were generally low during the air tests at around 10% or less, but were much higher in the oxygen test, averaging approximately 44%. Oxygen utilisation never achieved high levels and was lowest for the pattern drive test at 46%. Oxygen in the produced gas tended to increase throughout the tests, up to quite high levels. However, the apparent H/C ratio remained at low values ($H/C \leq 1.3$) during the air-line drive tests, but increased to $H/C \geq 4.4$ for both the oxygen and air pattern drive tests, indicating LTO reaction.
- 4 Under dry combustion conditions (present tests), the high water saturation present initially in the sandpack ($S_{wi} = 35$ to 45%) led to the development of a substantial steam-gas drive, with a volumetric sweep approaching 100 per cent. The resulting light ends vaporisation is therefore very significant in the process, but it may also act to limit an already marginal fuel availability.

SYMBOLS

EOR	enhanced oil recovery
H/C	atomic hydrogen to carbon ratio
IOR	improved oil recovery
MMBOE	million barrels of oil equivalent
OOIP	original oil-in-place
S_{oi}	initial oil saturation in sandpack, at waterflooded condition (%)
S_{wi}	initial water saturation in sandpack, at waterflooded condition (%)
t	combustion time (minutes)

REFERENCES

- 1 Gregory A T, 'DTI's Improved Oil Recovery Strategy', Trans IChemE, 1994, 72 Part A, 137-143
- 2 Yannimaras D V, Sufi A H and Fassihi M R, 'The Case for Air Injection into Deep, Light Oil Reservoirs', 6th European IOR Symposium, 1991, Stavanger, pp55-64
- 3 Hansel J G, Benning M A and Fernbacher J M, 'Oxygen *In situ* Combustion for Oil Recovery: Combustion Tube Tests', J of Petroleum Technology, 1984, 1139-1144
- 4 Shahani G H and Hansel J G, 'Oxygen Fireflooding: Combustion Tube Tests with Light, Medium and Heavy Crude Oils', SPE Reservoir Engineering, Nov 1987, 583-590
- 5 Tzanco E T, Moore R G, Belgrave J D and Ursenbach M C, 'Laboratory Combustion Behaviour of Countess B Light Oil', Paper No. CIM/SPE 90-63, CIM/SPE International Technical Meeting, 1991, Calgary, pp63.1-63.16
- 6 Ben Rahil M, 'Numerical Simulation and Experiments of *In situ* Combustion using Horizontal Wells', MPhil Thesis, University of Bath, 1995

ACKNOWLEDGEMENT

The authors are grateful to British Petroleum plc (Sunbury Research Centre) for supplying the Forties crude oil. M. Ben Rahil is grateful to the Arabian Gulf Oil Company for financial support during his period of research at Bath University.