How In-Situ Combustion Process Works in a Fractured System:
Two-Dimensional, Core and Block Scale Simulation

H. Fadaei\textsuperscript{1}, M. Quintard\textsuperscript{2}, G. Debenest\textsuperscript{2}, G. Renard\textsuperscript{1}, A.M. Kamp\textsuperscript{3}

\textsuperscript{1}Institut Français du Pétrole
\textsuperscript{2}Institut de Mécanique des Fluides de Toulouse
\textsuperscript{3}Open and experimental center for heavy oil (Chloe)

Abstract
Simulation of an in situ combustion process (ISC) was done for a fractured system at core and matrix block scales. The aim of this work was to: 1) To predict the ISC extinction/propagation condition(s), 2) understand the mechanism of oil recovery and 3) provide some guidelines for ISC upscaling for a fractured system. The study was based on a fine grid, single porosity, multi-phase and multi-component simulation using a thermal reservoir simulator. The following results were obtained: a) Firstly the simulator was validated for 1-D combustion using the corresponding analytical solutions. 2-D combustion was validated using experimental results available in the literature. It was found that the grid size should not be larger than the combustion zone thickness in order the results be independent of grid size. b) ISC in fractured system was feasible under certain conditions: The extinction/propagation of ISC was strongly dependent on the oxygen diffusion coefficient while the matrix permeability played an important role in oil production. c) Effect of each production mechanism was studied separately whenever it was possible. Oil production is governed mainly by gravity drainage and thermal effects; possible pressure gradient generation in the ISC process seems to have a minor effect. d) The nature of ISC at core scale was different between a single block and multiple blocks (oil production rate, saturations distribution, shape of the combustion front). The characteristics of different zones (i.e. combustion, coke, oil) at block scale were studied and some preliminary guidelines for upscaling are presented.

Introduction
In spite of its strategic importance, recovery of heavy crudes from fractured carbonate reservoirs (one third of global heavy oil resources) has found poor applications due to the complexity of such reservoirs. Extensive work has been done on the development of thermal processes (Pooladi-Darvish 1994; Akin et al. 2000). However, for in situ combustion (ISC) applied to fractured reservoirs, a multi-scale multi-process problem has to be dealt with, and many unknowns are still remaining. The recovery mechanism, reservoir and operational conditions at which the combustion can propagate in fractured systems are not clearly understood. In situ combustion has been a matter of concern for many researchers. Most of their studies have been done on conventional reservoirs where the highly heterogeneous nature of the reservoirs has not been taken into account (Moor et al. 1998; Akin et al. 2000; Castanier et al. 2003).

Few works may be found in literature concerning ISC in a fractured system. Schulte and de Vries (1985) studied ISC in a fractured core at laboratory scale. They simulated the fracture through the use of narrow pathway adjacent to the core situated vertically in a core holder in a combustion tube experiment. They observed that the process was governed by diffusion of oxygen into the matrix. The main oil production mechanisms were found to be thermal expansion and evaporation. A cone shape front was observed after cutting the core sample and the front inside the sample was lagged behind that in the fracture. The same experimental configuration was applied by Greaves et al. (1991). As in the other experiment the cone shape front was observed and the main oil production mechanism was found to be expansion and evaporation. In another study done by Miller et al. (1983) using a fractured core, 33% of the initial oil in place was produced as a result of the combustion process while 45% was used as fuel by the combustion. The combustion experiment with the fracture which was propped with glass beads was not successful because the air flow in this case passed through the fracture and was not supplied to the combustion front.
Some works are currently on-going at Stanford University on in-situ combustion in a fractured core (Awoleke 2007). It was observed that the combustion front was not hindered by small scale heterogeneity (average 0.025 m) while it was not sustained in the case of large scale heterogeneity (0.67 m). Simulation of in-situ combustion in a fractured core was done by Tabasinejad et al. (2005). Their results show that the combustion front propagated successfully in the tube and high oil recovery (>80%) was achieved although it was less than for a conventional combustion process. Air injection into a light oil fractured reservoir was studied by Lacroix et al. (2004). They performed a fine grid simulation at core scale where they found that the oxygen diffusion into the matrix and the thermodynamic exchanges between the gas in fracture and the oil in the matrix are controlled by matrix-fracture exchange.

The major contribution of this paper is firstly the study of ISC propagation condition(s) and oil recovery mechanisms at fractured core scale, and secondly the study of the process at block scale where one can address the two dimensional behavior of ISC at large scale. This will provide us with the determination of the dominant processes for combustion propagation at block scale and the characteristics of different fronts that exist in this problem.

Mathematical model used in the thermal simulator

Based on current knowledge of crude oil combustion in porous media, four phases are present in this problem: oil, gas, water and solid. The oil and gas phases are multi-component (i.e. hydrocarbon components in oil and gas phases, water also in gas phase), solid phase containing inert solid and coke; The water phase however is considered to have only one component. Reactions are taking place in the oil, in the gas and on the surface of the solid phase (when coke is present). Coke is formed due to pyrolysis and deposited on solid surface. Reactions in oil and gas phases are homogeneous but the coke reaction is heterogeneous. Detail of the mathematical model describing the mass, momentum and energy conservation can be found in (Fadaei et al. 2008).

Results

Simulator validation

Simulator validation was done for two problems. Two-phase (solid-gas) combustion in a porous medium initially containing a solid fuel and two-dimensional conventional dry combustion was studied. Aldushin and Matkowski (2000) provided the first problem that they solved analytically considering an infinite reaction rate which results in a sharp reaction front (sheet-like). Our simulation results fit well the analytical solution when reasonable numerical parameters (i.e. 10^{-3} m grid size) are applied. For the second problem, simulation results were compared with the results published by Kumar (1987). Cumulative oil and water production and the peak temperature obtained from simulation results and the corresponding values reported by Kumar were in reasonable agreement. Details of the validation results are presented elsewhere (Fadaei et al. 2008).

Core scale 2-D simulation results

Simulation of oil combustion in a fractured system

The extinction/propagation condition of the combustion front in a fractured system and the governing production mechanism(s) were studied. The geometry of the simulation model is presented in Fig. 1 and the input data for the model is given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Temperature</td>
<td>(K)</td>
<td>311</td>
<td>Oil saturation</td>
<td>(%)</td>
<td>65.4</td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td>(kPa)</td>
<td>13.8×10^3</td>
<td>Water saturation</td>
<td>(%)</td>
<td>17.8</td>
</tr>
<tr>
<td>Oil gravity</td>
<td>°API</td>
<td>26</td>
<td>Gas saturation</td>
<td>(%)</td>
<td>16.8</td>
</tr>
<tr>
<td>Porosity</td>
<td>(%)</td>
<td>40</td>
<td>Oxygen diffusion coefficient</td>
<td>(m^2/s)</td>
<td>0.667×10^{-5}</td>
</tr>
<tr>
<td>Permeability (matrix)</td>
<td>(mD)</td>
<td>1.27×10^{10}</td>
<td>Air injection rate</td>
<td>(m^3/hr)</td>
<td>0.0142</td>
</tr>
<tr>
<td>Permeability (fracture)</td>
<td>(mD)</td>
<td>1.27×10^{6}</td>
<td>Air injection flux</td>
<td>(m^3/m^2/hr)</td>
<td>4.52</td>
</tr>
<tr>
<td>Matrix tortuosity</td>
<td>-</td>
<td>1.5</td>
<td>Core superficial area</td>
<td>(m^2)</td>
<td>3.143×10^3</td>
</tr>
</tbody>
</table>
The core dimensions and the grid size of matrix and fracture are shown in Table 2. The petrophysical properties of the core and the oil properties are similar to those used in the previous section (Kumar 1987).

Table 2 — Dimensions of the simulation model

<table>
<thead>
<tr>
<th>Dimensions (m) [x, y, z]</th>
<th>Blocks number [x, y, z]</th>
<th>Δx_f (m)</th>
<th>Δx_m (m)</th>
<th>Δz_m (m)</th>
<th>Δz_f (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.064, 0.0488, 0.51]</td>
<td>[13, 1, 37]</td>
<td>0.002</td>
<td>0.0067</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

* f, m: fracture and matrix respectively.

The core was positioned vertically to mimic a so-called top-down process. The core had no temperature losses at its boundaries. The first row of blocks at the core top was heated with constant heating rate. The heat injection was maintained for 24 minutes until the ignition started in the core; This time is considered to be of the same magnitude as that used in a non-fractured core.

Figure 1: Geometry of the core simulation model

Cumulative oil production showed that for the base case most of the oil (about 70%) has been produced in the first half of the burning process. The ignition temperature was 325°C and after that, the peak temperature continuously increased. This increase may be due to an increase in coke concentration as the oxygen flux into the matrix is less than the rate of coke generation. This resulted in combustion zone expansion and peak temperature increase. Another reason was that not all the injected air passes through the matrix due to higher permeability in the fracture, so the cooling efficiency of injected air is somehow lower than in the non-fractured combustion case. The amount of oil which has been burnt during the combustion is calculated to be 13% of the total initial mass of the oil while it is 6.4% for a non-fractured core. This may explain the temperature increase in the fractured system.

Extinction/propagation condition

Among all the parameters that may influence the behavior of a combustion process as mentioned by many researchers (Schulte and de Vries 1985; Greaves et al. 1991; Awoleke 2007; Tabasinejad et al. 2005), two were studied: oxygen diffusion and matrix permeability. The former is believed to govern the crude oil combustion in the fractured core (Greaves et al. 1991; Schulte and de Vries 1985) and the latter is related to the inherent characteristics of carbonate reservoirs, which have naturally very low permeability (yet in a typical combustion tube, permeability is usually very high compared to that encountered in a real reservoir).

Several computations were performed using different values of oxygen diffusion and matrix permeability. The cumulative oil production, as a function of oxygen diffusion and matrix permeability, is shown in figure (2). This figure reflects the extinction or propagation of the combustion front. The x and y axes indicate the ratios of oxygen diffusion coefficient and permeability to their respective reference value (the reference being the base case). The base case corresponds to maximum oxygen diffusion and matrix permeability (Kumar’s experiment). In
this figure, zero production means that the combustion is not sustained, however, in such case there is a small amount of production due to natural gravity drainage.

From figure (2) it is evident that whether combustion sustains in the matrix strongly depends upon the oxygen diffusion coefficient. When this coefficient is 50 times smaller than in the base case, the combustion front does not propagate through the core. However if we reduce the permeability even 1000 times, the combustion is still sustained. On the other hand, the diffusion coefficient does not have a significant influence on oil production while oil production decreases sharply if we reduce the permeability 10 times. Some preliminary tests showed that for some cases where we do not have combustion, changing the initial condition may lead to propagation of combustion. Examples of such initial conditions are higher injection rate, longer initial heating time, more oil saturation in the first block.

**Oil production mechanisms in fractured reservoir under ISC**

In order to distinguish the effect of each driving force during the ISC process we have tried to study the effect of each mechanism separately whenever it was possible.

**Natural gravity drainage**

To study the effect of gravity we kept the same geometry as for the base case, removing all reactions and let the system drain by gravity. Oil production under only gravity drainage was very slow and less than 8% of oil was produced during 20 hr which is a typical burning time in ISC process. So natural is unlikely to be of economical interest.
Oil production in vertical and horizontal configurations

Figure (3) shows the oil production in a vertically and horizontally production case. Oil production in a vertical case is considerably faster than in the horizontal case, which confirms that gravity can play a role in an ISC process during which the oil viscosity is considerably reduced causing the effect of gravity to be noticeable. Higher produced cumulative oil in vertical configuration, suggest that oil burning was less in this case.

Oil production via ISC and programmed heating

In this practice, the temperature observed in an ISC process was applied by external heaters to the core while all reactions were removed from the model. The cumulative oil production by programmed heating after 15 hours (figure 3) is the same as that for ISC and even a bit more (2%). It indicates that temperature effects are predominant factors for oil production and non-thermal effects, such as differential pressure generation during ISC, do not play a major role. This may be also explained by the fact that the pressure gradient generated during ISC will be damped by high matrix permeability, initial gas saturation (18%) as well as the presence of fractures.

Conclusion of this part

Simulation results show that in-situ combustion is feasible for fractured porous medium at core-scale. The peak temperature and the extent of the coke zone were increased during the process while these two parameters are rather constant during conventional combustion. Oxygen diffusion coefficient was found to have a major influence on extinction/propagation of combustion and matrix permeability to play an important role in oil production. Considering the characteristics of the porous matrix for the base-case, the simulation results showed that more fuel was consumed during ISC in a fractured system than in a non-fractured case. Gravity drainage, when ISC is present, and thermal effects were found to be important in oil production. Any possible pressure gradient generation during the ISC process seems to have a minor effect on oil production.

Simulation of ISC process in single matrix block

Model

Two-dimensional simulation of a single matrix block surrounded by fractures was studied. The geometry of the system is shown in figure (4). Because of the symmetry that exists in this problem we have simulated half the block (in $x$ direction). The fracture at the bottom of the block is wider allowing for better production control. Block dimensions in $x$, $y$ and $z$ directions were 1, 0.05 and 0.5 (m) respectively. The matrix block is discretized by 16*16 grids in $x$ and $z$ directions and two grids are considered for fractures which resulted in a 20*20 simulation grid. Same reservoir
properties, initial condition and reaction scheme as in previous part were used except that here oil was more viscous at initial reservoir condition (4000 cp). Air was injected from the top-left and oil was produced from the bottom-left of the block. Heat losses from the block surroundings were considered to be zero.

**Some observations of combustion process in a single block**

**Temperature**

The temperature profile along the matrix diagonal is shown in figure (5). Generally peak temperature and size of the high temperature zone inside the block increase during the production (see also figure 15). After initial ignition (1hr), the peak temperature increases to about 410 °C (at 10hr) and then remains relatively constant until 50hr, after which it starts to increase again.

To explain the behavior of the system we may try to compare the magnitude of different processes that are involved in heat transfer during the combustion. In this regard, instead of treating the whole system, which is very complex, we will analyze some simpler cases for which some non-dimensional numbers may be derived. The simplified version of this process is a filtration combustion (FC) in which a combustion front passes through a porous matrix, initially containing a solid fuel. This process has been studied by many researchers (Debenest et al. 2005; Aldushin and Matkowski 2000). To determine the behavior of a FC process, Debenest et al. (2005) used the parameter $\Delta$:

$$\Delta = \frac{\varepsilon C_g (\nu - \nu_c)}{[\varepsilon C_g + (1 - \varepsilon) C_s] \nu_c} \approx \frac{\varepsilon C_g \nu}{(1 - \varepsilon) C_s \nu_c}$$

(1)

When $\Delta > 1$, heat is transferred from upstream (behind the front) to downstream (ahead of the front) by convicting gas flow. $\Delta = 1$ corresponds to a superadiabatic situation where heat remains in the vicinity of the reaction front and when $\Delta < 1$ there is no heat transfer from upstream to downstream. This analysis is based on the fact that the dominant heat flow regime is gas convection. In our case, however, we expect that heat diffusion is also significant.

![Fig. 5— Temperature along the block diagonal for different times for K=1270md](image)

To start the analysis we may write the energy balance equation was done by Aldushin and Matkowski (2000) for a 1-D system of solid-gas combustion in a coordinate system that is moving with the combustion front:
This energy balance is written in 1-D for a region near the combustion front. Upstream of the front the fluid phase is only gas phase and on the downstream at the vicinity of the combustion front the oil saturation is equal to its residual saturation and no water is present due to high temperature. Under this condition it is reasonable to consider only solid and gas phase in the energy equation.

Using the following non-dimensional variables:

\[
X = \frac{x}{L}, \quad \tau = \frac{t}{t^*}, \quad t^* = \frac{u_c}{L}, \quad \theta = \frac{T}{T_{ref}}
\]  

(4)

Here \(L\) is the length of the matrix and \(t^*\) is the time for combustion to travel the matrix length. Usually the gas phase heat capacity is negligible compared to solid phase heat capacity.

\[C_p = (1 - \varepsilon)C_s\]

The equation (2) reads:

\[
\frac{u_c C_p}{L} \frac{\partial \theta}{\partial \tau} + \left( \frac{\varepsilon g v_g}{L} - \frac{C_s u_c}{L} \right) \frac{\partial \theta}{\partial X} = k \frac{\partial^2 \theta}{\partial X^2}
\]

(5)

Dividing both sides of equation (5) by \(\frac{k}{L^2}\), we may have:

\[
\frac{(1 - \varepsilon) C_s u_c L}{k} \frac{\partial \theta}{\partial \tau} + \left[ \frac{\varepsilon g v_g L}{k} - \frac{(1 - \varepsilon) C_s u_c L}{k} \right] \frac{\partial \theta}{\partial X} = \frac{\partial^2 \theta}{\partial X^2}
\]

(6)

We can write this equation as:

\[
P_{c} \frac{\partial \theta}{\partial \tau} + [P_{c} \varepsilon v_g - P_{c} \varepsilon c] \frac{\partial \theta}{\partial X} = \frac{\partial^2 \theta}{\partial X^2}
\]

(7)

in which the \(P_{c}\) and \(P_{c} \varepsilon\) are the thermal Peclet number based on combustion front and gas phase velocities respectively.

To determine the order of magnitude of each parameter we will use the simulation result to calculate the gas phase velocity and the combustion front velocity. Calculation based on the simulation results for a typical case (\(K=1270\) mD) showed that the average gas phase velocity is in the order of 10-6 m/s close to the front position. The front velocity is not constant. At the initial times it is in the order of 5×10-6 m/s and then it reduces to 5×10-7 m/s and even smaller at later times. Typical value for gas and solid phases volumetric heat capacity is \(7.5 \times 10^4\) and \(3.2 \times 10^6\) J/m³°C. Thermal conductivity was calculated to be 1.01 J/ms°C and the porosity of the medium is 40%. The Peclet numbers are:

\[
P_{c} = \frac{0.4 \times 7.5 \times 10^4 \times 10^{-6} \times 0.5}{1.01} = 0.02
\]

(8)

\[
P_{c} \varepsilon = \frac{(1 - \varepsilon) C_s u_c L}{k} = \frac{0.6 \times 3.2 \times 10^6 \times 5 \times 10^{-7} \times 0.5}{1.01} = 0.45
\]

(9)

Comparison of these two parameters shows that heat transfer due to front movement is more important than gas phase convective heat transfer and both of them are less important than heat transfer by conduction. The combustion front velocity decreases with time thus at later times, heat
transfer due to front movement becomes less important compared to both gas phase convective heat transfer and conduction.

Based on this calculation we may explain the temperature behavior as follows: The initial increase of the peak temperature is due to the development of the combustion process where the combustion front velocity is high and the rate of heat generation by combustion is higher than the rate of heat transfer.

Subsequently the relatively constant temperature suggest that the heat produced by the combustion process is transported mainly by conduction to the colder part of the block and finally when the heat front reaches the symmetric no-flow boundary on the right side of matrix block, peak temperature starts to increase as conduction heat transfer is limited by this boundary.

Gas phase velocity vectors in figure (6) indicate that the gas phase does not bring the heat from upstream to the front (unlike the FC process), but rather remove heat from it. In this figure the red colour region shows the maximum temperature or the combustion front location. This is another indication that conduction heat transfer is dominant.

![Fig. 6 - Temperature profile (°C) and gas phase velocity vector (left), temperature profile (°C) and oil phase velocity vector (right)](image)

Oil phase velocity is shown in figure (6) with the flow vectors. The oil phase just ahead of the front drains relatively vertically but far from the front the drainage is inclined. This is because the oil at the upper right part of the block has lower viscosity than the oil underneath it. Velocity of the oil phase adjacent to the front is \(10^{-9}\) m/s and far from the front it is about \(3 \times 10^{-8}\) m/s. The oil phase thermal Péclet number near the front is:

\[
P_{\text{oil}} = \frac{v_o L}{\alpha} = \frac{10^{-9} \times 0.5}{0.54 \times 10^{-6}} = 0.9 \times 10^{-3}
\]

This value shows that the heat transfer by oil phase just ahead of the front is negligible compared to conductive heat transfer.

The oil phase thermal Péclet number far the front is:

\[
P_{\text{oil}} = \frac{v_o L}{\alpha} = \frac{3 \times 10^{-8} \times 0.5}{0.54 \times 10^{-6}} = 0.027
\]

This value indicates that although the heat transfer by oil phase far from the front is more important than to heat transfer near the front, still the conductive heat transfer is more important than convective heat transfer.

Considering oxygen diffusion coefficient equal to \(0.67 \times 10^{-5}\) m\(^2\)/s and characteristic length of 0.5 m for the matrix, the Péclet number for gas phase is:
This value shows that the process of oxygen delivery to the combustion front is also diffusion dominated.

**Coke zone**

Figure (7) shows the coke concentration across the diagonal of the block. The size of the coke zone increases during the production while the maximum coke concentration remains relatively constant. This shows that the heat transport ahead of the combustion front is faster than the advance of combustion front. On the other hand, the coke consumption by the combustion process is slower than its generation by the cracking reaction.

![Figure 7](image_url)

**Oil saturation**

The oil that is mobilized due to heating will form a so-called oil bank ahead of the high temperature combustion front. Initially this narrow thickness, high oil saturation zone will form close to the combustion front (figure 8). This happens because a large portion of the block is still at low temperature at which the oil is not mobile. Under this situation most of the oil production occurs through the vertical fracture. As the combustion front progresses, the size of the oil bank increases and finally it touches the matrix bottom and causes the oil being produced by matrix as well. This increase of oil bank size may be explained by the fact that heat transfer is faster than combustion front movement. At later times (>50hr) one can distinguish two main fronts for oil saturation: The one which is close to the combustion zone with low saturation (about 25%) and the oil bank which is far from it with oil saturation greater than the initial reservoir, oil saturation. At longer times no oil will be produced by the vertical fracture as the oil-bank is far away from it.
Front velocity

Figure (9) shows the front velocity calculated based on the oil saturation profile shown in figure (8). This figure shows that front velocity decreases with distance. Comparing these results with the analytical solution of the diffusion dominated combustion process studied by Aldushin and Matkowski (2000) reveals that the combustion process in our case is also governed by diffusion.

Oil upgrading

Oil upgrading is characterized by the amount of heavy oil that transformed to light oil due to a cracking reaction. Another product of reaction is coke, of which the amount inside the matrix increases during the production time. One may expect that the amount of light oil increases as well. Figure (10) shows the cumulative production of heavy oil, which corresponds to 2.5% of the initial volume of heavy oil in place. It reveals that more than 97% of the heavy oil has been cracked which is a huge upgrading that may not occur in reality. One possible explanation is that cracking reaction is faster than combustion reactions. Another important point is that only two components are considered for oil phase thermodynamics representation which is a strong simplification.
Oil production

Cumulative oil production as a function of time is presented in figure (11) for three cases with different matrix permeability. The air injection rate was 0.3 m$^3$/hr for all cases. Oil production at initial time (<60 hr) is small due to high viscosity (4000 cp) of the oil at reservoir condition and later production increases as heat penetrates into the matrix block.

The cumulative oil produced increases as matrix permeability increases. The increase of the oil production after 60 hr in high permeable (1270 mD) matrix is more pronounced than that is in the other two cases. Transition time of 60 hrs corresponds (for the high permeable case) to the time where the oil bank reaches the matrix vertical symmetry no-flow boundary. Figure (12) shows the progress of the oil bank during production. The size of oil bank is the maximal when it reaches this boundary.
In the study of ISC for a fractured system at laboratory scale, Greaves et al. (1991) reported that more than 75% of the oil was produced during the first half of the burn period. This is not the case in a block where most of the oil production occurs at the second half of the production period. We believe that the shape of the combustion front in a tube is totally different from that in the block. In the tube, after initial time necessary for development of the combustion, the front will pass through the tube from top to bottom and its horizontal displacement does not exist (Fadaei et al. 2008). However in a block both vertical and horizontal advancement of the combustion front occurs and consequently the resulted heat transfer will affect the amount of mobilized oil and eventually the production.

Comparison with gravity drainage models

We have attempted the development of a simplified model of the fractured medium ISC process. We based our model attempts on the analogy with gravity drainage, and in particular with steam assisted gravity drainage (SAGD). The reason that we think that there may be an analogy is that for the ISC process, any pressure increase is easily relaxed by gas flowing from the matrix block to the fracture, in order to be evacuated through the fracture system. This will allow little pressure build-up for oil production. Our first guess was therefore that the role of the combustion would be to heat the oil, decreasing its viscosity, and allowing it to flow downwards by gravity.

Gravity drainage, such as for example in SAGD, is characterized by an approximately constant oil production rate (Butler, 1991) which depends as a square root of matrix permeability. This approximation falls short when the steam chamber in SAGD reaches an adjacent steam chamber, or the boundary of a reservoir. The equivalent of this situation in our ISC is when the combustion front reaches the vertical symmetry plane of the matrix block. In such a situation, a decline of oil production is expected.
Figure 13 shows oil production rate versus time on a log-log plot for different matrix permeabilities. All three curves have a similar shape, characterized by four periods: (1) a period with almost no oil production, (2) a second period during which, after a steep rise, oil production rate steadily declines, (3), a period during which oil production rate increases, and finally (4) a decline period. Let’s consider the $k = 1270$ mD case. The transition times between the four periods are approximately 20 hours, 50 hours, and 90 hours. From Fig. 15 we estimate at 20 hours a front temperature of approximately 420°C. At 50 hours this has decreased to approximately 410°C. This decrease, which is probably due to the pre-heating of the block, generated an increase in oil viscosity. A reasonable guess is that during the second period oil production would have been approximately constant, if temperature had been constant.

At 90 hours, combustion front temperature has increased to around 480°C. It is likely that this increase was at least partly responsible for the increase in oil production rate, through a reduction of oil viscosity. The time of 90 hours may approximately correspond to the front reaching the vertical symmetry plane of the block. Precise estimation of this moment is cumbersome due to the difficulty in defining the exact position of a front. Gravity drainage theory predicts a steady decline of oil production rate after this time, which is also observed in Fig. 13. A quantitative analysis is required to confirm whether gravity drainage is the main mechanism of oil production, or whether substantial other contributions exist.

The results also show clear differences with processes such as SAGD. For example, during high temperature combustion (above 400°C), the mobile oil region seems wider (see Fig. 12) than what is assumed in SAGD.

Figure 14 shows the oil production rate at different times as a function of permeability on a log-log scale. Gravity drainage theory predicts straight lines with a slope of 0.5. However, such straight lines can only be expected comparing production rates for different permeabilities at equal temperature. In steam assisted gravity drainage experiments, where temperature is determined by pressure alone (because steam is saturated), such conditions are easily verified. In our case however, at any time, temperatures are not equal for different permeabilities. For this reason, it is useless to look for straight lines in such plots.
Fig. 14— Log-log plot of oil production rate vs. matrix permeability for different times
Conclusion
Simulation of ISC at block scale showed that the undergoing process is diffusion dominated both for heat and mass (i.e. oxygen) transfer. Heat transfer due to the movement of combustion front velocity is small compared to the heat transfer by conduction and convection; this is the reason for increase of combustion front temperature during the process. In this multi front process different zones can be distinguished for oil saturation and temperature which their sizes vary over time. The relative size of the heat and saturation zones and the change of their size during the burning process suggest that any up-scaling method should take into account these phenomena. In the other hand for a multi-block situation homogenizing the matrix block as a single node in the simulation model may introduce large errors as the nature of the process inside the matrix is highly heterogeneous. More detailed mathematical manipulation is needed to address this issue based on the characteristic length scale of the processes on-going in the matrix and the averaged values of different parameters. We will address these issues in future work.

Our results showed that oil production in ISC is somehow different from that in the SAGD process.

Acknowledgement
Total S.A. is kindly acknowledged for the sponsoring of the PhD of H. Fadaei and for the authorization to present the results included in this manuscript.
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>porosity</td>
<td></td>
</tr>
<tr>
<td>$v_g$</td>
<td>Gas Phase velocity (m/s)</td>
<td></td>
</tr>
<tr>
<td>$u_c$</td>
<td>Combustion front velocity (m/s)</td>
<td></td>
</tr>
<tr>
<td>$C_g$</td>
<td>Gas volumetric heat capacity (J/M$^3$.C)</td>
<td></td>
</tr>
<tr>
<td>$C_S$</td>
<td>Solid volumetric heat capacity (J/m$^3$.C)</td>
<td></td>
</tr>
<tr>
<td>$C_p$</td>
<td>Equivalent heat capacity (J/m$^3$.C)</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>Time (s)</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>Block characteristic length (m)</td>
<td></td>
</tr>
<tr>
<td>$Pe$</td>
<td>Péclet number</td>
<td></td>
</tr>
<tr>
<td>$\alpha^*$</td>
<td>Thermal diffusivity (m$^2$/s)</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>Mass diffusivity (m$^2$/s)</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Dimensionless temperature</td>
<td></td>
</tr>
<tr>
<td>$t^*$</td>
<td>Travelled time of combustion front</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Dimensionless time</td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>Dimensionless distance</td>
<td></td>
</tr>
</tbody>
</table>

References


Tabasinejad F., Karrat R., and Vossoughi S. Feasibility study of in situ combustion in naturally fractured heavy oil reservoirs. SPE 103969, Presented at the First International Oil Conference and Exhibition, Cancun, Mexico, 31 August-2 September 2006.