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MODELING SEGREGATED IN-SITU COMBUSTION PROCESSES THROUGH A VERTICAL DISPLACEMENT MODEL APPLIED TO A COLOMBIAN FIELD

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Recently it has been proposed the incorporation of horizontal well technologies in thermal EOR processes like the in situ combustion process (ISC). This has taken to the conception of new recovery mechanisms named here as Segregated In-Situ Combustion processes which are conventional in-situ combustion process with a segregated flow component. Top/Down combustion, Combustion Override Split-production Horizontal-well and Toe-to-Heel Air Injection are three of these processes, which incorporate horizontal producers and gravity drainage phenomena. When applied to thick reservoirs a process of this nature could be reasonably modeled under concepts of conventional In-Situ Combustion and Crestal Gas Injection, especially for heavy oils mobile at reservoir conditions. A process of this nature has been studied through an analytic model conceived for the particular conditions of the Castilla Field, a homogeneous thick anticline structure containing high mobility heavy oil which seems to be an excellent candidate for the application of these technologies.

Keywords: *In-Situ Combustion, segregated combustion, gravity drainage, heavy oil, thermal EOR, Castilla Field, horizontal well.*

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En los últimos años, se ha propuesto incorporar tecnologías de producción a través de pozos productores horizontales en procesos térmicos de recobro mejorado, como la Combustión *In-Situ* (ISC). Esto ha llevado a la concepción de nuevos mecanismos de recobro llamados aquí procesos de combustión segregada *in-situ*, los cuales corresponden a procesos convencionales de combustión en yacimiento, con un componente de flujo segregado. Tres de estos procesos son: *top/down combustion, combustion override split-production horizontal-well* y *toe-to-heel air injection*, en los cuales se han incorporado pozos productores horizontales y fenómenos de drenaje gravitacional. Cuando un proceso de este tipo es aplicado en yacimientos de gran espesor, el proceso es razonablemente modelado bajo conceptos de combustión in-situ convencional y procesos de inyección crestal de gases inertes, especialmente cuando en el yacimiento existe crudo pesado con algún grado de movilidad. Un proceso de esta naturaleza ha sido estudiado a través de un modelo analítico concebido para las condiciones particulares del campo Castilla, una estructura anticlinal bastante homogénea y de gran espesor, que contiene crudo pesado de alta movilidad; razones que lo hacen un posible candidato para la aplicación de dichas tecnologías.

Palabras claves: *Combustión In-Situ, combustión segregada, drenaje gravitacional, crudo pesado, recobro térmico, campo Castilla, pozos horizontales.*

NOMENCLATURE

A	Pattern area, [acres]
Ai	Air requirements of the process, [SCF/acre-ft]
A_I	Air requirements, [SCF/ft^3]
dNp/dt	Slope of the graph ‘Np vs t’, [STB/D]
F_1	Contribution of the natural residue, [lb fuel /100 Lb rock]
F_2	Contribution of the formed in-situ residue, [lb fuel /100 lb rock]
F_C	Fuel content of the system, [lb fuel /100 ft^{3}rock]
$\overline{F}_C$	Fuel content of the system, [lb fuel /100 lb rock]
h_b	Burned zone thickness, [ft]
h, h_i	Formation net thickness, [ft]
h_o	Oil bank thickness, [ft]
k_A	Air permeability, [md]
MD	Maximum deviation in function of Sgi, [%]
n	Hydrogen-Carbon atomic ratio of the fuel, [dimensionless]
Np	Produced oil, [STB]
OR	Mobile oil recovery, [%]
Piw	Air injection pressure, [psia]
Pwf	Bottom hole flowing pressure, [psia]
q_A	Air injection rate, [MMSCF/D]
q_o	Oil rate during the process, [STB/D]
q_{oi}	Oil rate at the beginning of the process, [STB/D]
r_{ext}	External edge radius or external border of the combustion surface, [ft]
r_w	Wellbore radius, [ft]
Sgi	Initial gas saturation, [%]
Sof	Fuel saturation, [bbl/acre-ft]
Soi	Initial oil saturation, [bbl/acre-ft]
So_M	Non-fuel oil saturation, [bbl/acre-ft]
t	Injection/production time, [D]
T	Process mean temperature, [°F]
T°	Initial reservoir temperature, [°F]
t_1	Required time needed to reach the maximum air injection rate, [D]
Vb	Burned volume, [ft^3]
VB	Percentage of burned volume, [%]
VBo	Percentage of burned volume until the front move forward, [%]
V_f	Combustion front mean velocity, [ft/D]
$V_{pattern}$	Pattern volume, [ft^3]
X	Volume fraction really displaced, [dimensionless]

NOMENCLATURE

Y	Deviation/Maximum deviation, [dimensionless]
z	Measured depth from the top of the formation, [ft]
z_f	Burned zone thickness at time ‘t’, [ft]
ε	Combustion efficiency, [fraction]
Φ	Rock porosity, [fraction]
θ	Dip mean angle, [grades]
°API	API gravity
ρ_f	Fuel density, [lb/ft^3]
μ_g	Air viscosity at mean temperature, [cp]
μ_o	Oil viscosity at depth ‘z’ y time ‘t’, [cp]
μ_{oi}	Initial oil viscosity, [cp]
$(qo)_i$	Instant oil production rate (the same ‘qo’), [STB/D]
ρ_R	Rock matrix net density, [lb/ft^3]
Δz	Step increment in depth (e.g. 1.0 ft), [ft] (it represents the summatory partition)

CONVERSION FACTORS

1 bbl x 0,15899	m^3
1 ft^3 x 35,3107	m^3
1 acre-ft x 1233,65	m^3
1 cp	mPa.s
1 ft x 0,3048	m
(°F-32)/1,8	°C
1 md x 0,0009869	μm^2
1 Psi x 6,8947	KPa
1 Lb x 2,2956	Kg

INTRODUCTION

Thermal Recovery is the most used enhanced oil recovery method for heavy oils since other mechanisms are ineffective, especially when they are used in high viscosity oils (Dietz, 1975). The two more important thermal EOR processes are In-Situ Combustion (ISC) and Steamflooding (SF). Both of them are proved processes, however, steam injection has been traditionally considered as a simpler and more accepted practice, because of its high performance. Strictly speaking the steam injection has had better results that the ISC process, in spite that ISC is a more thermally efficient process and has a wider applicability range. Some of the inconveniences of the conventional in situ combustion have limited the commercial expansion, except in exceptional cases like Suplacu de Barcau (Rumania), Horse Creek (USA), Battrum (Canada), Balol (India), among others. These inconveniences are mainly due to the stability and control of the combustion front, low sweep efficiencies, corrosion, production of flue gases and other operative problems. The worst inconvenient of the In Situ Combustion process are the fluid segregation (overriding) and the long distance displacement character of the process, which reduce the final oil recovery and production rates.

In spite of these internal limitations, a new horizon has opened up by incorporating production tools like the horizontal producer wells (Greaves, 1993), the high capacity pumps and high tolerance equipments. This technological synergy has allowed the development of processes like Top/Down Combustion (Coates, 1995) and the conception of others like Combustion Override Split-production Horizontal-well – COSH (Kisman, 1994) and Toe-to-Heel Air Injection – THAI (Greaves, 1997). These processes have a segregated flow component and use horizontal producer wells.

IN SITU COMBUSTION

In situ combustion (ISC) is a commercial process for heavy oil recovery, even in recent years it has proved its applicability to medium and light oil reservoirs. In this process an oxygen containing gas is injected into the oil zone with the purpose to support and propagate the previously formed combustion front. The burning front goes in the air flux direction, burning a small fraction of oil and providing both steam drive and intense gas drive (Kuhn, 1953).

The process is sometimes started by lowering a heater or igniter into an injection well. Air is then injected down the well and the heater is operated until ignition is accomplished. After heating the surrounding rock, the heater is withdrawn while air injection is continued to maintain the advancing combustion front. Water is sometimes injected simultaneously or alternately with air to form steam which contributes to better heat utilization and reduce the air requirements. The process will be finished by stopping air injection when pre-designated areas are burned out or when the burning front reaches the producer wells

Normally, the lighter steam vapors and combustion gases tend to rise into the upper portion of the oil zone (this phenomenon is called Overriding or Bypassing) reducing so the effectiveness of the combustion process. Alternately or simultaneously air-water injection could diminish the negative effects of this phenomenon (Counihan, 1977).

RECENT DEVELOPMENTS IN ISC PROCESSES

Recent developments in ISC processes include the use of horizontal wells to change a long distance displacement process in a short distance displacement one, similar to that of SAGD. Oil production through horizontal wells has been implemented in two Canadian ISC pilots, the Eyehil and Battrum projects, both in Saskatchewan. When applied to ISC processes, horizontal wells should reduce the negative effects of gas overriding and displacement through the large cold zone.

Next, we will describe three in-situ combustion processes employing horizontal wells: Top/Down Combustion (TD-ISC), Toe to Heel Air Injection (THAI) and Combustion Override Split-production Horizontal-well (COSH). The first one is an example of down-dip in-situ combustion (Coates, 1995). The second one is a promissory process tested in laboratory and object of multiple simulation runs (Greaves, 1997). The third one is a proposed process not proved yet but has been tested in numerical simulators (Kisman, 1994).

Top/Down combustion – TD-ISC

The conceptual strategy of the top down in-situ combustion 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. Combustion is initialized and maintained by injection of an oxygen containing gas at the top of the reservoir, with mobilized oil draining to a lower horizontal producer well. Most of the injected oxygen is consumed in the high temperature combustion reactions at the combustion front. Oxygen that passes unreacted through the front reacts in lower temperature reactions to produce a layer of coke which is subsequently burned as the combustion front moves through. Hot combustion gases and thermally cracked light ends mix with the oil ahead of the high temperature front, heating, upgrading and driving the oil by a top down gas drive. Gravitational forces help drain the oil to the horizontal producer.

Although the top down process holds great promise, there are potential problems which must be addressed before it can be considered for the field. The high bitumen saturation and viscosity of virgin heavy oil reservoirs must be overcome to obtain initial injectivity. Methods to obtain injectivity need to be assessed as does the ability to successfully apply the process to reservoirs that have already been partially depleted by a previous recovery operation. The stable advancement of the combustion front through the reservoir and the efficient draining of the mobilized oil to the producing wells both need to be proven (Coates, 1995).

Toe-to-Heel Air Injection – THAI

THAI is a new combustion process for the in-situ recovery of bitumen and heavy oil that combines vertical air injector wells with horizontal producer wells. During the process air is injected at the top of the reservoir near the toe of the horizontal well creating a combustion front nearby to it. The combustion front sweeps the oil from the toe to the heel of the horizontal producing well recovering an estimated 80 percent of the original oil-in-place (Greaves, 2000).

The created hot combustion gases mix with the oil, moving it ahead of the front, reducing its viscosity and upgrading it through thermal cracking reactions, then combustion gases, mobilized and upgraded oil, and steam are drained via gravity and differential pressure into the horizontal well located at the base of the formation. Fluids are moved to the surface via combustion gas lift, eliminating the need for artificial lift. Coke, is left behind the moveable oil thus providing the fuel to sustain the combustion front. The process (schematized in Figure 1) operates stably and continually.

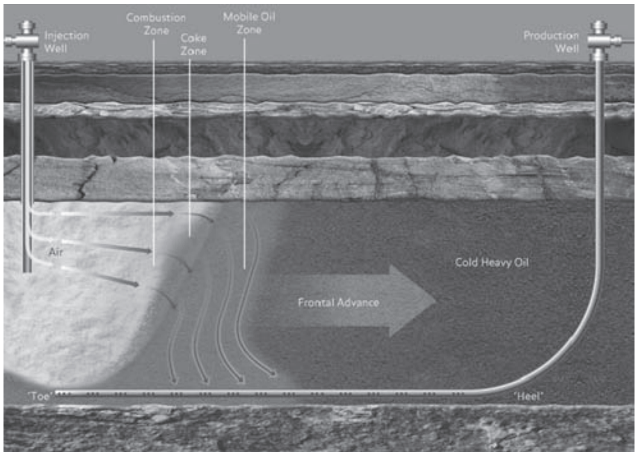

Figure 1. Schematic of Toe to Heel Air Injection – THAI (www.petrobank.com)

THAI has many potential benefits, including lower production cost per unit, minimal need to burn natural gas, minimal use of fresh water, reduction or elimination of diluents for transportation, a partially upgraded crude oil product at the wellhead, and lower greenhouse gas emissions. THAI also has the potential to operate in lower pressure, lower quality, thinner and deeper reservoirs than current steam-based processes.

COSH process

The COSH process was performed to combine the beneficial features of gravity drainage and horizontal producer wells. A gas containing oxygen is injected into vertical injector wells, most of the combustion gases are produced by the gas producer wells; while oil and water are produced by the horizontal producer well, as appear in Figure 2. A hot gas chamber is formed around the vertical injector well (similar to that of SAGD process). This hot gas-chamber is formed by steam, injected and combustion gases. Here, gravity drainage is the principal mechanism for the heated oil mobilization to the horizontal producer well. The producer wells are completed near the top of the reservoir initially. Although the main function of these wells is to collect the combustion gases, they may also be used to produce oil.

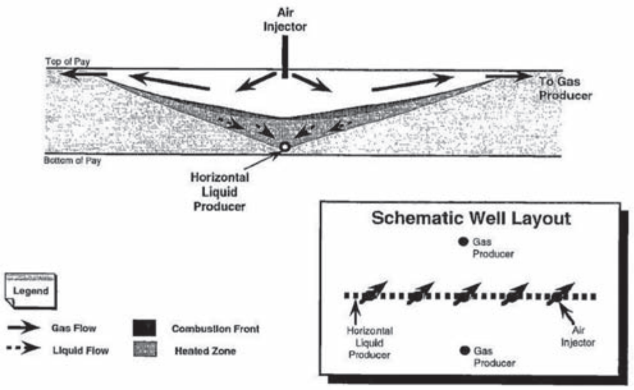

Figure 2. Schematic COSH process diagram

There is no experimental study on the COSH process. The first simulation study was conducted by Kisman and Lau in 1994 using CMG's STARS simulator to verify the physical sources used in the COSH design and to evaluate the potential of COSH by comparing its performance to that of SAGD. The COSH process provided better recovery than standard combustion processes and was less sensitive to oil composition and combustion kinetics.

SEGREGATED IN-SITU COMBUSTION PROCESSES

TD-ISC, THAI and COSH are essentially segregated *in-situ* combustion processes. In them, a gas chamber exists along the horizontal wells, whose size depends on well spacing and injection rates. In these processes, the combustion front overriding occurs, without affecting the process development.

Overriding of the combustion front

Generally, during the injection process, air tries to override the reservoir fluids causing its channeling until reaching the producing wells (this would generate a dangerous situation). For this reason an 'overburn' phenomenon occurs in almost every fireflooding process, which is described as the combustion process occurred at the upper section of the oil bearing formation. This effect is undesirable because it would reduce the project lifetime and swept efficiencies, possibly damaging the well completions, among other inconveniences (Gates, 1958).

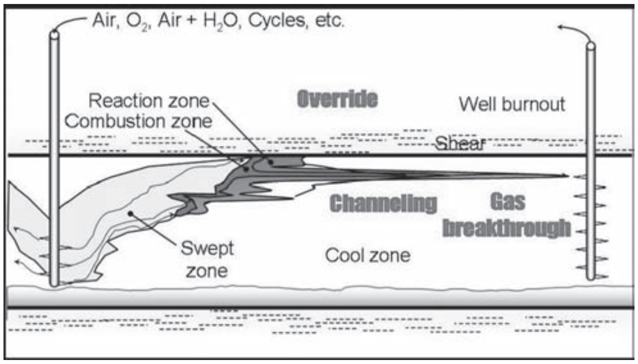

Figure 3. Overriding phenomenon (Bypass) of the combustion front ("Improving the base development case" – DTI heavy oil seminar, 25 November 2004, Aberdeen)

The overriding or overburn phenomenon presented in Figure 3 is pronounced when unfavorable conditions exist, which include: thick reservoirs containing a high viscosity oil, existence of a gas cap and high air injection rates; just to mention a few factors. The phenomenon is practically unavoidable; however it could be advantageous at the time to generate a segregated in-situ combustion process, similar to that observed by Binder (1977).

This phenomenon implies serious disadvantages, as follows:

1. Lower volumetric swept efficiency.

2. A substantial reduction in the rupture time of the heat front.

3. It implies the manipulation of hot wells (these are producer wells affected by the thermal front breakthrough).

The first disadvantage is solved if air injection is made at the top of the formation, obtaining so a vertical fluid displacement. The next two problems are solved by the fluid production through horizontal wells, which is the fundament of the new ISC technologies.

A segregated ISC process is schematized in Figures 4 and 5. Figure 4 represents a process applicable in thick structures and Figure 5 a process developed down-dip (a TD-ISC process), both having the vertical injection wells completed near de top of the structure and the horizontal producer wells located at the base of the oil zone. Here, fluids are displaced both in vertical and horizontal directions.

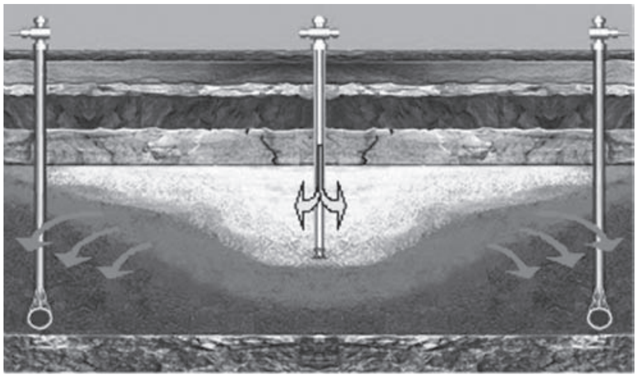

Figure 4. Scheme of a segregated in-situ combustion process

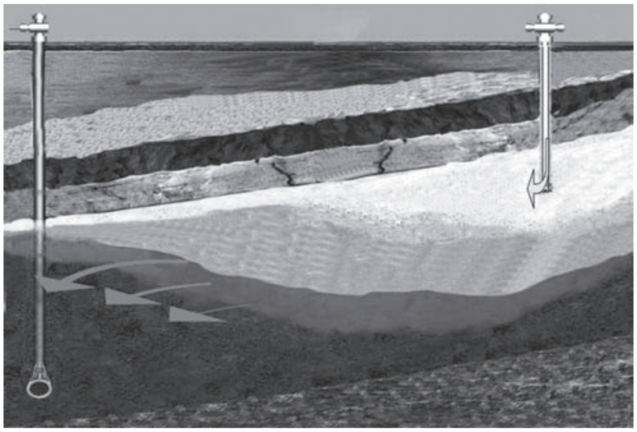

Figure 5. Scheme of a down-dip in-situ combustion process

A segregated ISC process would have the following advantages:

- Domain of the combustion front.
- It could be applicable in very thick sands.
- It could be applicable in high API gravity oils.
- It could allow high air injection rates.
- It reduces consistently the project lifetime
- Higher production rates that the forward combustion and other thermal processes.
- It increases the air-fuel contact area and therefore the heat flux.
- Higher swept efficiencies.
- It could be analyzed like a vertical piston effect (as proposed here).
- It isn't affected by the existence of an aquifer (being this active or not).
- It could incorporate the pressure maintenance effect.

Some disadvantages would be:

- It requires quantities of air quite higher than in the forward combustion case (this means big plants, compressors and gas disposal facilities).
- It requires homogeneous formations without shale intercalations.
- It requires very good vertical permeability.
- The injected air requires to travel considerably high distances through the formation (probably preventing the self-sustained combustion).
- It requires high injection pressures and therefore the formation must have high fracture pressures.

Process development and modeling

In a segregated in-situ combustion process, air is injected at a constant rate at the top of the oil sand, creating a thin gas cap that reacts with the residual oil left behind the combustion surface. The gas layer and combustion surface will continue expanding downward across the formation as the air is injected, displacing fluids toward the producer wells, located as near as possible to the sand base. This kind o processes was studied previously (Khelil, 1969). In the segregated in-situ combustion processes the combustion front is a large quasi-horizontal surface, which requires of high air injection rates to sustain the combustion front at its external edge. The front should penetrate at the lowest as possible velocity without engaging the self sustained combustion (this is a minimum velocity of 0,2 ft/day, which corresponds to the minimum air flux required of 1,6 scf/ft2-hr). On the other hand, reaching higher velocities will require of higher air injection rates that often are difficult to obtain, basically because of the well injectivity (Nelson, 1961). The process key is creating a low velocity, homogeneous and stable horizontal combustion surface which will advance from the top of the layer, displacing the formation fluids downward until reaching the producer wells.

The process involves additional phenomena to the sweeping action of the front, they are:

- The pressure maintenance effect characteristic of the formed gas cap will be responsible of great part of the production answer (Benton, 1983 and Gates, 1971, presented a similar conclusion in two studies carried out in West Heidelberg and Midway Sunset fields).
- The gravity drainage resulting from formed gases, distillation of light oil fractions and creation of multiple fluid phases of different mobility ratios and densities. These phases will cause the fluid segregation and the consequent drainage toward the producer wells.

- The thermal stimulation that will experience the producer wells when oil viscosity of the heated drainage area is reduced (increasing so the well productivity).

As the reservoir warms, the flow of fluids becomes less restricted, the production is increased and the pressure drop between the combustion front and the producer wells becomes less drastic. In this kind of processes air flux will be high at the wellbore proximities, decreasing notably at the external border. This makes the front being a curved surface quite similar to a hyperbola; this is, at the beginning, the combustion zone has a vertical shape, then it tends to conifying and later it tries to stabilize in a quasi-horizontal surface when the firefront has descended some feet across the formation (Figure 6).

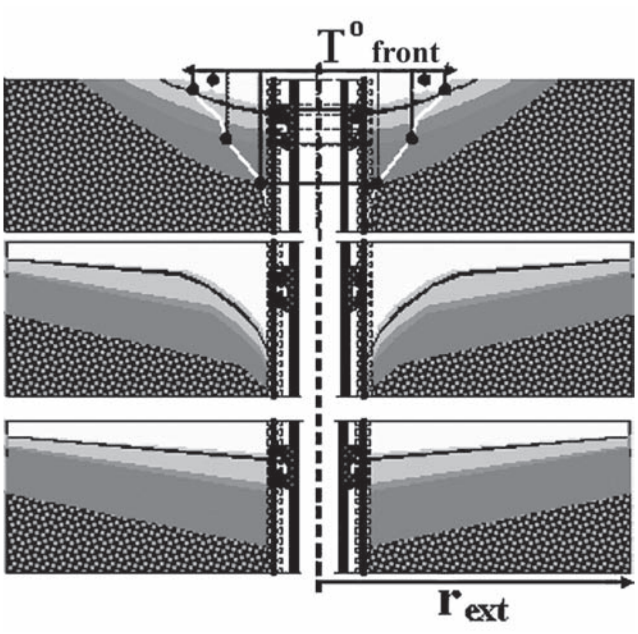

Figure 6. Stabilization of the combustion front with the process advance

Process variables

The basic variables involved in the calculus of a segregated in-situ combustion process include: fuel content, air requirements, front geometry and minimum air injection rates. With these variables it is possible to evaluate parameters like: air-oil ratio, shape and advance of combustion front, volume of formed and produced fluids, incremental oil recovery factor, extinction radius, economics and general performance.

The residual oil or coke corresponds to the fraction of oil left behind the steam and cracking zones, this is used as fuel and depends exclusively on oil composition and rock properties (Alexander, 1962). Air requirements are related to fuel composition, combustion and volumetric swept efficiencies (Dew, 1964). The segregated ISC processes when applied starting at the top of the formation implies a pattern confining, reason why the injected air efficiency is higher than in the conventional ISC processes.

Air injection rate depends on the minimum air flux required to reach the self-sustained combustion (Martin, 1958), which is function of the firefront radius 'r_f' and the injection rate to standard conditions 'q_A'. Once the geometry of the combustion front is known (or at least presumed) it's not complicated predicting when flow decays below the minimum air flux which has been reported as low as 1,0 scf/ft2-hr. Additionally, it must be pointed out that air injection rate depends on the well injectivity too and a critical value of air flux

Table 1. Segregated ISC model – general assumptions

Medium homogeneous, continuous and isotropic
There is no initial gas cap in the reservoir
The system is closed and there's no storage (pattern 100% confined)
All the injected air is used in High Temperature Oxidation reactions–HTO
Auto ignition occurs immediately after air injection starting
The combustion front is flat and circular
The horizontal well produces along the whole horizontal section
Front velocity is constant
Production is only due to the front sweeping
The formation can take the whole injected air
There's no air flux neither combustion beyond the external edge - r_{ext}
The combustion front consumes all the fuel, overcoming to the entire drainage area
Air flux is constant across the combustion surface
The temperature at the combustion front has a constant value of 750° F
The conifying effect will never occur at the horizontal producing wells

above which the combustion reaction loose efficiency. Modeling this kind of processes requires some assumptions, like those presented in Table 1.

Heat and oxygen fluxes at the external edge will be probably too poor, possibly creating there an inefficient combustion reaction. Nevertheless, for the planning of the proposed model it has been supposed that air flux at the external border is essentially the same that in the injection well proximities. This approach will be valid if the horizontal reservoir permeability is very high (Figure 7 shows a physical model for this approach).

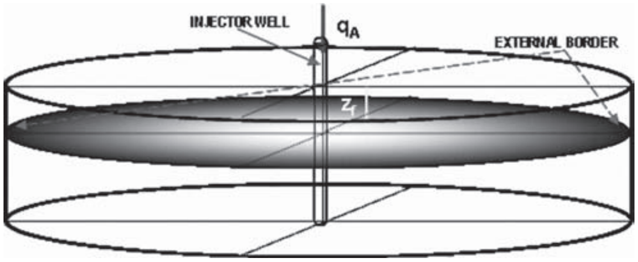

Figure 7. Idealized horizontal combustion front displacement

PROCESS MODELLING

The general assumptions presented in Table 1 resume all the characteristics needed for the creation of an analytic model of the process which is initially based on results reached from field and laboratory experiments and studies, such as those developed by Gates and Ramey (1958) who determined a response for the produced oil; and the investigations developed by Martin (1958), Alexander (1962), Showalter (1963) and Orkiszewski (1968), referent to the fuel consumption and air requirements. Additionally, an injection pressure equation for the new process configuration was derived from the Nelson and McNiel studies (1961).

The references here presented are the basis of the ISC theory. From these studies was carried out a model whose equations involve mass and heat transfer. The main variables are related to fuel deposition, air requirements and minimum air flux. The fuel deposition "F_C" is related to reservoir temperature and oil density as it shows the *Equations 1, 2* and *3*.

$$\overline{F_C} = F_1 + F_2 \tag{1}$$

Where:

$$F_1 = -0,00008\,(°API)^3 + 0,0059\,(°API)^2 - 0,1623\,(°API) + 2,1813 \tag{2}$$

$$F_2 = 6,9342\,(T°)^{-0,5105} \tag{3}$$

The deposited fuel is the sum of these two contributions; the first one is the contribution of the combustion reactions and the second one is the contribution of the natural residue. Once the parameters F_1 and F_2 have been obtained, F_C is calculated first in "$lb_{fuel}\,/ft^3{}_{rock}$" (*Equation 5*).

$$F_C = \overline{F_C}\,(1-\phi)\,\rho_R \tag{4}$$

The air requirement is expressed in MMSCF/acre-ft, and is defined by the relation:

$$A_i = \frac{78.626\rho_R \overline{F_C}(1-\phi)(1+\frac{n}{4})}{(n+12)\varepsilon} \tag{5}$$

The front velocity is related to air flux and air requirements by the *Equation 6*. All these variables depend on the minimum temperature required to sustain an active combustion process which has been reported experimentally as 750 °F.

$$V_f = 1,04544 * 10^6\ \Phi_f / A_i, \quad [ft/D] \tag{6}$$

INJECTION/PRODUCTION RESPONSE

Gates and Ramey (1980) proposed a simple method to calculate the oil recovery obtained from an ISC process. This approximation depends essentially on the burned volume and initial gas saturation. The method is sensitive to each case; however is a good approach of what one could expect. The correlation depends on factors like initial oil and gas saturations and fuel concentration. The equations allow us to construct a curve 'VB vs OR', from which it's possible to develop the whole analysis. The parameters are presented next.

$$OR = 100\,X + Y\,MD \tag{7}$$

Where ‘X’, ‘Y’ y ‘MD’ correspond to:

$$X = [VB - VBo] / [100 - VBo] \tag{8}$$

$$VBo = 0.1474\ Sgi + 0{,}01071\ Sgi2 \tag{9}$$

$$\begin{aligned} Y &= 6{,}7752\ X - 15{,}9478\ X2 \\ &+ 16{,}1872\ X3 - 7{,}0146\ X4 \end{aligned} \tag{10}$$

$$MD = 26{,}82295 – 0{,}46787\ Sgi \tag{11}$$

The production schedule is constructed by relating burned volume ‘VB’, time ‘t’ and oil recovery ‘OR’, with the *Equations 12* to *21*.

$$N_P = \frac{(OR)S_{OM}Ah}{100} \tag{12}$$

Where:

$$SoM = Soi - Sof \tag{13}$$

$$Sof = 7758\ FC / \rho F \tag{14}$$

Finally, we obtain the relation:

$$N_P = \frac{(OR)\left(S_{oi} - 7758\, {}^{F_C}\!\!/_{\rho_F}\right)Ah}{100} \tag{15}$$

The instant oil rate is calculated from the graph “NP vs t”, according to:

$$(q_o)_i = \frac{\Delta N_p}{\Delta t} = \frac{dN_p}{dt} \tag{16}$$

The burned volume can be defined as:

$$V_b = \frac{q_A t}{A_i} \tag{17}$$

The pattern volume is:

$$V_{pattern} = A\ h \tag{18}$$

Then:

$$VB = \frac{100 q_A t}{A_i (Ah)} \tag{19}$$

Once the model has been adapted to the reservoir geometry, it’s possible getting an injection/production schedule of the process. The main consideration is that the air injection rate increases gradually as the front go through the formation. Therefore, the production increases as the combustion front and the burned volume increase.

An equation relating geometry, injection rate and burned volume at different times is presented next. Before anything, it’s important noting that this equation has been adapted for a defined pattern geometry, which in this case corresponds to a process applied at the crest of an anticline structure.

$$q_A = 24\pi \left(\frac{V_f t}{\tan\theta_b} \right)^2 \Phi_{A,\min} = \left(\frac{24\pi V_f{}^2 \Phi_{A,\min}}{\tan^2\theta_b} \right) * t^2 \quad \text{[SCF/D]} \tag{20}$$

$$(q_o)_i = \frac{\left[\left(OR_{(t)} - OR_{(t-1)} \right) * \left(S_{oi} - 7758\, {}^{F_C}\!\!/_{\rho_F} \right) \right] Ah}{100 * \left[(t) - (t-1) \right]} \quad \text{[STB/D]} \tag{21}$$

Where OR(t) and OR(t+1) represent the oil recovery reached at ‘t’ and ‘t+1’ times. These values are obtained with the Gates and Ramey correlation.

Once air injection rate has been determined, it is possible to calculate the required injection pressure. An equation adapted from the Nelson and McNiel studies (1961) is proposed below.

$$P_{iw}{}^2 = P_{wf}{}^2 + \frac{q_g \mu_g (T + 460)}{0.703 k_g z_f} * \left[Ln\left(\frac{r_{ext}{}^2}{r_w V_f t_1} \right) - 1.238 \right] \tag{22}$$

Where:

$$t_1 = \frac{q_g}{\pi z_f V_f{}^2 A_i} \tag{23}$$

These equations can be integrated in a spreadsheet to evaluate the general performance of the process. Other operative and technical parameters that should be treated include: ignition process, air-oil ratios, heat transference, temperature profiles, sweep efficiency, gas breakthrough and economics (a more detailed description is presented in Guerra, 2003).

Farther down the theoretical response of a segregated ISC process has been made for the Castilla field case. This field has desirable conditions for the process development.

THERMAL FRONT DETECTION

In general, segregated ISC processes have the qualities of an immiscible displacement process (like a crestal gas injection) with the near miscibility of the fluids which are being injected at high pressures. Furthermore, the thermal component of the combustion process gives to it the capacity of recovering additional oil due to the thermal stimulation phenomenon. The proposed model requires determining when the thermal front arrives to the horizontal well. This parameter will determine the technical limit of the project and will let us regulate the injection and production rates previously to the air injection shut-in. Miller (1985) proposed a relationship between cold oil production and thermal oil production. The *Equation 24* allows the prediction of the moment in which the front reaches the horizontal well.

$$\frac{q_o}{q_{oi}} = \frac{\mu_{oi}}{h_i} \int_{h_b}^{h-h_b} \frac{dz}{\mu_o} = \frac{\mu_{oi}}{h_i} \sum_{0}^{h_o} \frac{\Delta z}{\mu_o} \tag{24}$$

The previous equation relates the oil production prior to the thermal stimulation effect on the oil production once the thermal front approaches the horizontal well. When the firefront is near to the horizontal well, the oil production suffers a sudden increase due to the reduced oil viscosity and the stability of the reservoir pressure. In fact, the *Equation 24* is transformed in the *Equation 25*, which can be easily solved for not depleted reservoirs under steady or pseudo-steady state simply by taking a viscosity-temperature function and varying appropriately the parameter "oil bearing formation thickness - h_o".

$$\frac{q_o}{q_{oi}} = \frac{\mu_{oi}}{h_i \mu_o(T)} \int_{h_b}^{h-h_b} dz = \frac{\mu_{oi}}{h_i \mu_o(T)} \sum_{0}^{h_o} \Delta z = \frac{\mu_{oi} h_o}{h_i \mu_o(T)} \tag{25}$$

The last equation gives a response similar to that shown in Figure 8 where it is reflected the thermal effect produced on a horizontal well which at the start of the ISC process produce 1000 STB/D of oil under steady state conditions. However, 500 days after initiated the process, the front approaches to the horizontal leg in such a way that oil viscosity is notoriously reduced and therefore, oil fractional flow is rapidly increased.

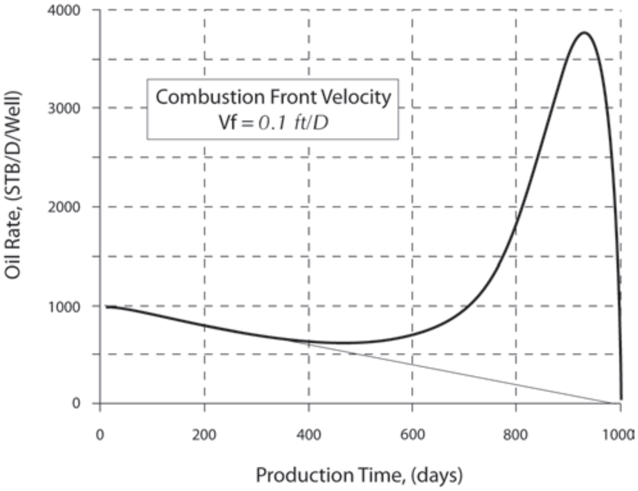

Figure 8. Incremental oil production due to the thermal front arrival

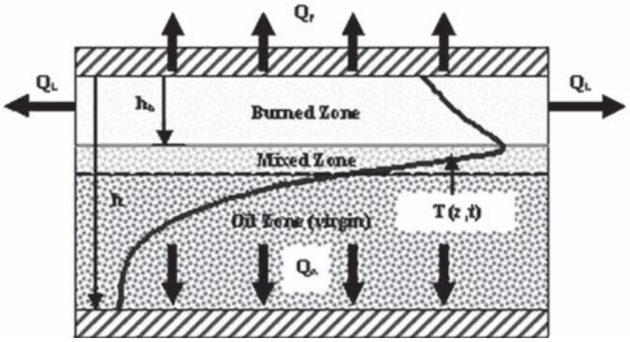

Figure 9. Distribution of the zones in the model

The model schematized in Figure 9 assumes that viscosity reduction of oil located below the combustion front is completely caused by the rock and fluid heating. Here, the heating source corresponds to a constant temperature overriding combustion surface. The mixed zone corresponds to the flux of volatile and condensed phases of oil and water and it should be treated by a multiphase flow study. Here, however, this zone is considered to be negligible.

APPLICATION CASE

As previously stated, the ISC processes have been conceived for the recovery of heavy oils; however a segregated ISC process could be applied in medium and light oils like High Pressure Air Injection process (HPAI), as proposed by Koch Exploration Co. in multiple air injection projects developed in USA (Kumar, 1995). Then, a process of this nature should include analysis of miscible and immiscible displacement; however, in the present study this more complete analysis won't be taken into account and just will be considered the incremental oil recovery due to the thermal component of the Process.

Castilla field has been considered for the present analysis. This field is located near the Colombian foothills. The reservoir has two main producer bodies: the Upper Guadalupe and Massive Guadalupe formations. There are many differences between them, but for the purpose of this study the more outstanding are permeability and formation thickness. These parameters are essential to decide about the applicability of a segregated ISC process. The high permeability and thickness of Massive Guadalupe makes it appropriated for the process development. Even, the low oil viscosity favors the fluid displacement in the cold virgin zone.

The analytical model created was employed to describe the process performance. Table 2 shows the most important parameters involved. The formation corresponds to an anticline structure faulted at west. The process is established by a row of 7 injectors, located at the top of the structure and two producer wells, located downdip to approximately 700 ft from the injector wells. The pattern developed has an area of 46 acres and just one pilot pattern was considered for the calculations.

Table 2. Reservoir and fluid properties

Reservoir pressure	P_R	2800 psi
Reservoir temperature	T_R	200 °F
Mean porosity	$\varnothing$	19,5 %
Initial oil saturation	Soi	90 %
Api oil gravity	°API	13,5 °API
Reservoir mean depth	h_m	6500 ft
Wellbore radius	r_w	0,25 ft
Air permeability	k_A	35 md
Initial gas saturation	Sgi	0 %
Initial water saturation	Swi	10 %
Fuel density	ρ_{of}	62,4 lf/ft^3

Table 3. Preliminary results

Fuel concentration	S_{of}	16,5 %
Air requirements	A_I	14,1 MMSCF/ac-ft
Air/oil ratio	R_{AO}	13,7 MSCF/STB
Fuel saturation	S_{of}	216 BBL/ac-ft
Combustion surface	A_C	46,2 acres
Initial oil saturation	S_o	1307 BBL/ac-ft
Eor recovery factor	FR_{real}	41,68 %
Final recovery factor	FR_{real}	49,68 %
Operation time	t	2500 d
Minimum air flux	υ_{min}	1,35 SCF/ft^2-hr
Max. Air injection rate	$q_{A\ max}$	64,92 MMSCF/D

Some calculated parameters are shown in Table 3. The fuel content is one of the most important parameters, especially in this case, where its value is high with respect to other ISC projects. The reason for this is the low sand porosity (18-22%) and the low oil gravity (13,5ºAPI) in spite of the high initial oil saturation (92%). Although fuel saturation reaches almost 17% OIP (another ISC process presents fuel saturations around 10%), the process still could be profitable. Also, it is possible to inject water as a combined thermal drive

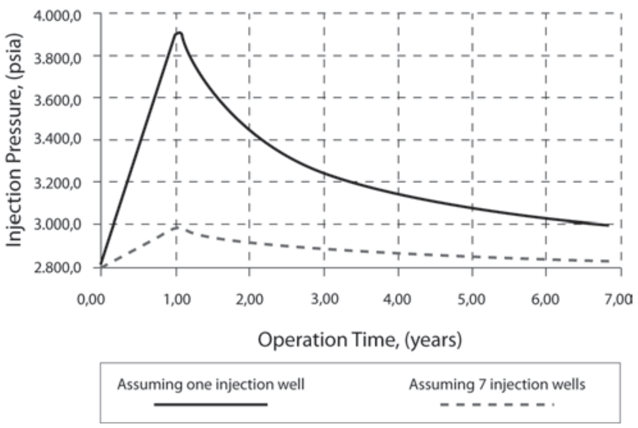

Figure 10. Injection pressure schedule

process, reducing so the air requirements and hence the power costs on surface.

The process requires injecting air to 64 MMSCF/D divided among seven injection wells, each one injecting approximately 9 MMSCF/D/well (this value is high in comparison with normal air injection rates). Since a process of this nature has a big combustion surface, it is required large air volumes to sustain the High Temperature Oxidation (HTO) reactions. Also, these injection rates require of higher air injection pressures which in this case are no problem, mainly because of the high formation fracture pressure. The peak pressure required to supply an air flux of 1,35 SCF/ft^2-hr across a combustion surface of 6,6 acres for each injection well is about 3000 psi. This pressure is reached about a year after process beginning, when combustion front is close to the wellbore and fluid saturations across the pattern are near the original ones. Figure 10 shows the pressure profile required to satisfy the air requirements.

Oil recovery is shown in Figure 11. Here, the final recovery almost reaches the 50% (the expected primary oil recovery will reach 8% approximately) with a process efficiency of 57%. This recovery is achieved when the front has descended 250 ft across the formation seven years after process starting, approximately. The vertical and areal sweep efficiencies were determined from statistical results obtained from numerous field projects. In general it was observed that projects where the process was propagated down-dip reached higher swept efficiencies than those operated in a conventional way. It's really important to get an excellent approximation of this value.

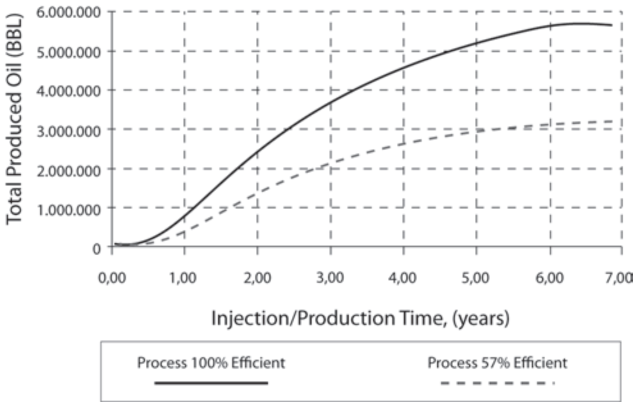

Figure 11. Oil cumulative recovery at two process efficiencies

Again, it's important to clarify that the production response is only due to thermal front expansion (this corresponds to an ISC process) and no other phenomena were considered in the calculus. For simplicity, it is assumed that auto ignition occurs in this project, mainly due to the high Asphaltic content of the crude and the high temperature of the reservoir; however it is recognized that only a laboratory test can resolve this query. Therefore, the problems inherent to the ignition and self-sustained combustion are not considered here.

The reservoir response is considered under an efficiency of 57%, which corresponds to a vertical sweep of 95% and an areal sweep of 60% (Figure 12). Another alternative to determine sweep, could involve the consideration of a segregated inert gas injection system conformed by the injected and formed fluids. In such system,

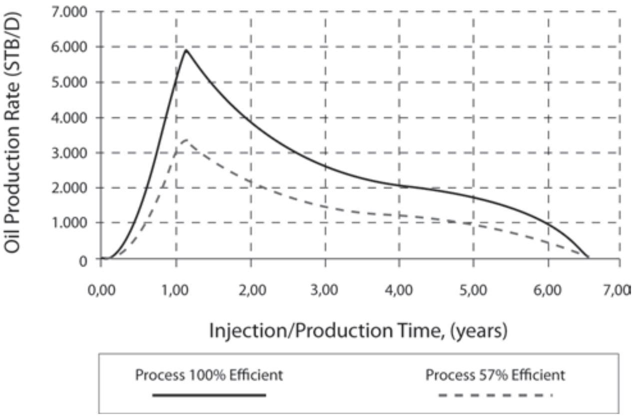

Figure 12. Oil production rate per horizontal well for two process efficiencies

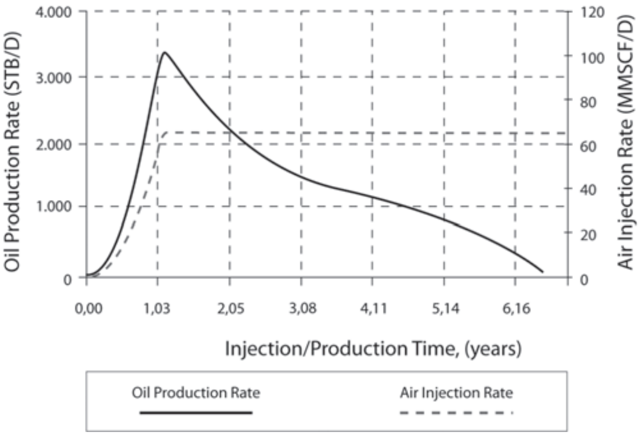

Figure 13. Total air injection rate and oil production per horizontal well

the injected gases react with the deposited fuel, sweeping the formed oil-water mixture. These considerations would imply the analysis of fractional and multiphase flow, however, for simplicity, this will be obviated again.

As presented in Figure 13, the average oil production corresponds to 1360 STB/D/well (this corresponds to 2720 STB/D for a pattern conformed by two horizontal wells). This response is essentially due to the combustion process, although it's important clarifying that actual oil production rates ranges between 2000-3000 STB/D according to each well, so that the here proposed process could increase the oil production by 50%, minimizing the water cut and sweeping the attic oil.

FINAL REMARKS

The process could be implemented in this field as an incremental recovery program; however, actually this is unnecessary because of the high reached production rates. It will take some time before the production decays enough as to consider the implementation of any enhanced oil recovery program.

Finally, three important aspects should be stood out. The first one has to do with the strong water drive experimented in the Castilla field case. Although this is the main driving force, a process of double displacement assisted by ISC, probably will increase the oil production avoiding the rapid water breakthrough and would sweep in a more efficient way the attic oil.

The second one has to do with the general results presented here (oil production, air injection rates and other operative parameters). It must be recognized that a complete analysis of the process should include information about the thermal front distribution, the miscible and immiscible components of the displacement process, laboratory tests and simulation runs; therefore this paper only pretends to present the basis of the calculus, focused on a Segregated ISC process similar to those presented initially. The last one has to do with the disposition and treatment on surface of produced gases. This is usually the fact that determines the technical limit of ISC projects. In the particular case outlined in this paper, high flue gas volumes are expected at the downstream. Probably, it will be required high investments in treatment facilities which will reduce notably the profitability of this kind of processes. Therefore, a perfect balance between compression and gas processing facilities should be had into account.

CONCLUSIONS

- Horizontal producer wells favor the segregated combustion processes, producing the oil located below an overriding combustion surface and delaying the air breakthrough.
- The segregated ISC processes take advantage of phenomena like the gravity segregation and the gas-cap expansion to stabilize the combustion surface, increasing so the sweep efficiencies and d combustion front size.
- Castilla field appears to be a good candidate for air injection processes, however, it must be established first, the influence of each driving mechanisms on the ISC process. It shouldn't be estrange to get a multiple displacement process formed by a Thermal Front, Gas cap and Aquifer Expansion. Probably, a process of this nature would have a better performance; however, it will be more difficult to model it too.

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