Influence of air injection rate in the combustion process

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Extended abstract to obtain the Master Degree in

Petroleum Engineering

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July of 2014

1. Abstract

In-situ combustion consists in oxidation reactions promoted by the injection of oxygen inside the reservoir. If the reservoir temperature exceeds a specific temperature, oil and oxygen react and from this chemical reaction there is the release of a high amount of heat energy, designated by combustion front. The heat generated induces a decrease of the oil viscosity, and consequently its mobility. Also this heat is responsible to convert heavy fractions of oil into fuel, and the production and consumption of fuel along the reservoir allows the propagation of the combustion front from the injector wells to the produced wells.

In order to understand the combustion process and evaluate oil combustion behaviour for a specific reservoir it is commonly performed combustion tube tests. From these experimental tests parameters such as chemical reaction stoichiometry, air requirement, fuel consumed and combustion front velocity are estimated. However it does not provide information about the kinetic model that describes it.

This study aimed to evaluate the influence of air injection rate on the combustion process and effect of heat transference through the wall of the combustion tube to the mixture. Four tests were performed in the combustion tube using different air injection rates and it was used a heavy oil from a Brazilian field (15 °API). The analysis of the results was based on the combustion conventional parameters, in the combustion front velocity and on the growth of the steam zone. It was observed that with the increasing of the air injection rate the velocity of the combustion front was higher and there was an early production of fluids. Another result observed was an increasing of the light composition on the produced oil and, consequently, the upgrading of the heavy crude oil. By the increasing of the air injection rates, and hence the combustion front velocity, there was a decrease in the speed and length of the steam plateau, resulted of the lower contribution of the heat transference from the tube wall to the mixture. The thermal conductivity of the tube material is higher than the heat transference rate inside the mixture, so as higher the combustion front speed, lower will be the influence of heat transference from the tube to the mixture.

Numerical models can simulate these experiments in order to predict combustion behaviour in pilot or field scale.

Key words: in-situ combustion; combustion tube, thermal simulator, heat transfer

2. Introduction

The constant demand for oil has resulted in the exploitation of fields where the quality of the oil is greater or where extraction is easier. For many years the oil industry faced the exploitation of reservoirs with heavier oils as the "era" after the exploitation of oil fields of medium and light oils. However, with the emergence of large reserves of *shale gas* and the pre-salt, where the quality of the oil is higher, oil companies moved into these projects, leaving again the focus on the exploitation of heavy oil fields.

Despite the heavy oil fields are considered as *backup* solution, it is important to note that conventional oil reserves constitute approximately 30% of world reserves, with the remainder split between heavy oils (15%), extra-heavy oils (25%) and bitumen (30%), so that the exploration of these fields will be part of the portfolio of oil companies' reserves (Schlumberger).

In mature fields or in fields with the presence of high-viscosity oils, secondary recovery methods may be somewhat effective, it is necessary to implement the increase of the reservoir's energy through modifying its properties and/or the properties of existing fluids. The main enhanced recovery methods focus on increasing the efficiency of the displacement of the fluids within the reservoir. When the viscosity of the injected fluid is lower than the oil in place, the fluid can find preferred porous paths to the producing wells without causing displacement of the remaining oil in a satisfactory and efficient manner. To overcome this problem can be carried out an increase of the water viscosity or decrease the oil viscosity. Enhanced recovery methods are grouped into three distinct groups: miscible methods; chemical/biological methods; and thermal methods.

The present paper is dedicated to a detailed study of one of the enhanced recovery method: in-situ combustion (ISC), and particularly in the influence of the air injection rate in the process. It was proposed a set of experimental tests increasing the rate of injection of air, which consequently causes an increase of the speed of the combustion front. Thus, four trials were conducted where did vary the rate of air injection (2.5 L/min 3.0 L/min 3.3 L/min and 3.8 L/min).

3. Theoretical fundamentals

The process of in-situ combustion falls in thermal recovery methods where energy is used on the form of heat in order to change the viscosity of the oil in place. However, other effects resulting from this process benefit the increasing of oil recovery, like the distillation of oil with the vaporization of lighter fractions and formation expansion creates a kind of displacement which is miscible blends with the thermal methods. The oil expansion caused by increase of temperature has also an influence on the increasing of oil recovery.

The oil temperature has a large effect on its viscosity, so that when oil is subjected to a temperature increase is observed a sharp decrease on its viscosity. This relationship between temperature and viscosity is more pronounced for more viscous oils in their initial conditions.

There are several thermal methods, however it is common to make a classification according to the source of energy: hot fluids injection methods (water or steam), where thermal energy is generated at the surface and injected into the reservoir; and *in-situ* combustion, where power is generated inside the reservoir by the oxidation of oxygen.

Hot fluids injection methods have some drawbacks due to the *in-situ* combustion: its application is limited to the maximum depth of the reservoir (approximately 900 meters, because the heat losses recorded from this depth hamper the oil heating); and injection methods require the installation of large surface infrastructure and so it would be difficult to accommodate it in *offshore* fields. However, the major advantage of *in-situ* combustion is that by utilizing the energy generated inside the reservoir it will be considerably higher than the heat energy carried by the injected fluids, with higher efficiency in terms of heat utilization and efficiency in drive mechanisms (Rodriguez, 2004). Despite the many advantages cited for the combustion process due to the methodology of injection fluids, and given the complexity of the combustion process other recovery processes are inherent in lower operational risks and therefore are frequently used.

3.1. In-situ combustion

In-situ Combustion process is not more than a combustion reaction where air is injected in the reservoir and in the presence of an ignition source, a fuel, in this case the oil in place undergoes oxidation releasing heat energy. The peak temperature that is released is called a combustion front. Other reactions occur together to form fuel that is responsible for the chain reaction, allowing the combustion front scrolls the reservoir from the injection wells to the production wells.

Ignition of oil can occur spontaneously if the natural temperature of the reservoir is sufficient to promote oil ignition and when the oil is sufficiently reactive. The complexity of this process of enhanced recovery due to combined effects movement of steam, heat transfer, chemical reactions with high complexity of reaction kinetics dependent of temperature and pressure, among others, rise a misconception about its low probability of success. In reality, the combustion process is an economically attractive recovery method and proved to be economically able to recover a large fraction of oil *in place* (White, 1983).

During the combustion process can be featured distinct zones between the injection and the produced wells, where it occurs predominantly a set of chemical and/or transport phenomena of heat and mass transfer reactions. In Figure 1 a simplified scheme of these areas in a reservoir is presented. In reality in field described zones may appear overlapping or in different sequences. From those areas it should be made special reference to three: the front combustion zone, the thermal cracking zone and the steam plateau. The zones of combustion and thermal cracking are characterized by the occurrence of a series of reactions predominate each, and that will be studied later in more detail when studying these reactions. The steam plateau is particularly important because it is considered by some authors as functioning as production mechanism in the combustion process.

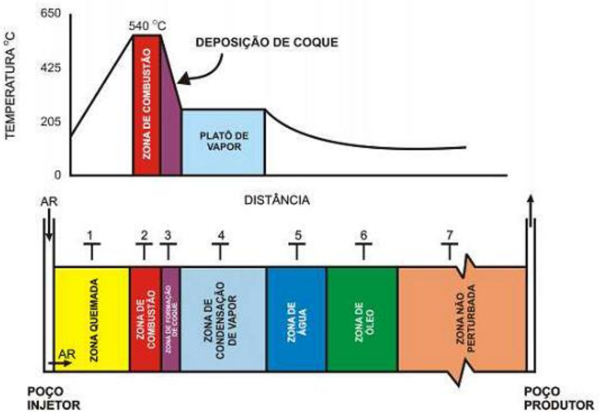


Figure 1 - Profile of temperature and saturation in different zones of the reservoir (Gonçalves, 2010)

The process of in-situ combustion has some variants:

- Dry or wet Combustion, depending if whether or not simultaneous or alternating injection of water and air. In the dry combustion enriched air can be used, which despite the costs of the specialized plants which are necessary to increase the molar concentration of oxygen in the air, has the advantage of increasing the heat released by the combustion front, and greater is the miscibility of carbon dioxide in oil. In wet combustion can be improved oil recovery up to 25 % because the specific heat of water is much higher than the air, the so transport of heat by the combustion front is more efficient. However, this method is limited by the viscosity of the oil.
- Direct or reverse combustion, based on the direction of air injection due to the combustion front. In direct combustion,

also combustion front and the injected air move in the same direction and in the reverse combustion, combustion front progresses in the opposite direction to the direction of the injected air. Both processes were studied either by laboratory testing or by field tests, but the reverse combustion was never used in industrial projects (Rodriguez, 2004).

As mentioned above, the kinetic study of the chemical reactions involved in the combustion process is of great importance because they are responsible for the whole process dynamics, both in laboratory studies or the field phase. The success in the knowledge and understanding of *in-situ* combustion process is based on understanding the kinetic behavior of a set of chemical reactions that occur during the contact between oxygen and oil (Araújo, 2012).

The complexity of this process is associated with several phenomena: simultaneous heat and mass transport in a multiphase environment; numerous chemical oxidation reactions of the numerous components of oil that occur simultaneously; the reactive character depends on the nature of the oil-rock system, which also influences the temperature regime to be established (Costa Silva, 2001).

In order to simplify the analysis of these reactions, they were grouped into different regimes according to the temperature in the reservoir:

- Reactions of low oxidation temperature (*LOT*) are heterogeneous reactions (gas/liquid) which typically occur at temperatures below 350 °C and which depend largely on the nature of the oil. It is observed the formation of hydrocarbons having higher viscosity than the oil, but they also increase the reactivity of oil at high temperatures;
- Average temperature reactions (*OMT*), hydrocarbons react at a less rate with oxygen molecules occurring reactions of pyrolysis/cracking, where it is formed solid residue, coke, which will serve as fuel for the *HOT;*
- Reactions of high oxidation temperature (*HOT*), are heterogeneous and exothermic reactions, which occur above 350 °C and where there is a high oxygen consumption, since it reacts with the unoxidized oil. The combustion of the injected oxygen between the air and coke generates the necessary energy to sustain and propagate the combustion front (Chicuta, 2009).

The combustion tube tests do not allow to define the kinetic model, but provide enough data to establish the stoichiometry of chemical reactions, since this only depends on temperature, pressure and composition of the oil, and they can be reproduced in combustion tube tests (Sarathi, 1999). The stoichiometric coefficients of the reactions of cracking and oxidation are determined from the molar ratio of nitrogen, oxygen, oxide and carbon dioxide produced during the stable period of the combustion process.

3.2. Applicability of the method of in-situ combustion

Combustion can be applied in several types of reservoirs, but it is required a high knowledge of petrophysical properties of the reservoir and oil (Reid, 1996). Below is presented a set of properties that should be evaluated before the implementation of a process of *in-situ* combustion:

- Nature of Formation: the rock type is not important, since the matrix/oil system is sufficiently reactive to sustain combustion. Another important aspect is the existence of preferential paths since they are harmful because they prevent homogeneous there scanning the entire reservoir by combustion front;
- Depth: The depth should be large enough to ensure the containment of injected air in the reservoir. There is no depth limit, unless this may affect the injection pressure;
- Pressure: pressure may have implications on process economics, but does not affect technical aspects of combustion;
- Temperature: Temperature only affects the auto ignition process;
- Reservoir thickness: the thickness should be greater than about 4 meters to avoid excessive heat losses to the surrounding formations. Very thick formations may present sweep efficiency problems because of gravity override;
- Permeability: permeability shall be sufficient to ensure the flow of injected air. The air injectivity is especially important for heavy oil reservoirs;
- Porosity and oil saturation: These two properties have to be large enough to allow economic oil recovery;
- Nature of oil: In heavy oil projects, this should be readily oxidizable at laboratory experiments.

3.3. Combustion tube

The implementation of in-situ combustion projects in a field scale require a fairly rigorous preliminary techno-economic study and so it is required the knowledge of a set of parameters. One of the most suitable processes for this study involves conducting laboratory tests that allow the estimation some of these parameters. The combustion tube is a way to physically simulate a small volume of reservoir subjected to conditions which seek to replicate the some of the conditions existing on the reservoir.

Besides low costs and risks, another of the great advantages of carrying out laboratory tests, is that they allow performing the parameterization of reservoir properties, fluid or operating conditions. Thus, it can be inferred that the system's behavior by changing one of the properties, and thus to understand which properties are of greatest importance in the process.

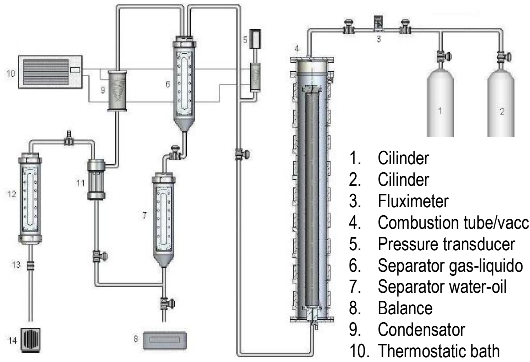
4. Methodology

4.1. Materials used in the mix

An infinitesimal volume portion of the reservoir was represented by a mixture of sand, clay, water and oil. The sand used was industrial sand JUNDU MINING LTD., with a particle size between 0.177 mm and 0.250 mm, washed and dried in the oven and the clay employed was BENT CREAM 331/325 of BrasilMinas composed by bentonite. The fluids used were distilled water and a heavy oil (15.03 API), from the Espirito Santo Basin. To represent the initial reservoir conditions saturations 50 % oil, 25 % water and 25 % gas were used.

4.2. Experimental apparatus

The experimental apparatus for testing in-situ combustion consists on a set of specific systems: air injection system, combustion tube and vacuum jacket, production fluids system, gas analysis system, and a system of data control, on which it was used Elypse SCADA software. In Figure 2 is presented a scheme of the equipment used on the experimental apparatus.



1. Cilinder
2. Cilinder
3. Fluximeter
4. Combustion tube/vaccum jacket
5. Pressure transducer
6. Separator gas-liquido
7. Separator water-oil
8. Balance
9. Condensator
10. Thermostatic bath
11. Purgator
12. Dissecator
13. Filter
14. Gasometer

Figure 2 - Experimantal apparatus (Gonçalves, 2010)

4.3. Experimental Design

Four experimental trials were performed and was varied the air injection rate. The test where they used an injection rate of 3.0 L/min was carried out under the doctoral study of (Mercado & Trevisan, Ensaio em Tubo de Combustão Seca - Bacia de Espírito Santo, 2013), which is why the pressure of injection and production pressures are different from the other trials. Table 1 summarizes the operational conditions under which each test was performed.

Table 1 - Operating conditions of performed trials

Id Assay	*ETCIS 1*	*ETCIS 2*	*ETCIS 3*	*ETCIS 4*
Air injection rate [L/min]	2.5	3.0	3.3	3.8
Injection pressure [bar]	17	27	17	17
Production pressure [bar]	10	20	10	10

4.4. Simulation model

Based on the laboratory model it was designed a numerical model of the combustion with the aim of reproduce the same conditions used in the laboratory tube, and compare the response of the numerical model with experimental results.

First it was designed the fluid model which should be the most representative possible of the fluid behavior used in the experimental campaign. The software used was Computer Modelling Group WinProp® - version 2012.10. It was used the state equation of Peng Robinson 1978 it was fitted to the data provided by (Mercado & Trevisan, Modelo de Fluidos de um óleo da Bacia de Espirito Santo, 2012). The fluid model was characterized by three pseudo-components: H_2S*to*C_3, IC_4*to*C_{19} e C_{20+}

The numerical model of the combustion tube was designed on the numerical simulator Computer Modelling Group STARS® - version 2012.10. The combustion tube was represented by a radial *grid* with 4x1x100 divisions in the direction *r, θ* and *k,* respectively, totaling 100 inches long, 7.31 cm outer diameter and 6.93 inches inside diameter of the combustion tube. The properties of the porous medium and the combustion tube were the same used by (Mercado & Trevisan, Numerical Simulation of a Dry Combustion Tube Test for a Brazilian Heavy Oil, 2013). The permeability was of 15303 milidarcy to the porous medium and for cells that simulate the sand placed on the top and bottom of the tube was considered a permeability of $1x10^7$ milidarcy. The porosity used was 43.14%. Relative permeability curves were used according to the *template* of STARS®, making proper adjustments to the study case, particularly, adapting the residual oil percentage. The curves used are shown in Figure 3 and Figure 4.

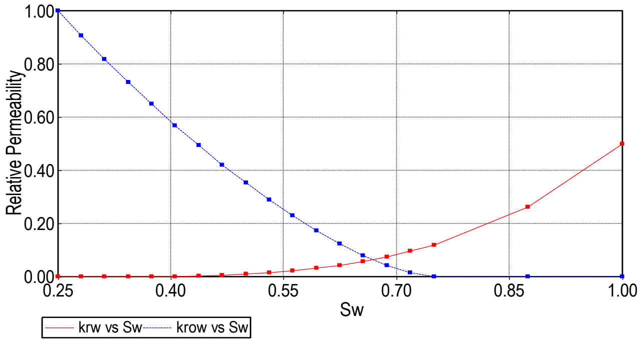


Figure 3 - Relative permeability curves water-oil

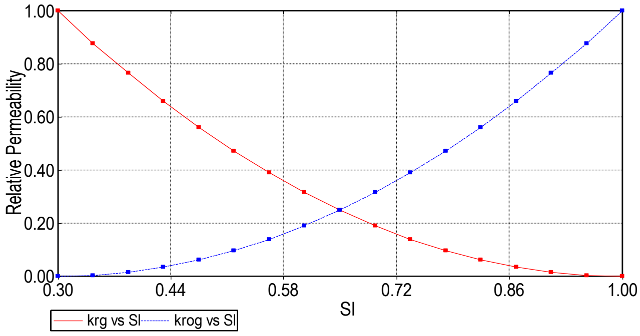


Figure 4 - Relative permeability curves gas-liquid

The chemical reactions model consider a set of four reactions that allow characterize this process. These reactions are presented in Table **2** . Kinetic parameters were the same used by (Mercado, Numerical Simulation of a Dry Combustion Tube Test for a Brazilian Heavy Oil, 2013).

Table 2 - Stoichiometry of the equations used to model the combustion tube

Cracking reaction	$1{,}0000\ [C_{20+}] \rightarrow 1{,}6823[IC_4toC_{19}] + 24{,}5202\ [Coque]$
Coke oxidation	$1{,}0000\ [Coque] + 1{,}2692\ [O_2] \rightarrow 0{,}5762\ [H_2O] + 0{,}9863\ [CO_2]$
Heavy fraction oxidation	$1{,}0000\ [C_{20+}] + 62{,}2442\ [O_2] \rightarrow 28{,}2575\ [H_2O] + 48{,}3663\ [CO_2]$
Mean fraction oxidation	$1{,}0000\ [IC_4toC_{19}] + 18{,}4995\ [O_2] \rightarrow 8{,}3984\ [H_2O] + 14{,}3749\ [CO_2]$

5. Analysis and discussion of results

One of the most important data that must be carefully analyzed is the temperature profiles along the tube. Figure 5 Figure 6 Figure 7and Figure 8 present the temperature profiles of each experimental test.

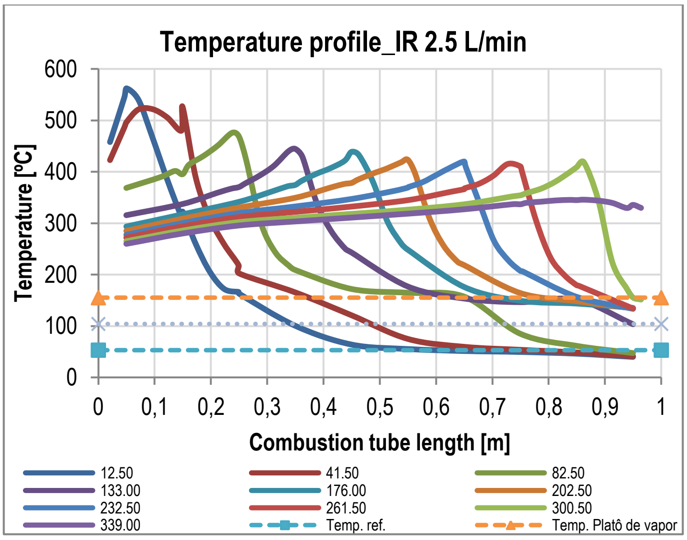


Figure 5 - Temperature profile from air injection rate run of 2.5 L/min

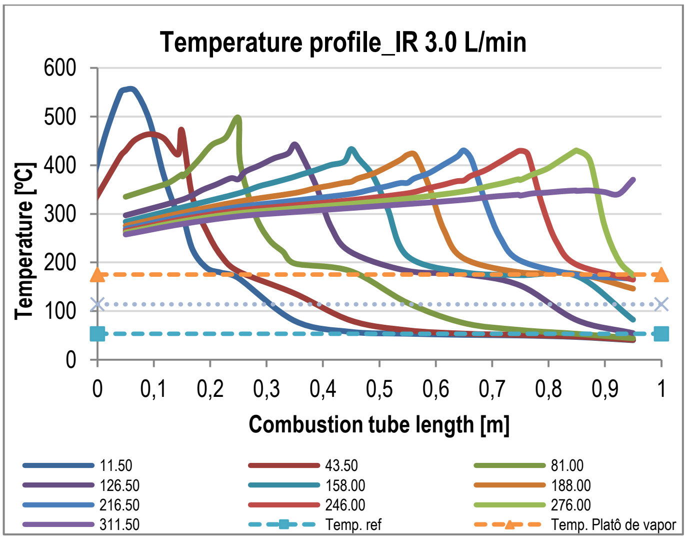


Figure 6 - Temperature profile from air injection rate run of 3.0 L/min

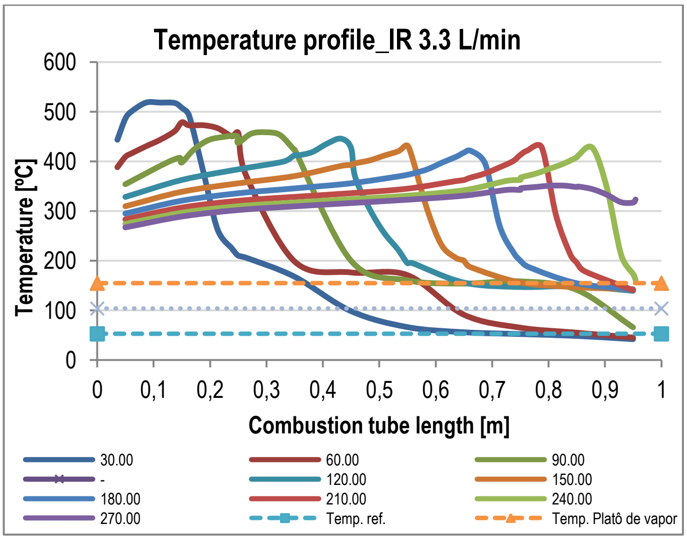


Figure 7 - Temperature profile from air injection rate run of 3.3 L/min

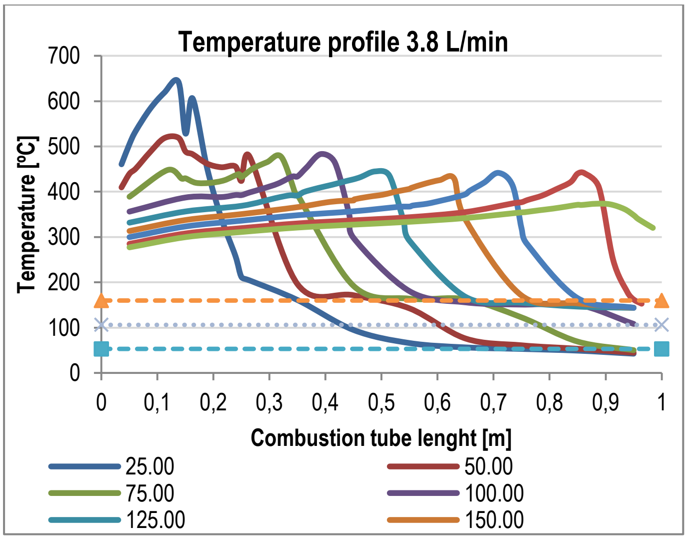


Figure 8 - Temperature profile from air injection rate run of 3.8 L/min

5.1. Comparison of the results obtained in the experimental campaign

A comparison of the results obtained in the various tests was carried out through the study of several parameters, among which are the following: combustion front velocity, condensation front velocity, fluids production, gases production, jacket temperature of the tube combustion and jacket vacuum.

All the trials were conducted according to the same procedure, yet it is not possible to accurately reproduce the same mixture, whereby Table 3 summarizes the main properties porous mixture in each test.

Table 3- Properties of porous mixture in each test

Id Assay	*ETCIS-1*	*ETCIS-2*	*ETCIS-3*	*ETCIS-4*
Air injection rate [L/min]	*2.5*	*3.0*	*3.3*	*3.8*
Rock mass [g]	5112.0	5111.7	5117.2	5113.8
Oil mass [g]	768.1	777.1	755.2	757.7
Water mass [g]	311.9	314.8	320.6	316.0
Oil saturation [%]	50.0	50.0	50.0	43.7
Water saturation [%]	25.0	25.0	25.0	22.3
Gas saturation [%]	25.0	25.0	25.0	34.0
Porosity [%]	43.1	43.1	43.1	46.2

5.2. Front Combustion

By the analysis of the temperature profiles of the combustion front of each test it was observed that the front's temperature was higher than 400 °C, particularly during the stable period, indicating the predominance of high oxidation temperature reactions during the combustion process in all tests. The position that the combustion front occupied throughout each test allow the determination of its velocity, which is also defined as the rate of advance of the combustion zone. According to (Zhang, Liu, & Che, 2013) the combustion front velocity is directly proportional to the amount of injected oxygen (air flow) and inversely proportional to the amount of fuel deposited. From Table 4 it is possible to note this proportionality between the propagation of the combustion front velocity with the increasing of the air injection rate.

5.3. Steam plateau

In the combustion process, after the temperature peak occurs, that is, right ahead of the combustion front, there is a sharp drop in temperature, where there is the deposition of fuel until it reaches a zone where temperature remains almost constant in a portion of combustion tube. This zone where the temperature profile is practically isothermal is defined by steam plateau. As noted earlier in the temperature profiles graphs (Figure 5, Figure 6, Figure 7 and Figure 8), in all trials it is observed the formation of a clearly defined steam plateau. The temperature of the plateau is strongly influenced by steam partial pressure of water vapor, and for this reason the test at the rate of 3.0 L/min and the temperature was higher level, since this test was performed at a pressure greater than the other tests.

The study of the steam plateau and its growth rate provides important information about the production mechanism of fluids, however to perform this analysis is necessary to determine the velocity of the condensation front.

5.4. Condensation front

After the steam plateau there is a new zone where there is a decrease of temperature generated by heat losses, whereby the fluid condense. This phenomenon generates the formation of a zone highly saturated by water and light fraction of oil, which contribute to the displacement of fluids. The velocity at which this phenomenon occurs is called the condensation front velocity. From the position of the front condensation in function of time can be estimated velocity of the condensation front.

Difference between the velocities of the combustion front and the front of condensation it can be evaluated the growth of the steam plateau. Since the velocity of the combustion front increases with the increase of the injection rate and the velocity of the condensation front is practically constant, the increase in steam plateau is lower as higher is the air injection rate. Table 4 synthesizes the velocities of the combustion and condensation fronts and the growth of steam plateau.

The importance of the of the steam plateau growth is related to the fact that it can function as an oil production mechanism, the greater is the length of the steam plateau more heat energy will be transmitted to remote areas of the combustion front. This heating promotes a decrease in oil viscosity, and thus anticipates the production of oil.

Table 4 - Velocities of combustion and condensation fronts and steam plateau growth in all tests

Air injection rate	*2.5 L/min*	*3.0 L/min*	*3.3 L/min*	*3.8 L/min*
Combustion front velocity	4.2 m/day	4.9 m/day	5.5 m/day	6.3 m/day
Condensation front velocity	7.8 m/day	7.6 m/day	7.5 m/day	7.5 m/day
Growth of steam plateau	3.6 m/day	2.7 m/day	2.0 m/day	1.2 m/day

5.5. Production fluids

As higher is the air injection rate it can be observed anticipation on the fluids production. This increase can be seen in Figure 9.

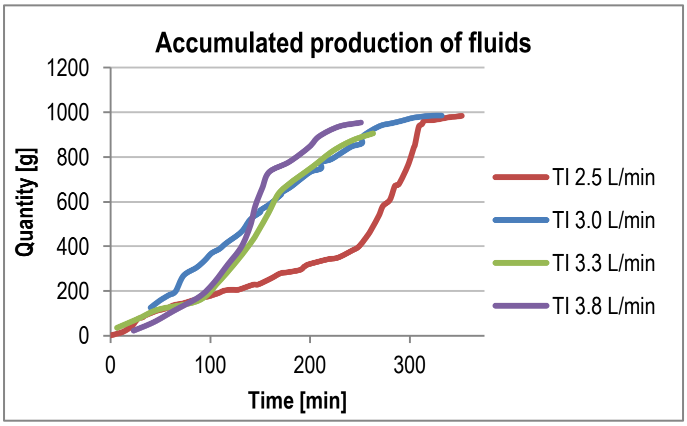


Figure 9 - Production of accumulated fluids in the various assays

Figure 10, Figure 11, Figure 12 e Figure 13present the volumes of produced fluids along the respective tests. In general, it is observed an initial period of production fluids on a constant rate followed by a significant oil and water production rate. However, despite the production of water stabilize the production of oil maintains its rate of growth. This change in production rate can be indicative of the arrival of a water bank followed by a bank of oil to the producer well.

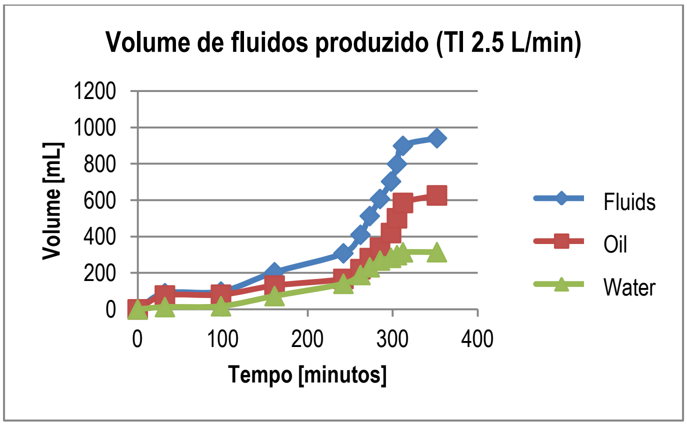


Figure 10 - Volume of fluid produced in the test with injection rate of 2.5 L/min

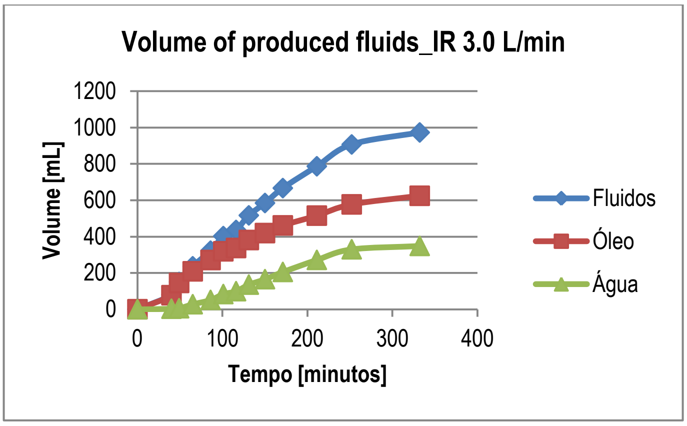


Figure 11 - Volume of fluid produced in the test with injection rate of 3.0 L/min

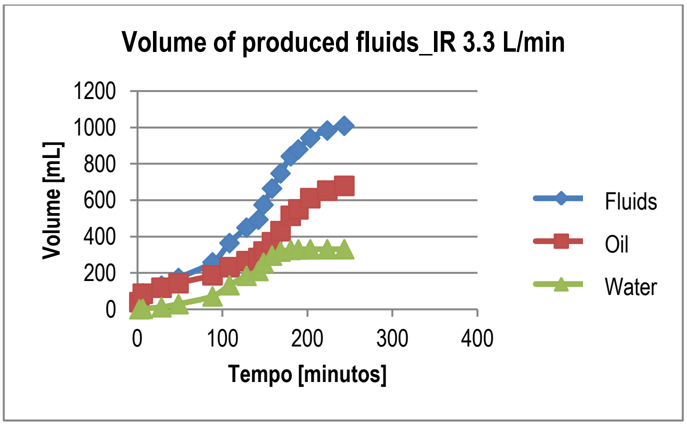


Figure 12 - Volume of fluid produced in the test with injection rate of 3.3 L/min

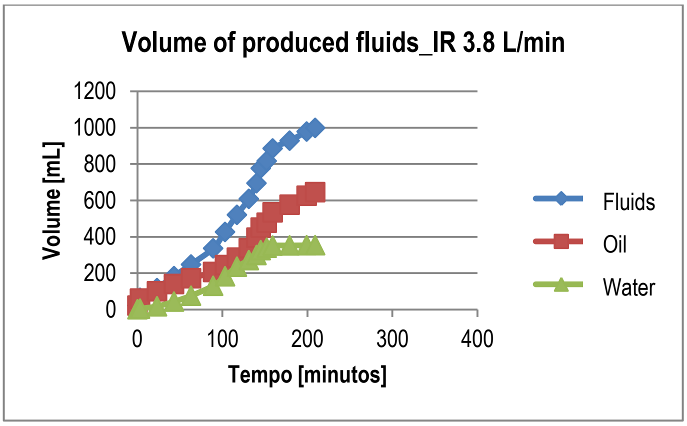


Figure 13 - Volume of fluid produced in the test with injection rate of 3.8 L/min

From the amount of oil and water produced is possible to determine the recovery factor obtained in each test. Table 8 presents the fluids production data of from each test as well as the recovery factor. According to the results it was observed that the recovery factor is always greater than 85 % has been reached maximum recovery of 95 %. These high values are related, among other factors, with the fact of being a porous medium for use with high porosity and oil saturation, and the reduced tube diameter induces a total sweep of the combustion tube.

Table 5 - Fluid production in all tests

Air injection rate [L/min]	**Volume of oil in the mixture [milliliters]**	**Volume of water in the mixture [milliliters]**	**Production volume before Karl-Fischer [milliliters]**		**Production volume after Karl-Fischer [milliliters]**		**Recovery factor [%]**
			V_{Oil}	V_{Water}	V_{Oil}	V_{Water}	
2.5	736	368	951	79	703	327	95 .0
3.0	736	368	759	213	624	348	85 .0
3.3	736	368	951	58	679	330	92 .0
3.8	688	351	954	34	645	353	94 .0

The fluids production started practically from the beginning of air injection at a relatively low rate. When fluids condense and accumulate downstream of the steam plateau reach the production well causes an increased production of fluids, especially water. After the water production stabilizes there is an exponential increasing on oil production. From these observations it can be inferred that the steam plateau is divided in two separate areas: one where there is high oil saturation, located closer to the cracking zone; and one where there is the coexistence of oil and water, closer to the produced well. Because water has a higher relative permeability than oil, water accumulates closer to the oil production well, which could indicate that the water bank is downstream of the oil bank. As the combustion front progresses, the fuel deposition zone close to the production well and the level of vapor becomes increasingly shorter until it ceases to exist and there is no further oil production.

When comparing the temperature histories of the various tests is noted that in trials where a higher rate of injection was used for the production of early oil against the test with lower injection rate. This difference in the production fluid is related to the operation level of engine output as a vapor. For trials where there is a lower rate of air injection the level of steam is higher plus the area included since the end of the deposition of fuel until the end of steam level is considerably higher. Thus it can be assumed that in the test injection rate less large part of the oil eventually accumulate in this area, this being the reason which explains the late oil production in this assay.

From the tests it was also noted a decrease in the specific gravity as the oil is being produced, which indicates that there was a chemical changes, i.e., there was an upgrading of heavy oil. Table 6 presents the API degree of oil samples collected throughout the trials.

Table 6 - API degree of some oil samples collected during the tests

2.5 L/min		*3.0 L/min*		*3.3 L/min*		*3.8 L/min*	
Beaker	API	Beaker	API	Beaker	API	Beaker	API
2	16:11	2	15.86	2	16.94	2	16:30
4	18.58	5	16:42	5	17:42	5	17.67
6	17:16	7	17:29	8	18:50	8	18:26
8	19:26	9	17:10	11	16.66	11	18.62
11	19:50	12	28.72	15	21:31	15	20.71

5.6. Gas Production

In combustion tube trials is collected various data such as temperature, pressure and composition of the oil, enabling to establish the stoichiometry of the chemical reactions occurring during the process. (Sarathi, 1999) The stoichiometric coefficients of the reactions of oxidation and cracking are determined from the molar ratio of nitrogen, oxygen, oxide and carbon dioxide produced during the stable period of the combustion process composition.

Gas concentrations were recorded by the gas analyzer and determined by gas chromatographic analysis. The concentrations obtained by the two methods are similar, only by registering a lower oxygen concentration in the samples subjected to chromatography, but higher concentration of carbon monoxide in the gas analyzer. From gas concentration was possible to determine certain characterizing parameters of the combustion process. The results obtained for these parameters showed no significant variations in the various tests, especially when it makes the comparison of data obtained by gases analyzer. Table 7 lists the parameters of combustion for each test, where it is observed that the parameters which show major differences are apparent

Hydrogen/Carbon ratio, the air-fuel ratio, fuel consumption and air required.

Table 7 - Concentration of generated gases and combustion parameters determined in the stable period of all tests

The injection rate	*2.5 L/min*		*3.0 L/min*		*3.3 L/min*		*3.8 L/min*	
Parameters	**Gas analyzer**	**Chromatography**	**Gas analyzer**	**Chromatography**	**Gas analyzer**	**Chromatography**	**Gas analyzer**	**Chromatography**
$[O_2]$	0 .91	0 .09	0 .86	0 .05	1 .04	2 .23	1 .09	2.71
$[N_2]$	8 3:39	84 .60	83 .41	84 .25	83 .40	81 .10	8 3:36	81.24
[CO]	0 .58	4 .11	0 .58	3 .94	0 .54	4 .17	0 .57	4:22
$[CO_2]$	15 .11	11 .20	15 .15	11 .75	15 .02	1 2:50	14 .99	11.83
Ratio apparent H/C	1 .16	2 .04	1 .16	1 .86	1 .16	0 .83	1 .15	0.91
Ratio Fuel-air [m^3 std/kg]	11 .92	11 .61	11 .89	11 .43	12 .02	11 .19	12 .02	11:57
Oxygen used [Fraction]	0 .96	1 .00	0 .96	1 .00	0 .95	0 .89	0 .95	0.87
Excess of oxygen [Fraction]	0 .05	0 .00	0 .04	0 .00	0 .05	0 .12	0 .05	12:15
Oxygen converted to carbon oxides [Fraction]	0 .77	0 .63	0 .77	0 .65	0 .77	0 .81	0 .77	0.79
Fuel consumption [kg/m^3]	18 .90	19 .68	20 .88	21 .95	19 .96	20 .85	19 .54	19.78
Required Air [m^3 std/m^3]	225 .22	228 .49	248 .31	250 .82	230 .17	22 3.81	234 .85	228.89
Ratio $(CO_2 + CO)/CO$	26 .95	3 .72	27 .15	3 .98	28 .76	4 .00	27 .13	3.81
Ratio $(CO_2 + CO)/N_2$	0 .19	0 .18	0 .19	0 .19	0 .19	0 .21	0 .19	00:20
Ratio $(CO_2)/CO$	25 .95	2 .72	26 .15	2 .98	27 .76	3.0 0	26 .13	2.81

The apparent Hydrogen/Carbon ratio (H/C) assesses the stability of combustion process. This parameter must be between 1 and 3, since this is the range for which there is a predominance of high temperature oxidations (Zhang, Liu, & Che, 2013). Another important aspect of the H/C ratio is that for values above 1 are also an indicative that most of the fuel is from the heavy oil fractions.

Analyzing the values obtained by the gases analyzer, the H/C ratio is almost the same in all tests, being slightly lower in the test with higher injection rate. However, when the same analysis is carried out by chromatography of the data it is observed that higher injection rates of the value obtained is significantly lower. The apparent H/C ratio of these assays was unusually low, as the chromatographic analysis revealed an abnormally high concentration of oxygen.

The air-fuel ratio informs the volume of injected air that is required to burn 1 kg of fuel. From the results obtained it is observed that there is no significant variation in the different tests, ranging between 11.9 and 12.2 m^3 std/kg in the results obtained by the gases analyzer and 11.2 to 11.6 m^3 std/kg by chromatography.

Lower fuel consumption indicates that it requires a smaller amount of injected air. This parameter is also often regarded as an indicator of deposition of fuel during the combustion process, which indicates that there is greater deposition with increasing injection rate. This result is consistent with what was expected, since it was expected that lower injection rates would promote lower velocities of the combustion front, and consequently, greater amount of fuel deposited.

The required air indicates the volume of injected air required to burn 1 m^3 of sand. The fraction of oxygen used was above 95% in all tests, except the test where a rate of 3.3 L/min was used and by the evaluation of the chromatography data, whose fraction of oxygen used was 89 %. Considering the analysis by gas analyzer was obtained an excess of oxygen of 5 %, while this parameter for the chromatography was 12 % in the assay at a concentration of 2.23 % oxygen and 2.71 % for the remaining tests. The fraction of oxygen converted to carbon oxides was similar in all trials. This parameter indicates that the oxygen was used predominantly for the oxidation of high temperature.

5.7. Heat transfer along the tube

Combustion tube is made of stainless steel and it has a high thermal conductivity compared to the conductivity of the mixture inside it. This makes the transfer of heat by conduction through the wall of steel faster than through the mixture. For the temperature difference generated by this phenomenon there is heat transference from the steel to the mixture ahead the combustion zone. This heat input promotes the formation and growth of the steam plateau, which in turn contributes to an early production fluid and, consequently, on the efficiency of the combustion process.

The following analysis can be performed to account for the influence of heat transfer from the wall of the tube: for lower injection rates the propagation velocity of the combustion front is lower, but the temperature of the combustion front is approximately the same independently the air injection rate used, which induces that the transfer rate along the tube is similar in all trials. Thus, for a faraway point from the combustion front the influence of combustion heat transfer from the tube to the mixture will be considerably higher for lower injection rates. This is heat that increases the length of the level of steam to lower rates of injection. Figure **14** allows the observation of the influence of jacket temperature on the formation of vapor level.

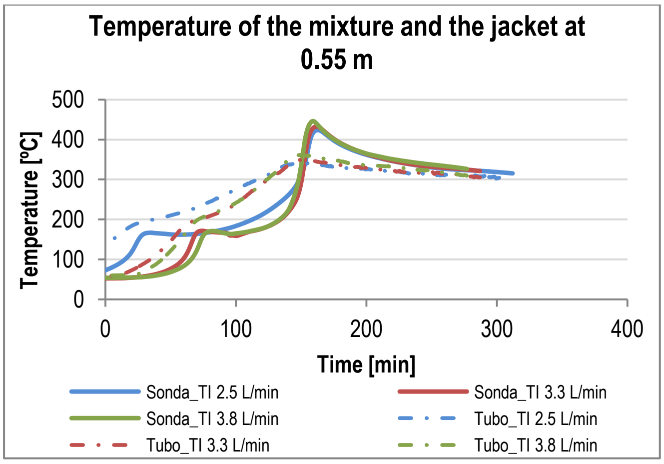


Figure 14 - Temperature of the mixture and the jacket where the combustion front is 0.55 m at the position of the combustion tube

Based on the above analysis, it can be inferred that the increase in injection rate, and therefore the velocity of the combustion front, there is a decrease in the length of the steam plateau resulting from the smaller contribution of heat transferred from the tube to mixture. The thermal conductivity of the tube is greater than the mixture thus the higher the velocity of the combustion front, the lower the contribution of heat transferred from the tube to mixture.

6. Numerical modeling

The results of the experimental combustion tube trials were used to calibrate the numerical model. Initially it was adjusted the initial saturation fluids, then the relative permeability curves and some kinetic parameters, and finally made the adjustment of heat losses of the tube.

The adjustment of the combustion tube model has been made considering the results of the last test performed, where it was used an air injection rate of 3.8 L/min. The results of the initial model is presented on Figure 15 where it is plotted also the historical temperatures profiles from the experimental test. From this chart it can be seen that the initial numerical model has a higher combustion front velocity, in addition to the temperature of the combustion front is significantly higher. Fuel production shown in Figure 16 and it is necessary to proceed to an increasing of fuel production on the numerical model. Fluids production is shown in Figure 17 where we observed a deficient production of oil and excessive production of water.

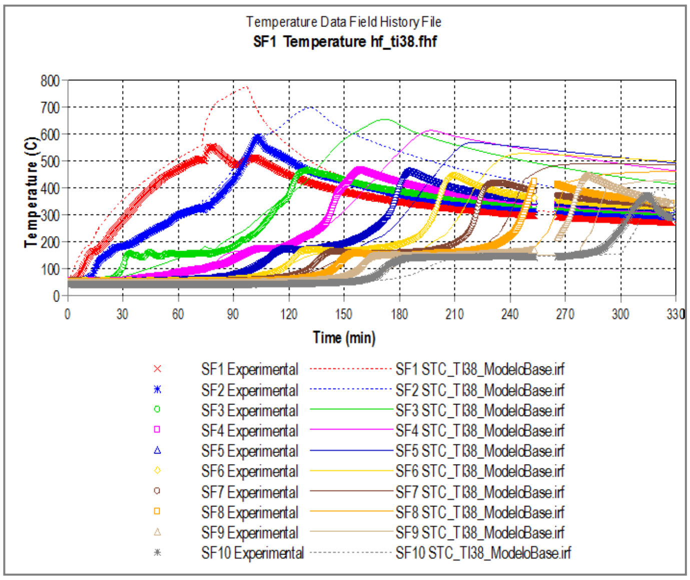


Figure 15 - History of temperature profiles from experimental test using an injection rate of 3.8 L/min and results of numerical simulation of the base model

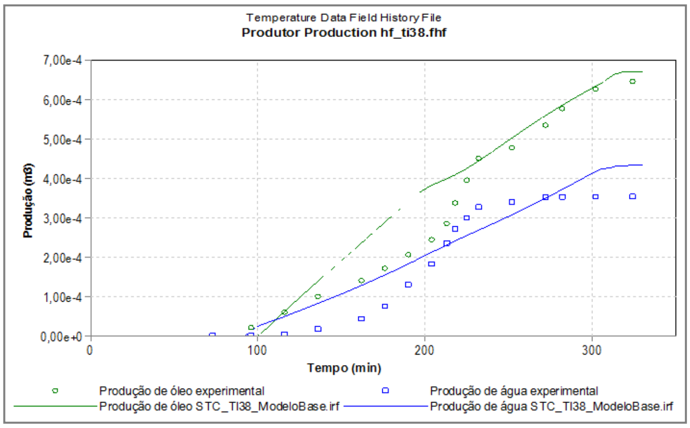


Figure 16 - History of accumulated fluids production from experimental test using an injection rate of 3.8 L/min and results of numerical simulation of the base model

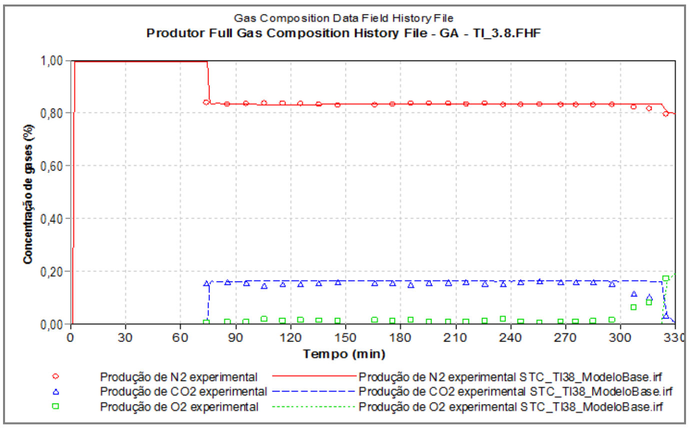


Figure 17 - History of the composition of the produced gases from experimental test using an injection rate of 3.8 L/min and results of numerical simulation of the base model

6.1. Adjust of the initial saturations

The base model used the initial fluid saturations that were provided (50% oil, 25% water and 25% gas). However in this experimental test a small portion of the mixture remained, so the initial fluid saturations and porosity were again estimated and the model was adjusted to these parameters. The saturations were recalculated and it was obtained 44 % oil, 22 % water and 34 % gas. The porosity was also recalculated having been obtained a value of 46.02 %. The model was modified and it was found that the amounts of original oil and water have not yet corresponded to the amount initially used in the mixture. For this reason the initial saturations were changed in the simulation model in order to adjust the initial amount of fluids. The change of saturation and porosity in the numerical model is summarized in Table 8.

Table 8 - Properties of porous medium and initial volume of fluids in-place obtained by adjusting the initial saturation of fluids in the numerical model

	Experimental model	*Initial numerical model*	*Adjusted numerical model*
Porosity [%]	43	43	46.02
Oil saturation [%]	50	50	46
Water saturation [%]	25	25	20
Gas Saturation [%]	25	25	34
Oil volume [ml]	6.88E-04	7.43E-04	7.29E-04
Water volume [milliliters]	3.51E-04	3.70E-04	3.16E-04

6.2. Adjustment of relative permeability curves

From the fitted model were adjusted the relative permeability curves, in particular by adjusting the percentage of residual oil observed in experimental test. The relative permeability curves have particular impact on the flow of fluids through the porous medium. The set of relative permeability curves are shown in Figure 18 and Figure 19.

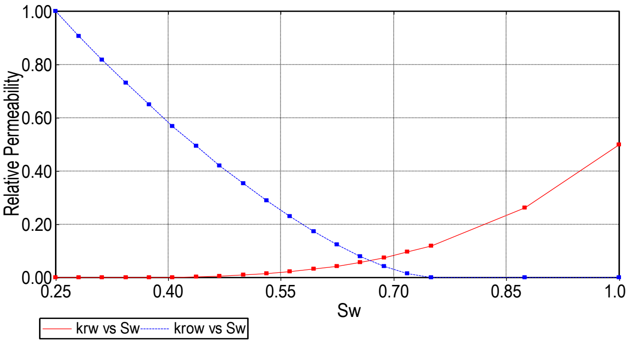


Figure 18 - Adjusted relative permeability curves water-oil

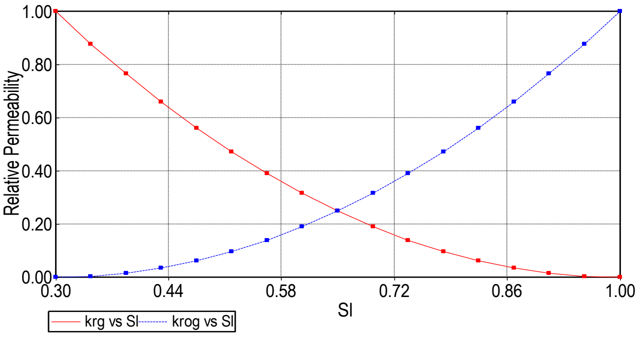


Figure 19 - Adjusted relative permeability curves gas-liquid

6.3. Set the activation energy

The amount of fuel deposited in the initial model was substantially lower than that observed in experimental trial, which were approximately 19.6 kg/m^3. In order to increase the amount of fuel deposited in the simulation model was increased the activation energy of the cracking reaction to 7.2x10 ^{4} J/gmole. With this procedure it was possible to increase the amount of fuel, and consequently the temperature of the combustion front also increased.

6.4. Adjust of heat losses

During the ignition there is no fluid flow in the system and it was chosen this period to adjust the heat loss of the tube. Heat losses were considered only in the top and bottom of the tube because along the sides of the tube the adiabatic control process minimize its losses through the resistors installed in the jacket. With this procedure it was possible to reduce the temperature of the combustion front, especially at the beginning of the tube. In Figure 20 are shown the profiles of the test and the numerical model temperature and in Figure 21 the amount of fuel deposited throughout the study is presented. The production fluid is in Figure 22 and the composition of the gas produced in Figure 23.

Based on the comparison of experimental data and results from the numerical model of the combustion tube may be inferred that the model represents the main phenomena observed during the experimental trial. It should be noted that only the temperature of the simulation model was slightly higher than the temperatures recorded in experimental testing and that it was not possible to adjust the start of production fluids. It is also important to note that the numerical model does not consider two factors are very important:

- Heat transfer along shirt is not reproduced in the model, and this way the influence it has on production fluids cannot be reproduced;
- The adiabatic control is not played and this influences the production of fluids.

However it is considered that this model is generally representative of combustion test tube.

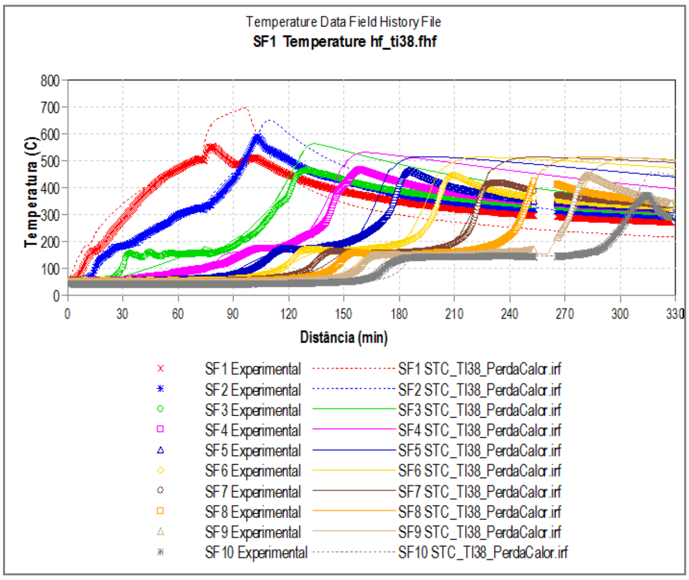


Figure 20 - History of temperature profiles in the combustion tube using an injection rate of 3.8 L/min and results of numerical simulation of the adjusted numerical model

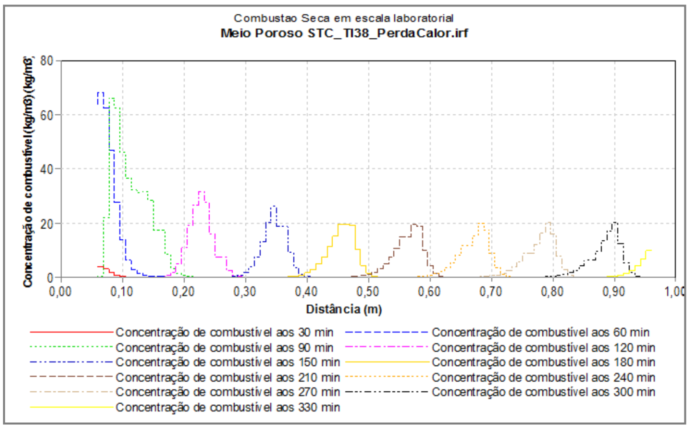


Figure 21 - Concentration of fuel (kg/m3) set in the adjusted numerical model

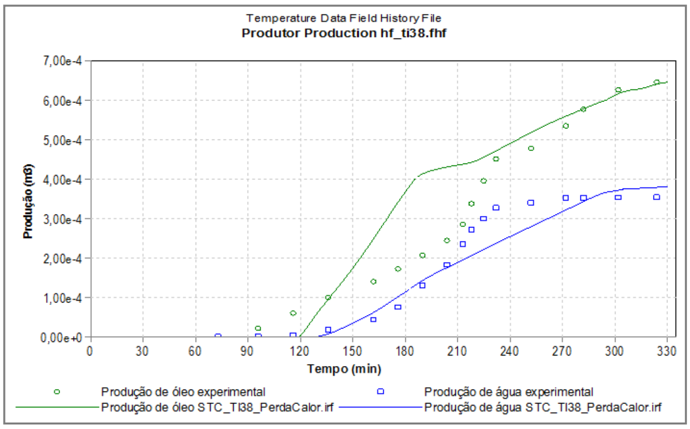


Figure 22 - History of accumulated fluids production from experimental test using an injection rate of 3.8 L/min and results of numerical simulation of the adjusted model

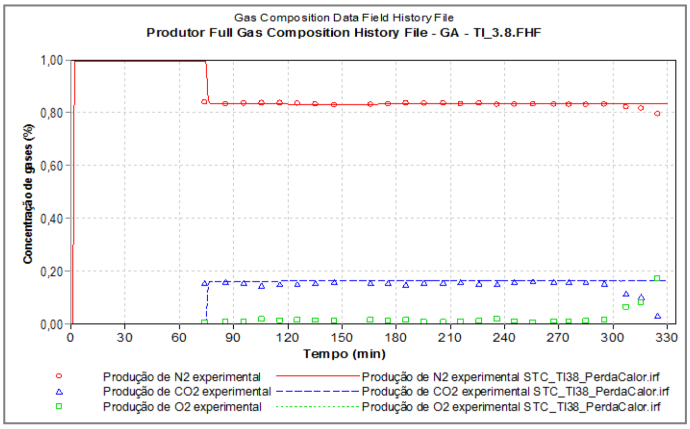


Figure 23 - History of the composition of the produced gases from experimental test using an injection rate of 3.8 L/min and results of numerical simulation of the adjusted model

7. Conclusions

The present study aimed to evaluate the contribution of the increasing of the air injection rate in the combustion process through laboratory tests and their numerical modeling. To this were designed and performed four experimental tests.

Regarding what was described about the in-situ combustion process it can be concluded that this is a very interesting recovery process because there is a natural segregation of the fractions of the oil: light oil fractions are produced, while the heavier fraction is selectively burned and their residues remain in the most convenient location: the shell itself. Results like there is a "dynamic refinery" developed in the reservoir (Moczydlower, 2006).

The analyses of the experimental and numerical results allow the following conclusions on the in-situ combustion:

- *Temperature of the combustion front*: All tests conducted the temperature of the combustion front during the stable period was higher than 400 °C;
- *Velocity of the combustion front*: the velocity of the combustion front is directly proportional to air injection

rate, i.e., the higher the rate the higher the injection velocity of the combustion front;

- *Velocity of the condensation front*: the velocity of the condensation front was not sensitive to changes in the rate of injection;
- *Growth of steam* plateau: the steam plateau presented a greater length for smaller air injection rates. This growth is affected by the influence of heat transfer from the tube to the mixture;
- *Mechanism of fluids production*: It was noted that there are three distinct stages in the production of fluids:
- Initially production occurs at a low and constant rate;
- When the condensation front reaches the produced well there is an increase in fluids production, especially water;
- When water production stabilizes, there is a considerable increase in oil production.
- *Gases production*: gases production is relatively constant since the beginning of air injection. When comparing the results from the analyzer and the gas chromatography, it is considered that there is a higher uncertainty in the gases analyzer method however it is most practical than chromatography, and whose data processing is faster, with a key to monitor the combustion process throughout the test;
- *Quality of the oil produced*: the combustion process proved to be a great method of producing heavy oil, and greatly to improve the quality of the oil produced. The last collected samples showed an increase of 25 % of API grade;
- *Residual oil in final mixture*: It was noted that the percentage of residual oil in the final mixture is below 1%, indicative of uniform scan throughout the combustion tube;
- *Model simulation*: the simulation model presented reproduces the main phenomena of the combustion process and can serve as a basis for modeling the reservoir model at a field scale.

References

Araújo, J. S. (2012). *Estudo paramétrico do Processo de combustão in situ.* Universidade Federal do Rio Grande do Norte, Natal.

Burger, J. S. (1985). *Thermal Methods of Oil Recover.* (T. Editions, Ed.)

Chicuta, A. M. (2009). *Estudo Experimental Sobre Recuperação de Óleo Pesado através da Combustão In situ – Dissertação de mestrado em Ciências da Engenharia de Petróleo.* Unicamp, Campinas.

Costa Silva, A. (2001). *Lição de Sintese - A integração dos Dados e da Informação Sísmica, Geológica, Petrofísica e de Produção na Construção de Modelos Descritivos de Reservatórios de fluidos.* Lisboa.

Gonçalves, L. I. (2010). *Estudo experimental da Combustão molhada na Recuperação de óleo pesado.* Unicamp, Dissertação de mestrado em Ciências da Engenharia de Petróleo, Campinas.

Green, D. W., & Willhite, G. P. (2003). *Enhanced Oil Recovery.* Richardson, TX: Society of Petroleum Enginners.

Mercado, D. (2013). *Numerical Simulation of a Dry Combustion Tube Test for a Brazilian Heavy Oil.* Unicamp, Campinas.

Mercado, D., & Trevisan, O. (2012). *Modelo de Fluidos de um óleo da Bacia de Espirito Santo.* Unicamp, Campinas.

Mercado, D., & Trevisan, O. (2013). *Ensaio em Tubo de Combustão Seca - Bacia de Espírito Santo.* Unicamp.

Mercado, D., & Trevisan, O. (2013). *Numerical Simulation of a Dry Combustion Tube Test for a Brazilian Heavy Oil.* Unicamp, Campinas.

Pereira, A. N. (2008). *Estudo Termoanalítico e Cinético da Combustão.* Campinas.

Rodriguez, J. (2004). *Experimental and Analytical Study to Model Temperature Profiles and.* Texas A&M University.

Sarathi, P. (1999). *In-Situ Combustion Handbook -- Principles and Practices.* United States: USDOE Office of Fossil Energy (FE) (US).

Schlumberger. (s.d.). *www.slb.cm/services/technical_challenges/eor/screening.aspx*. Obtido em 07 de 12 de 2013, de Schlumberger: www.slb.cm/services/technical_challenges/eor/screening.aspx

White, P. D. (1983). *Thermal Recovery Methods.* PennWell Publishing Company, Tulsa, Oklahoma.

Zhang, X., Liu, Q., & Che, H. (2013). Parameters Determination during In Situ Combustion of Liaohe Heavy Oil. *Energy & Fuels*, 3416−3426.