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SIMULATION OF *IN-SITU* COMBUSTION PROCESS IN LABORATORY SCALE

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Abstract. In-situ combustion is a good alternative for oil recovery in heavy oil reservoirs, since it has a high recovery factor and low operating cost. However, its degree of complexity is high. Therefore, the objective of this work was to simulate the in-situ combustion process by means of a thermally isolated combustion reactor in order to obtain information about the combustion process. The temperature of the reactive porous medium and the rate of fuel consumption inside the equipment were monitored. A mixture of similar composition was used to simulate the composition inside the reservoir. Based on literature data, the airflow rate was set at a Darcy velocity of approximately 0.05 m/s. The average peak temperature obtained was 847°C, what indicates that high temperature carbon oxidation happened. The velocity of the combustion front was 7.5 mm/min, considered high for similar mixtures proposed by other authors. The reaction zones were also defined and measured and it was observed that the oxidation of the fixed carbon begin 28 mm before the front temperature peak. As a result, it was confirmed that the combustion front has behaved in a stable and self-sustaining way.

Keywords: Reactive porous medium, Heavy oil recovery, In-situ combustion,

1. INTRODUCTION

Some economics forecasting predict that heavy oil will be the world's leading source of fossil fuel in 2025 due to the continued decline in light oil reserves (Jia *et. al.*, 2006; Kang *et al*., 2012; Sousa Junior and Mothé, 2008). However, heavy oils can not be recovered from the reservoir by conventional production methods. Therefore, development of new techniques and/or improvement of existing techniques in order to increase the reservoirs recovery index is a important matter for oil companies (Deniz-Paker and Cinar, 2017).

Among the methods for oil recovery are the thermal methods, which consist in adding heat to the reservoir to decrease the viscosity of the oil and facilitate its flow and, consequently, increase the productivity index of the producing wells (Deniz-Paker and Cinar, 2017; Nesterov *et* al., 2013; Rodriguez, 2004). Thus, due to the tendency of heavy oils to have high viscosity (Kelesoglu *et al*., 2012; Deniz-Paker and Cinar, 2017), what makes it difficult to recover, the thermal methods can be employed to facilitate the flow of heavy and extra-heavy oils inside the reservoirs porous medium (Ribeiro Junior, 2009). In fact, due to its high viscosity, a procedure to facilitate heavy and extra heavy oils transport after its recovery is to add water to it in order to form oil-in-water emulsions to facilitate the pipeline transport (Zolfaghari *et al*., 2016). There are two main thermal recovery methods, the heated fluid injection method and the *in-situ* combustion (ISC) method (Kokal and Al-Kaabi, 2010).

The injection of heated fluid method heat is generated externally to the reservoir and then transmitted by the fluid into its interior. Although widely applied in practice, the cost for steam generation, which is the main fluid used to carry heat into the reservoir, is high (Shokrlu *et al.,* 2013). In addition, the deeper the reservoir, the greater the thermal losses in the injection wells and the lower method efficiency (Chicuta, 2009). On the other hand, in the *in-situ* combustion method, heat is generated inside the reservoir by burning part of its own oil (de Araújo, 2012, Xu *et al*., 2017). Thus, the ISC has the advantage over the hot fluid injection methods of not using external energy to the reservoir to maintain the process, since after the ignition the process is self-sustaining (Rodriguez, 2004). Another advantage is that as combustion occurs inside the reservoir, the combustion gases can be channeled into the producing wells and injected

back into the reservoir, preventing their release into the atmosphere (Kokal and Al-Kaabi, 2010). Therefore, this method consists in propagating of flame that "sweeps" the reservoir and is sustained by an air injection. The fuel used is called coke and is a residue from the cracking, pyrolysis and vis-breaking process that occurs downstream of the combustion front due to the heat released in the combustion process (Rahnema et al., 2017, Xu et al., 2017). However, since it involves several chemical reactions and fluid mechanics, the CIS has the disadvantage of being a complex method, (Rezaei et al., 2013; Ribeiro Junior, 2009), so that according to Rahnema et al., (2017), many failures have already occurred in the field during attempts to improve recovery by means of CIS. Therefore, it is of great importance to study the variables that influence the behavior of the flame front, its velocity of propagation and how the combustion parameters influence the productivity of the reservoir.

Understanding the combustion front propagation in a reactive porous medium is still a challenge for scientists and researchers in the areas and energy and mass transfer. Due to the effects of the front propagation, at least three global reaction zones can be observed in the process (Monhol et al., 2013). The first is the drying zone in which the heat from the combustion front promotes the fuel drying. The second zone is Pyrolysis, which occurs in the absence of oxygen at temperatures above 250 °C. Third, the oxidation zone, which is the burning itself. It slowly starts to take place at temperatures above 450 °C and becomes faster at temperature above 550 °C. Oxidation occurs due to a reaction between the oxidizing agent (oxygen) and the fuel. This reaction is exothermic and results in a rapid rise in temperature, which can reach up temperatures about 1200 °C.

Because pilot field studies are very expensive, an initial assessment of *in-situ* combustion parameters can be done experimentally with laboratory-scale combustion reactors (Penberthy and Ramey, 1966). Thus, laboratory tests on one-dimensional combustion reactors are the first step in the study of the implementation of ISC in an oil reservoir (Sarathi, 1999).

The reactors may only be thermally insulated or quasi-adiabatic. In both cases, it is common to use a thin wall tube, which has its interior filled with the material to be analyzed, and surrounded by an insulating material. In thermally insulated reactors, only thermal insulation is used in an attempt to mimic adiabatic combustion inside a reservoir (Belgrave et al., 1990). Besides the thermal insulation, the quasi-adiabatic reactors also use heaters, usually electric, around the reactor. As the flame propagates, the heaters release heat and keep the outside temperature of the tube equal to the internal temperature, so that there is no temperature difference on the inner and outer sides of the tube walls. This way, combustion is said to be adiabatic. However, quasi-adiabatic reactors are more difficult to operate and heaters can add heat to the process rather than just keep it adiabatic, which would lead to erroneous results in the ISC runs (Castanier and Brigham, 2003). On the other hand, only thermally insulated reactors are easier to operate, but require a higher flow of air than would be used in the field (Castanier and Brigham, 2003).

In addition, it is common practice to replace the complex reservoir rock containing samples of the oil and other compounds by a known and simpler fuel, such as a mixture of sand and charcoal. These analyzes with simulated fuels can be made to evaluate the ignition behavior, characteristics of the combustion front and for the reactor calibration (Martins et al., 2010; Monhol, 2015).

The objective of this work was to obtain information on *in-situ* combustion by means of a combustion reactor developed by the authors. Among the information analyzed are: influence of process parameters such as flow and air pressure, fuel saturation, stability and speed of the combustion front and rate of fuel consumption.

2. EXPERIMENTAL PROCEDURE

The *in-situ* combustion run with a simulated fuel was performed in an experimental laboratory scale bench that was built by the authors. This workbench was based on national and international literature data. Its components include, as shown in Fig. 1: a thermally insulated combustion reactor that allows a heat loss of less than 15% of the heat released in the combustion, with a 63 mm internal diameter, ten type K thermocouples aligned on the axial axis of the reactor to monitor the temperature in its center during the test, an exhaust system with high temperature resistant piping, and a gas wash tank, a computer for recording the data and a scale for monitoring the rate of fuel consumption. The insulation is composed of two layers: a thermal blanket with a thickness of 3 mm (Kaowool 700 E, Thermal Ceramics) with thermal conductivity of 0.114 W/mK at 816 °C and density equal to 176 kg/m³, and a fiber (Kaowool M 42 Board, Thermal Ceramics) with thermal conductivity of 0.15 W/mK at 816 °C and a density of 320 kg/m³. In addition, a simulated fuel sample was prepared consisting of 5% by weight of charcoal (fixed carbon) and 95% by weight of sand (inert material) to simulate the immediate analysis of bituminous shale (Martins, 2010). The charcoal was milled and sieved, and the sand was only sieved to obtain uniform grains with a mean diameter between 1 and 4 mm. The air supply was made by a compressor and regulated by a needle valve and a rotameter for a flow rate of 0.68 kg/h or 0.57 m3/h, so that the Darcy velocity equal to 0.05 m s, below the limit of 0.062 m s recommended by Martins (2008). The ignition was carried out with the aid of an oxyacetylene torch flame through an opening in the upper part of the reactor.
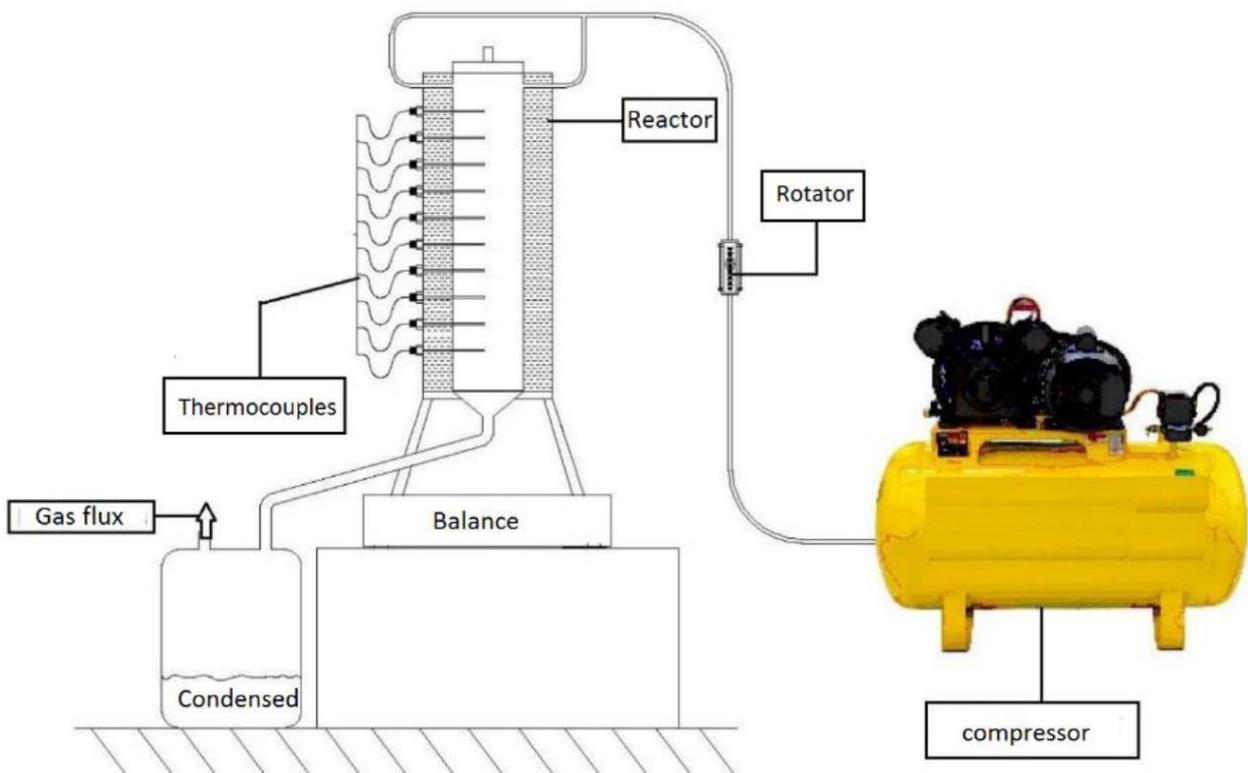
Figure1. Experimental bench layout.

3. RESULTS AND DISCUSSION

As can be seen in Fig. 2, the peak temperature of the thermocouple T1 is about 685 °C and for the other thermocouples the average temperature is 847 °C. The T1 thermocouple is probably different from the others because it is more influenced by the ignition and the reactor is still cold. A similar result was obtained by Monhol *et al*. (2013) for a mixture of snad and charcoal.
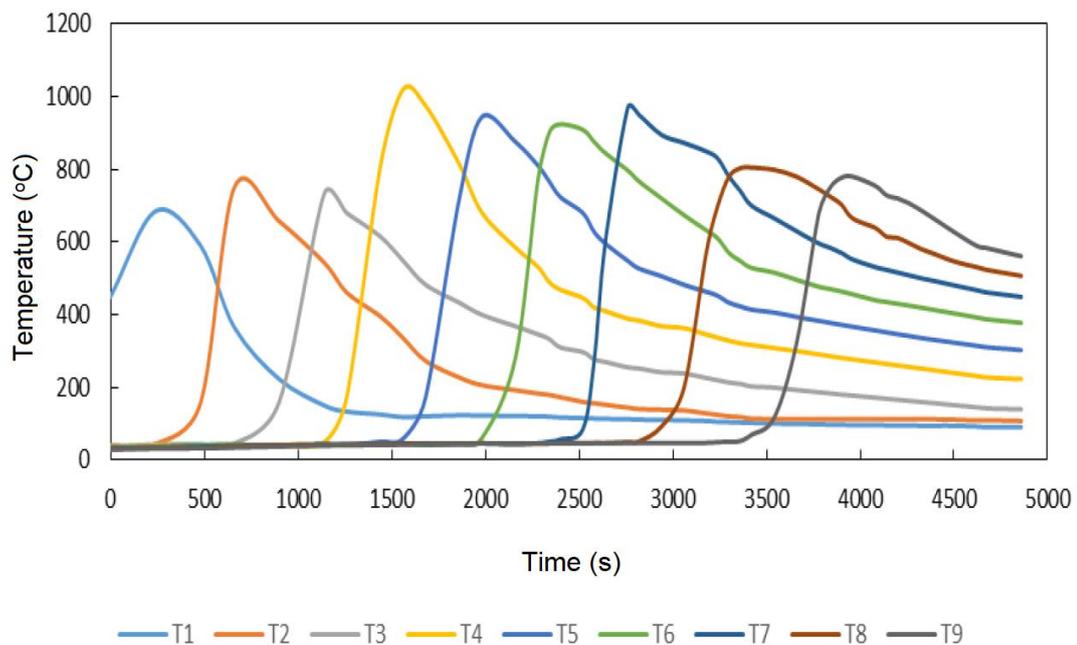

Figure 2. Temperature evolution of the thermocouples positioned along the axial axis of the reactor *versus* time.

Figure 3 shows the position of the combustion front with time. The combustion front velocity, Fig. 4, was determined by means of the time derivative of the function fitted to the experimental data from the front position versus time, Fig. 3. The adjusted function is a polynomial of second order. Figure 3 was obtained based on the time each thermocouple recorded its maximum temperature. The zero time in Fig. 3 and 4 is the time at which the combustion front reached the first thermocouple.

The average velocity of the combustion front, which was approximately 0,125 mm/s, was 53% higher than that obtained by Martins (2010), which used a similar fuel mixture and obtained an average velocity of 0,067 mm/s . This difference can be explained by the difference in the efficiency of the thermal insulation used in the reactors. The reactor of the present work presented a loss by its wall to the environment of about 15% of the heat generated in the combustion, whereas the reactor used by Martins (2010) presented a loss about 42%. Thus, as the losses to the environment are lower in the present work, the flame propagation becomes faster, since a greater amount of energy is available to propagate the combustion front.

$$y = -4E\text{-}06x^2 + 0.1246x - 3.0773$$
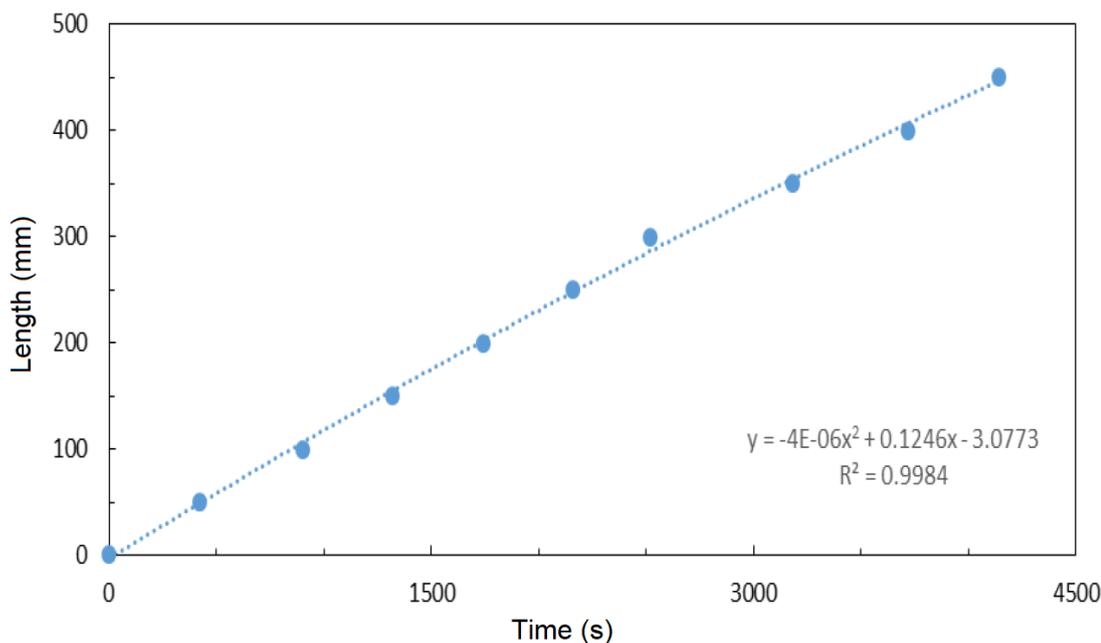$$R^2 = 0.9984$$

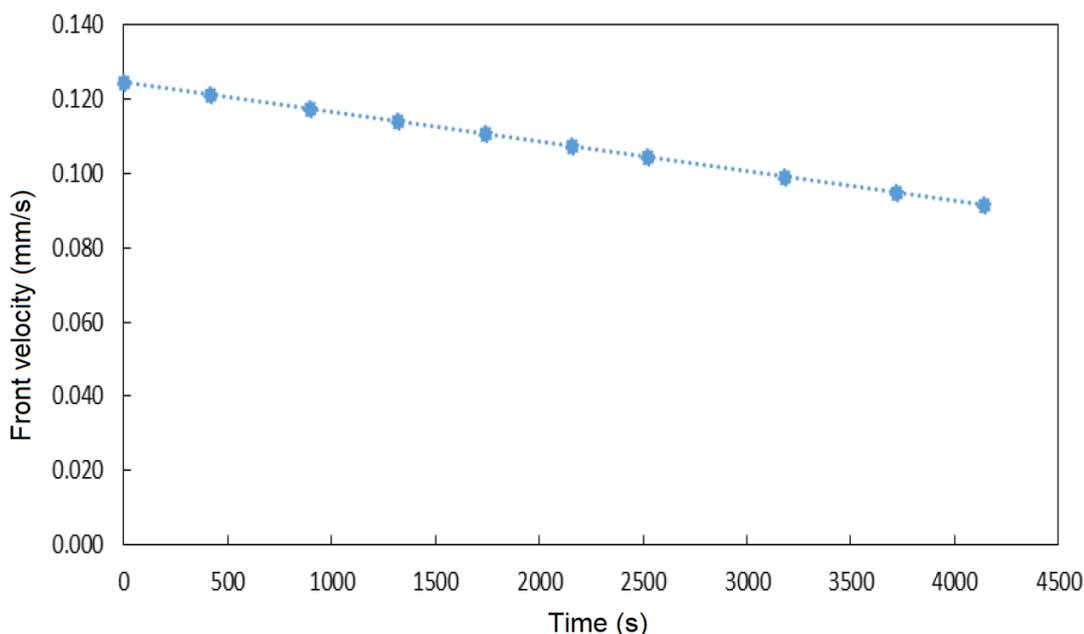Figure 3. Position of combustion front with time.

Figure 4. Combustion front velocity with time.

As can be seen in Fig. 3 and 4, the front speed slightly decelerates with time. This can be explained by the reduction of the air pressure at the compressor outlet, which in addition to reducing the air velocity, also reduced its partial pressure. According to Moore *et al.* (1995), the pressure in the reactor and the oxygen partial pressure are parameters that influence the flame stability.

Figure 5 indicates the temperature distribution along the axial axis of the reactor at different test times. From this temperature distribution it is possible to obtain the thermal structure of the combustion front within the bed, and the respective dimensions of the reaction zones. It is possible to observe that the temperature profile is practically uniform for the different times, indicating that the combustion front has remained stable. It can also be observed that the temperature upstream of the flame decreases slowly. This is because the sand is able to retain a large amount of heat and the air entering the reactor removes heat from the sand slowly. This heat retained by the sand is considered a loss, since this energy is not being used to propagate the flame. If water had been injected with air, the water would remove the heat lost in the sand more efficiently and lead it forward combustion, improving the process efficiency.
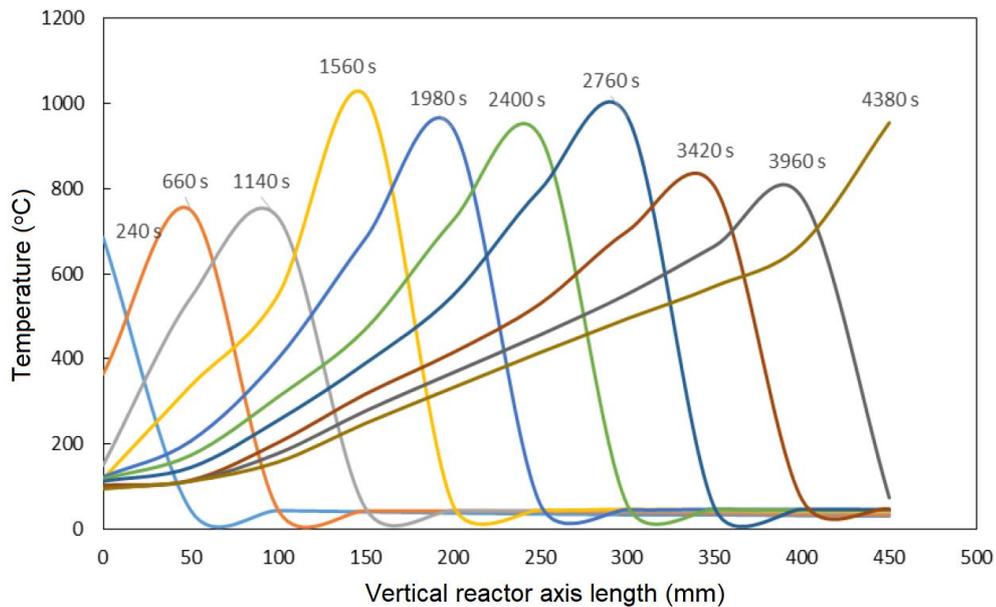

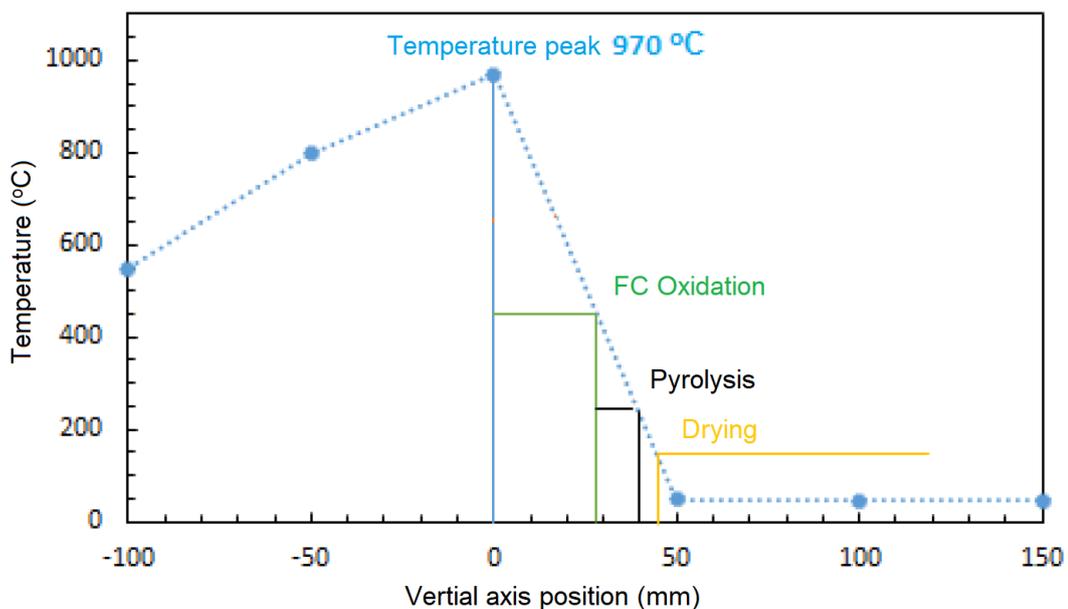Figure 5 – Perfil de temperatura axial do reator em diferentes tempos.

Figure 6. Front structure assessed from the temperature profile with peak in the thermocouple T7.

Figure 6 shows the bed temperature distribution at the time 2760 s of the combustion run, when the front temperature peak reaches thermocouple T7. It can be considered that the drying zone ends at 150 °C, pyrolysis occurs between 250 and 450 °C and that the oxidation of the fixed carbon (FC) occurs at temperatures above 450 °C, as indicated by Martins (2010). In Fig. 6 it is possible to observe that the drying zone is approximately 45 mm from the combustion front, while the pyrolysis starts and ends at 40 mm fand 28 mm from the front, respectively. Fixed carbon oxidation begins at approximately 28 mm before the peak of temperature.

Figure 7 shows the variation of the fuel mass in the reactor as a function of time. It is possible to see that the charcoal mass is consumed slightly faster at the end of the experiment. This is probably due to the high sensibility of balance to small movements of the air around the reactor. The charcoal and sand mixture prepared for the test contained 90 g of charcoal and 1710 g of sand. An extra 10g of charcoal was added to the top of the mixture to facilitate ignition with the flame of the torch. Influenced by the movement of the air or not, it was possible to verify that all mass of fuel as was burned.
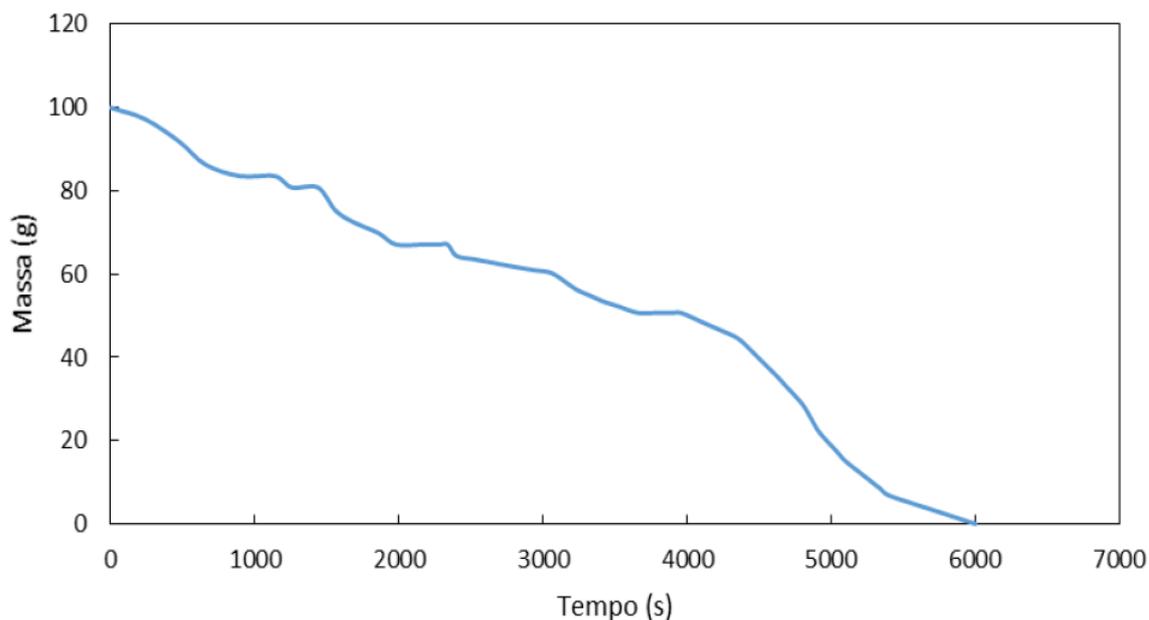

Figure 7. Variation of the charcoal mass in the reactor.

4. CONCLUSIONS

It was observed that the combustion front behaved in a stable manner and that its velocity, although decreasing over time, did not vary much. An explanation for this deceleration may be the pressure drop at the compressor outlet to achieve the desired flow rate. Thus, because of this decrease in the oxygen partial pressure, the front velocity also decreased. It was also observed that the front temperature was always above 650 °C which is an indicator that the high temperature oxidation was stable and that the process was self-sustaining. The thermocouple readings were satisfactory. All fuel has been consumed, which is also an indicator of flame stability and the concentration of fixed carbon and inert material used was able to maintain a stable combustion. The high velocity of the combustion front can be explained by the efficiency of the insulation that allowed most of the heat released in the combustion to remain inside the reactor and was used to continue the process and not lost to the medium through the insulation. Due to the high temperature decrease of the sand behind the front, it can be inferred that the transport of heat front the sand to the front by the air it not efficient.

Thus, it was verified by means of the simulated fuel test that the reactor developed in this work allows to obtain several data on the behavior of the front in the combustion process in-situ. The replacement of simulated fuel by an original sample of the reservoir rock should provide further insight into the feasibility of using ISC method in a given reservoir. It is possible to obtain the evolution of the temperatures inside the reservoir during the process to know in advance if it is possible to apply the method; it will also be possible to observe the probable fuel consumption rate of the well, and the dimensions of the reaction zones from the front propagation. Therefore, the proposed test makes possible the preliminary laboratory-scale study of the feasibility of applying the thermal in-situ combustion recovery method to a heavy oil reservoir.

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