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ROCK OIL RESERVOIR STRUCTURE INFLUENCE ON THE IN-SITU COMBUSTION RECOVERY METHOD FLAME PROPAGATION

Felipe Negrís

Lucas Henrique Pagoto Deoclecio

Filipe Arthur Firmino Monhol

Antonio Carlos Barbosa Zancanella

Instituto Federal do Espírito Santo, *campus* São Mateus - Rodovia BR 101 Norte Km 58, Litorâneo, São Mateus, ES, 29932-540

e-mails: felipenegrís@hotmail.com, lucas.deoclecio@ifes.edu.br, filipe.monhol@ifes.edu.br and antonio.zancanella@ifes.edu.br

Abstract. *The world heavy oils reserves are abundant, making it an important source of energy. The in-situ combustion oil recovery method consists in using the available energy inside the reservoir, by means of burning a portion of the oil, to reduce the oil viscosity, increasing its mobility, unlike conventional methods that inject hot fluids for this purpose. The goal of this work was to experimentally investigate the reactive porous bed composition (granulometry and fuel concentration) influence on flame stability, and consequentially on the in-situ combustion recovery method applicability. The tests were carried out in a single-dimensionally thermal insulated reactor with a simulated fuel composed of sand (inert material) and charcoal (fixed carbon). The 2k factorial design tool was employed to assess each factor influence on the flame stability parameters: bed capacity of sustaining the flame, reached temperatures, average velocity and reaction zones size. The granulometry and fuel concentration were varied in two levels, 180 to 850 μm and 850 to 1700 μm , and 3.5% and 7.0%, respectively. The results showed that the combustion fronts were self-sustaining and that an increase in fuel concentration and a reduction in porous size tended to increase the maximum and average temperature, the front stability and recovery of oil.*

Keywords: *oil recovery, heavy oils, reactive porous media, in-situ combustion, factorial planning 2k.*

1. INTRODUCTION

Heavy oil reservoirs are difficult to exploit, but are found in abundance compared to light oil reservoirs (Sierra, 2015). Therefore, the production, especially in mature source rock, of heavy and ultra heavy oil is a technical and economical challenge for the oil industry. The thermal recovery methods consist in increasing the reservoir temperature in order to reduce the oil viscosity and, thus, facilitating its displacement. This increase in temperature can be caused by the injection of hot fluids (usually steam), where the heat is generated outside the reservoir and transported into it by injections well (Barillas, 2008). The hot fluid injection method is currently the most used for oil recovery (Barillas, 2008). This method has the disadvantages of the steam generation cost associated with burned fuel and the heat losses along the injector wells, making the method impracticable for deep wells (Araújo, 2012). Another way to generate heat is by injecting oxygen into the formation and burning a portion of the reservoir own oil, about 10 %, a method known as in-situ combustion (ISC).

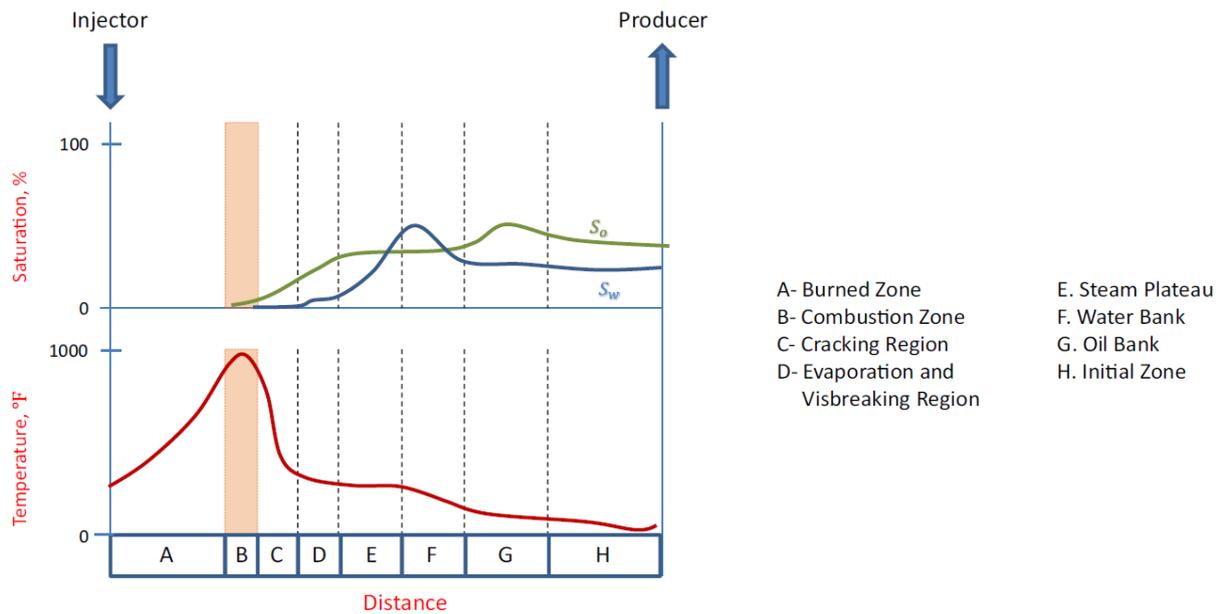
The ISC has the potential to overcome the hot fluid injection problems of steam generation cost and heat losses (Rosa et al., 2006). Thus, in-situ combustion may present higher thermal efficiency, better oil recovery and lower environmental impact (since the CO₂ generated in the burning process remains inside the reservoir) (Rodríguez, 2004). However, ISC projects have high operational complexity due to the reservoirs structure, composition and heterogeneities. Besides, the ISC process creates a number of zones with different temperatures and fluid saturation percentage ranges inside the reservoir, as can be seen in Fig. 1. The front propagates from left (injection well) to right (producer well). Zone A corresponds to the region already burnt, with little traces of unburnt fuel. Zone B is the thin region where the combustion reaction takes place. In zones C and D the heavy oil, without the present of oxygen, under goes pyrolysis to produce fuel for the combustion reaction and the lighter portion of the oil evaporates and it is sent forward. In the steam plateau and in the water bank, zones E and F, water and the lighter portion of the oil condense, releasing latent heat that increases the local oil temperature and reduces its viscosity. The displaced oil is found in zone G, the oil bank. Finally, zone H, the undisturbed region (not yet affected by the front) of the reservoir (Aleksandrov, 2015; Sarathi, 1999).

In order to the ISC to be viable, the combustion reaction must be self-sustaining, and capable of heating up the reservoir zones by means of transportation of hot liquids and gases, so the oil may be displaced. Additionally, the

released heat must produce enough fuel in zone C (cracking region) to keep the process and reach temperatures over 450 °C, so high temperature oxidation reaction (HTO) (combustion) may occur (Martins et al, 2010).

Factorial experiments analysis with factors varying at two levels are known as 2k factorial experiments, where k is the number of factors analyzed. 2k factorial experiment allows to assess the factors effects on process parameters with a minimum number of experiments runs, and hence, it allows to determine the best process conditions.

Figure 1. Characterization of ISC zones with temperature and fluid saturation profiles (Aleksandrov, 2015).



This way, experiments in laboratories with combustion reactors are fundamental for the feasibility analysis of applying the ISC method in an actual reservoir (Chicuta, 2009). These experiments are faster and have a lower cost when compared to the field experiments (Brigham and Castanier, 2007). Thus, the objective of the present work is to evaluate the behavior of the combustion front as a function of the bed characteristics, porous diameter and the components concentration, by means of a factorial experiments analysis. The flame stability parameters evaluated were flame propagation velocity, reached temperatures and reaction zones size.

2. METHODOLOGY

The reactive bed studied was an oil shale source rock, modeled by a mixture composed of sand (inert material) and charcoal (fixed carbon) as studied by Martins et al. (2010). The rock source features studied were the grain size, factor 1 (F1), which represents the rock porous diameter, and charcoal concentration, factor 2 (F2), representing the amount of oil laid down as fuel for the combustion process. Both factors levels were based on the works of Martins et al. (2010) and Chicuta, (2009). The analyses used the 2k factorial experiments to assess the effects of the factors on the flame stability parameters. The four bed compositions used (each of the two factors at two levels) are presented in Tab. 1. After the removal of foreign particles and sieving, the sand and charcoal went through a process of weighing and mixing according to the percentages of each run to obtain a homogeneous sample of charcoal and sand. A mixture of charcoal and sand just before being fed to the reactor is shown in Fig. 2.

Table 1. Mixtures used in the runs.

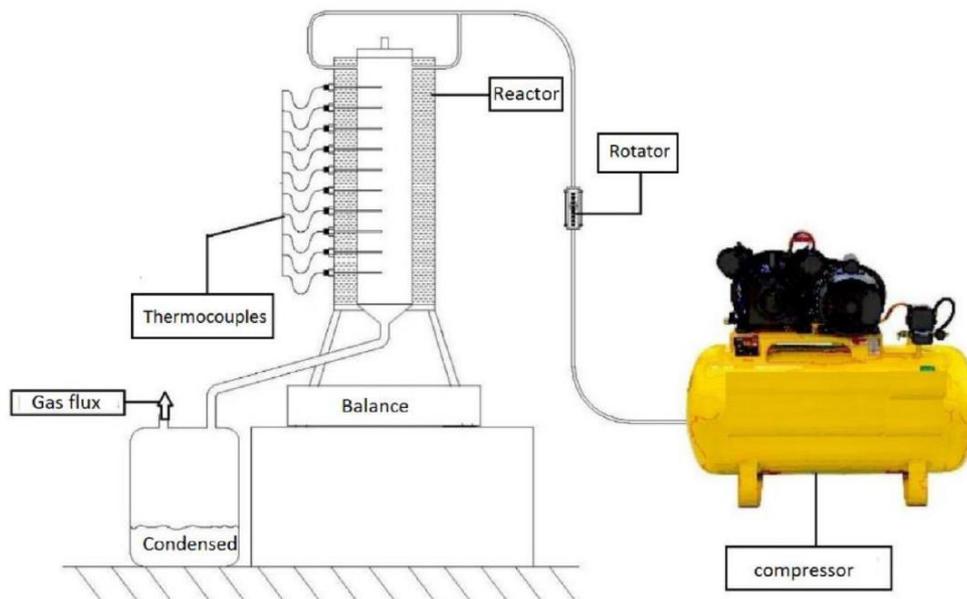
Mixture	Factors		
	Mixture Granulometry	Charcoal % m/m	Factors Level
1	180 a 850µm	3,5%	F1 – e F2 –
2	850 a 1700 µm	3,5%	F1 + e F2 –
3	180 a 850 µm	7%	F1 – e F2 +
4	850 a 1700 µm	7%	F1 + e F2 +

Figure 2. Sample of sand and coal with granulometry of 850 to 1700 μm .



The reactor used for combustion was built by Deoclecio and Monhol (2017) and its schematic layout is shown in Fig. 3. It consists of a stainless steel tube (610 mm long, 63 mm internal diameter and 73 mm external diameter). The ignition of the biomass was done with an oxyacetylene torch through a hole in the reactor cap, close just after ignition. The air injection was made with a compressor with a maximum pressure of 8 bar. A rotameter with a scale of 10 to 100 SCFH, cubic feet per hour, or 7.896×10^{-5} to 7.896×10^{-4} m^3/s , was used for flow measurement and the flow control was done by the needle valve present at the compressor outlet. The flow rate was taken based on the Darcy velocity used by Martins et al. (2010) in the value of 0.024 m/s , or 9.5 SCFH. The temperature measurement is done by 10 type K thermocouples equally spaced 50 mm along the reactor axial axis. Two Arduino Mega 2560[®] boards and one Arduino Uno[®] board were used to read the thermocouple temperature measurements.

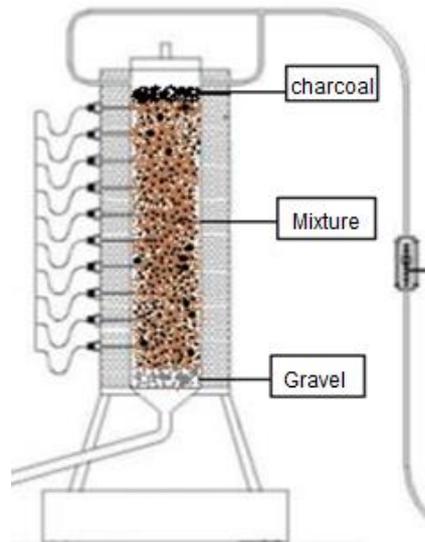
Figure 3. Experimental bench scheme (Deoclecio and Monhol, 2017).



As shown in Fig. 4, a first layer of 100 % m/m charcoal was used on top of the reactor do facilitate ignition. Additionally, a layer of gravel was set at the reactor bottom to prevent the sand and charcoal particles to pass through the sieve placed at the reactor bottom and to clog the exhaust pipes.

In addition to checking if the bed was actually able to sustain the flame in the first place (if the flame does not go out), the effect of the particle size and fuel concentration on the combustion front parameters: maximum and mean temperatures, propagation velocity and front structures (oxidation, devolatilization and drying) size were evaluated to indicate which type of reservoir the ISC best applies.

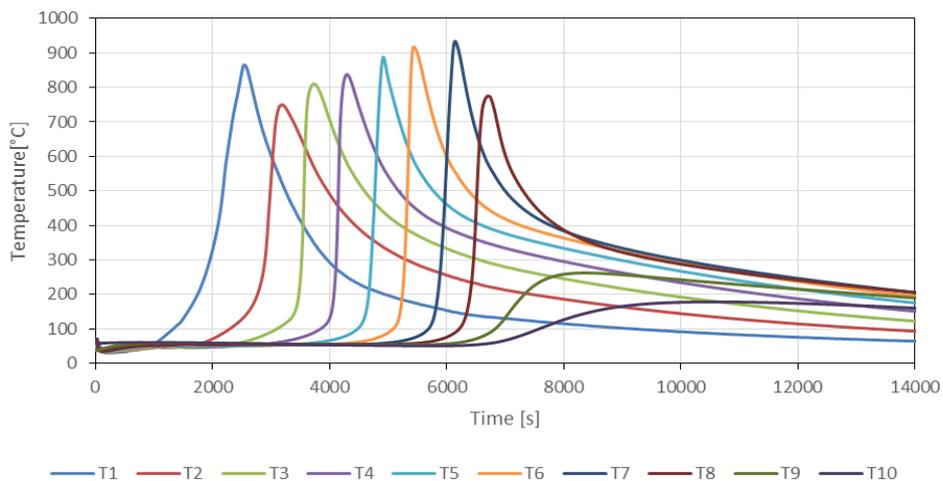
Figure 4. Reactor load with the sand charcoal mixture. Adapted from Deoclecio and Santos (2016).



3. RESULTS

Figure 5 shows the bed temperature profile with time measured by the 10 thermocouples for Mixture 1 (180 a 850 μm and 3,5 %). It is noticed that the bed was able to propagate the flame, since the maximum temperature obtained is higher than 450 ° C, the temperature for the high-temperature oxidation reaction (HTO) (Martins et al, 2010), with the exception of thermocouples T09 and T10. This is probably because during the filling operation of the cell with the mixture, the sand specific mass is greater than the charcoal specific mass, therefore, the former tends to accumulate in the reactor bottom, causing the coal concentration to be lower in there. All other runs showed similar results. All studied beds (all runs) were capable of propagating and sustaining a combustion front; however, heterogeneities in bed composition, as occurred with thermocouples T09 and T10, can affect the flame stability, decrease the temperature and increase the chances of low temperature oxidation (LTO), which should be avoided.

Figure 5. Temperature profile of the mixture 01, particle size 180 to 850 μm and 3,5% of charcoal.



In addition, run 2 (high level of granulometry and low level of fuel concentration) presented the less stable combustion front (although still capable of sustain the flame), and, therefore, more susceptible to low temperature oxidation. Table 2 presents the results of flame propagation velocity, maximum and mean temperatures and reaction zone size for all runs.

Table 2. Results of the stability parameters obtained in the runs.

Mixture	Propagation Velocity [mm/s]	Maximum Temperature [C°]	Mean Temperature [C°]	Reaction zones length [mm]		
				HTO	Devolatilization	Drying
1	0,0848	933,91	722,04	24,5	10	46
2	0,0629	688,34	498,78	21	19	45
3	0,0373	1016,18	772,48	40	29	92
4	0,0602	1002,91	813,46	34	12	65

The reaction zones were defined according to the work of Martins et al. (2010), according to the temperature ranges in which the drying (lower than 150 °C), devolatilization (between 250 e 450 °C) and HTO (between 450 °C and peak temperature) zones occur. Figure 6 presents the front structure for all 4 runs at the maximum measured temperature peak. Mixtures 03 and 04 (higher level of fuel concentration) have bigger devolatilization and drying zones size due to the greater amount of heat released. Bigger devolatilization and drying zones indicates more fuel generated and more oil displaced, respectively, and hence that ISC combustion tends to be more stable and efficient.

Figure 6. Comparison of the temperature profiles along the reactor when the maximum peaks of temperature are reached for all the experiments.

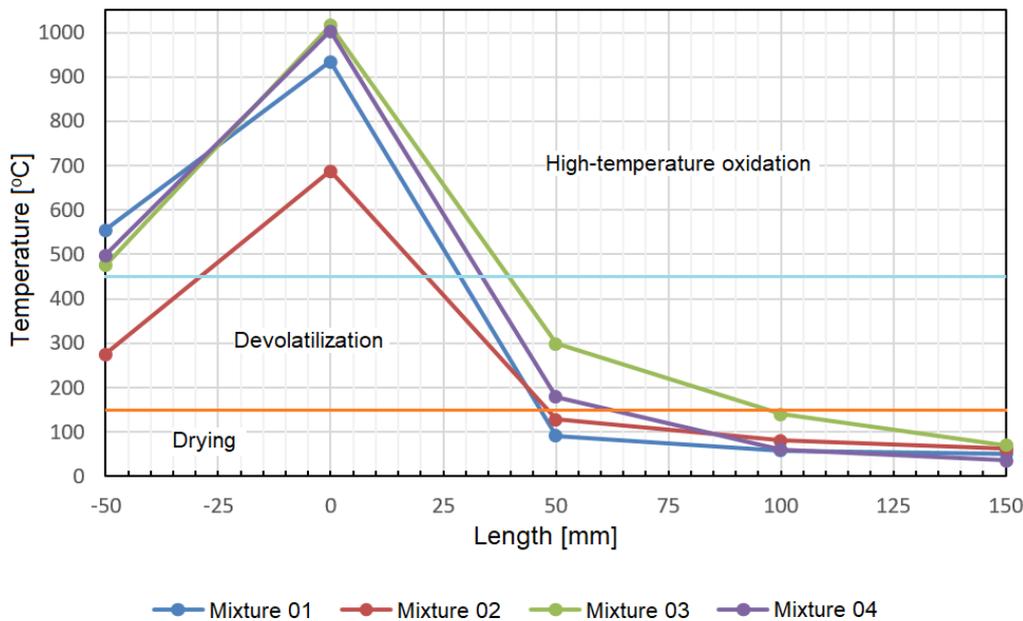


Table 3 and Fig. 7 to 12 present the effects (assesses by means of the 2k factorial analysis) of the factors particle granulometry, fuel concentration, and interaction between these two factors on the flame stability parameters. As can be seen in Fig. 7, 8, 10, 11 and 12, and except for the propagation velocity (Fig. 9), an increase in granulometry, or reservoir rock porous diameters, has a negative effect on the analyzed parameters. Therefore, the larger the particle size, the lower the reached temperatures and the size of the reaction zones. On the other hand, as already expected, an increase in the amount of fuel laid down (charcoal) has a positive effect on the temperature and the size of the front structures; however, the propagation velocity is reduced. Since high temperatures and bigger front zones size indicate a more stable and efficient ISC process, low propagation speed may also be an indicative of stable and efficient ISC process.

The effect of the factors interaction is also significant for the analyzed parameters, showing that an isolated change in porous size or fuel concentration may depend on the other factor level. It is possible to see in Fig. 7 and 8 that a change in the front maximum and mean temperature is not significant for fuel concentration at high level (7,0%), while for low level fuel concentration (3,5%), a decrease in temperature with increase in particle size is significant. However front propagation speed seems do not to be significant for big particle sizes, while for small particle sizes the propagation speed tends to higher at low fuel concentrations.

For the front structures size, the interaction effect on the oxidation zone size is not significant (Fig. 10). For the devolatilization and drying zones sizes, an increase in both factors has the interaction effect of reducing these zones size (Fig. 11 and 12).

Table 3. Effects of particle size and carbon concentration on flame stability parameters.

Stability Parameters	Factors Effect		
	Main Effects		Interaction Effect
	E1 Granulometry	E2 Charcoal %	E12
Propagation Velocity	0,00051 mm/s	-0,02518 mm/s	0,02238 mm/s
Maximum Temperature	-129,42 °C	198,42 °C	116,15 °C
Mean Temperature	-91,137 °C	182,556 °C	132,117 °C
Fixed Carbon Oxidation	-4,75 mm	14,24 mm	-1,25 mm
Devolatilization	-4 mm	6 mm	-13 mm
Drying	-14 mm	33 mm	-13 mm

Figure 7. Main effects and interaction effects for maximum temperature.

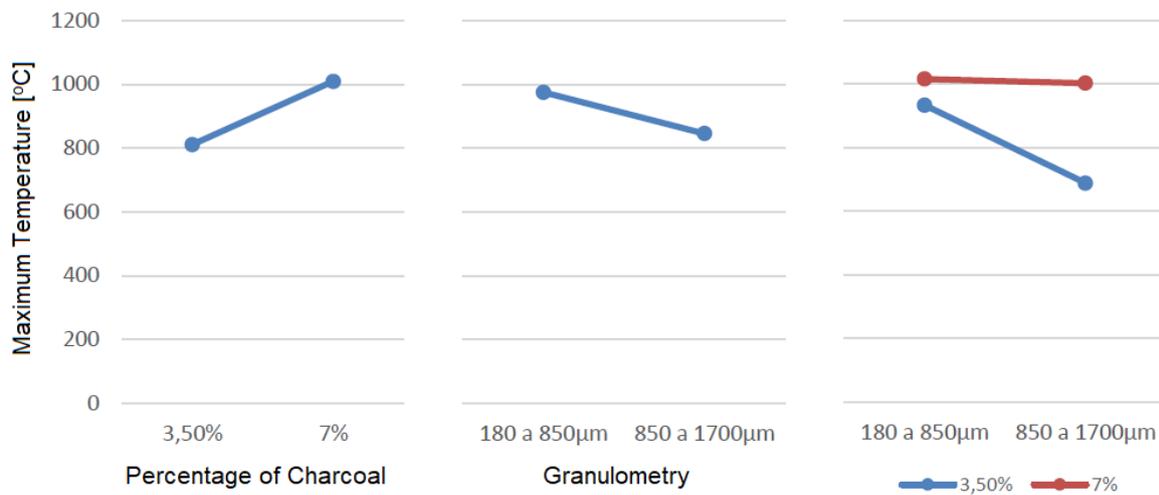


Figure 8. Main effects and interaction effects for mean temperature.

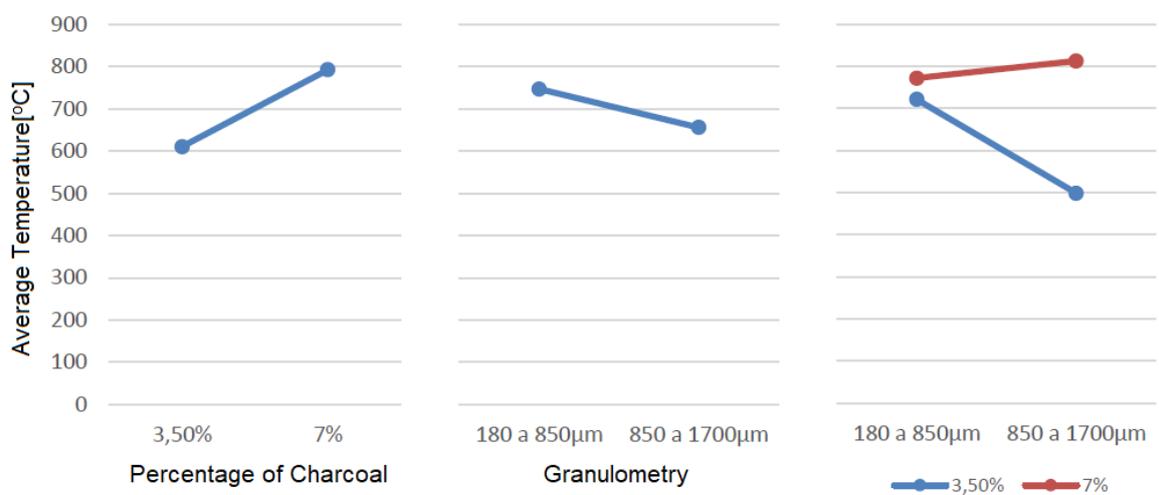


Figure 9. Main effects and interaction effects for the propagation speed

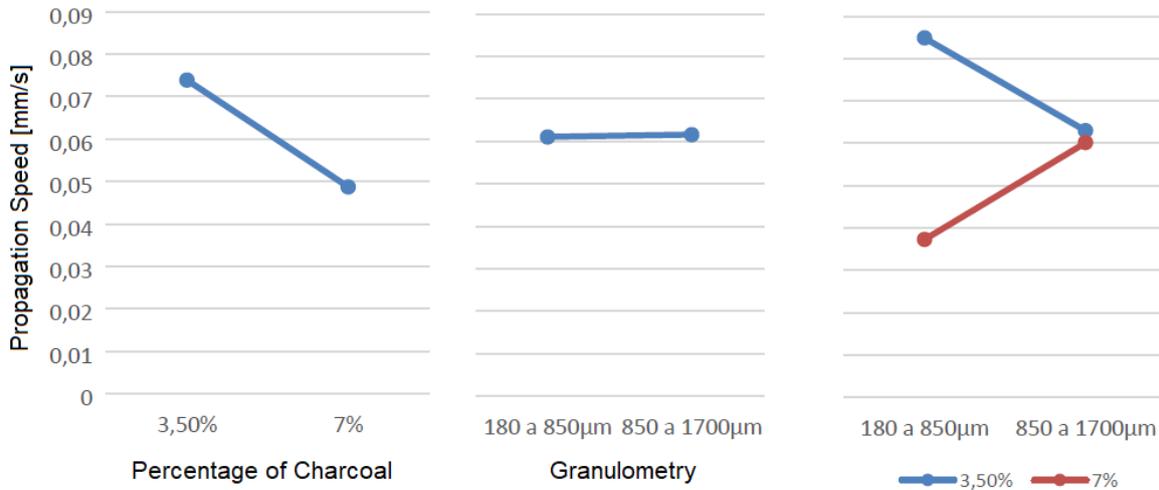


Figure 10. Main effects and interaction effects for the high-temperature oxidation zone size.

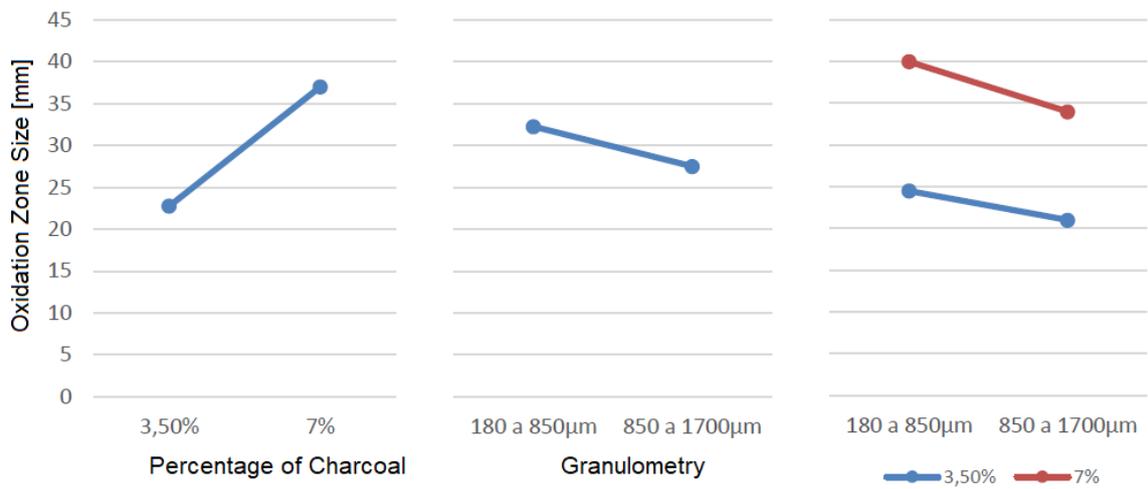


Figure 11. Main effects and interaction effects for the devolatilization zone size.

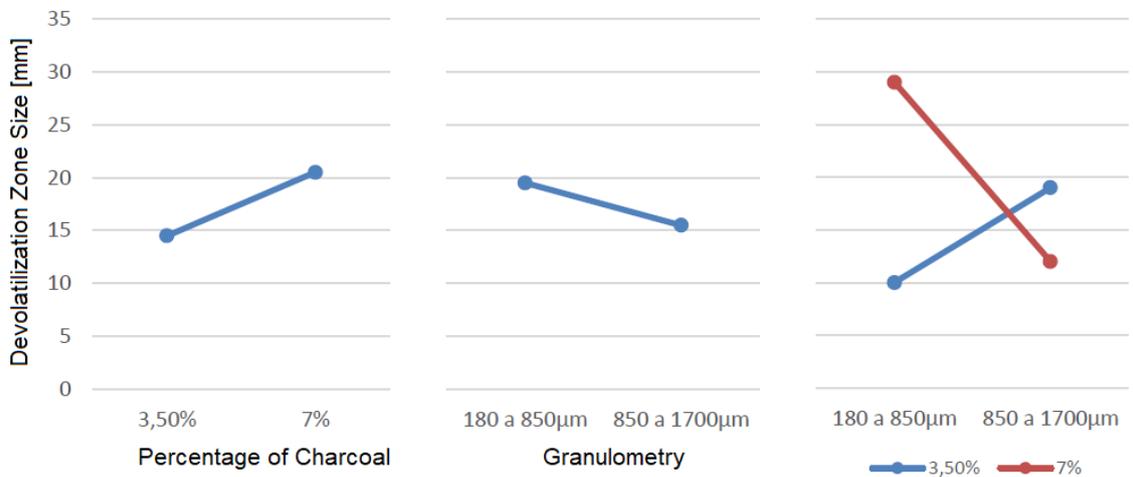
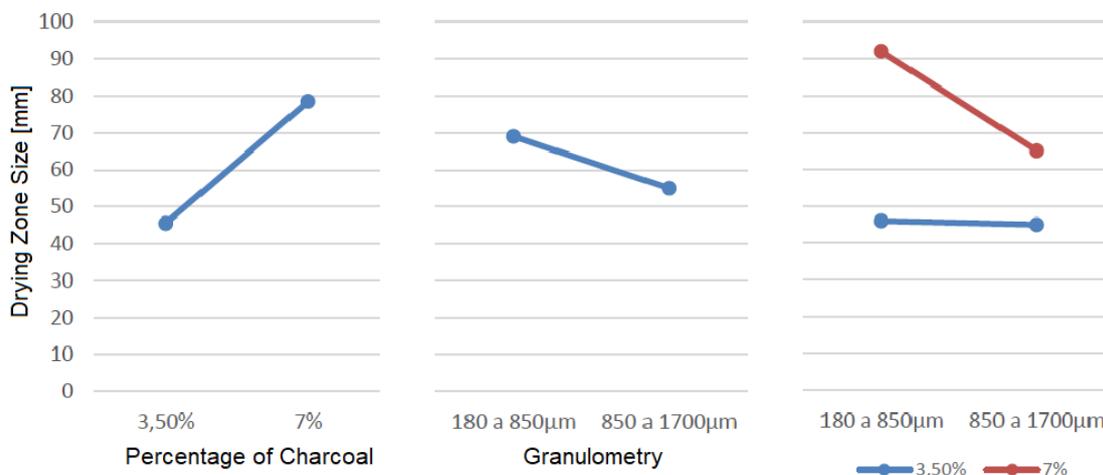


Figure 12. Main effects and interaction effects for the drying zone size.



4. CONCLUSIONS

In this work, the influence of composition and porosity of the reservoir rock on the parameters maximum temperature, average temperature, average velocity and combustion front structures size were assessed by means of a 2k factorial experiments planning in a thermal insulation reactor. A simulated fuel was composed of sand (inert material) and charcoal (fixed carbon) to model the reservoir rock. Based on the works of Chicuta (2009) and Martins (2008), the granulometry used was between 180 to 850µm and 850 to 1700µm with a percentage of charcoal ranging between 3.5% and 7%.

The results showed that an increase in fuel concentration and a decrease in particle size tend to increase the flame stability and the amount of oil recovered. This is probably due to the greater amount of heat released and mixture larger surface area with reduced particle size, which facilitates heat exchange between the flue gases and the region downstream of the combustion front. Thus, with a preheated sand and charcoal, the energy available to sustain the reaction is greater than if the downstream bed were colder. This explains why run 2 was the less stable, once its charcoal concentration was at the lower level and particle size was at the higher level. The increase in flame propagation velocity may be an indicator of flame instability.

Zone sizes are tied to temperature values, the higher the temperature observed, the larger the zones, indicating that the front has higher stability, or available energy.

The farther the drying zone is from the peak temperature (combustion front), the more energy will be available downstream of the combustion front, indicating more energy to heat up the oil, and, consequently, increasing the amount of oil recovered in an actual reservoir.

Heterogeneities of the reservoir rock may compromise the ISC application, since in certain regions of the reservoir the porosity and/or materials concentration may not be able to sustain combustion front.

The nature of the 2k factorial planning to indicate trends allows concluding that the obtained results can serve as a basis to estimate the behavior of the front outside the ranges of granulometry and fuel concentration studied; however, new experiments are necessary to confirm this trend.

5. REFERENCES

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