24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

# COBEM-2017-0903
# DESIGN OF A REACTOR FOR THE ANALYSIS OF COMBUSTION IN A REACTIVE POROUS MEDIUM

**Lucas Henrique Pagoto Deoclecio**
**Filipe Arthur Firmino Monhol**
Instituto Federal do Espírito Santo, São Mateus *Campus*, Highway BR 101 Norte km 58, Litorâneo, 29932-540, São Mateus-ES, Brazil.
e-mails: lucas.deoclecio@ifes.edu.br; filipe.monhol@ifes.edu.br

**Daniel Ribeiro**
Federal University of the Espírito Santo-CEUNES, Highway BR 101 Norte km 58, Litorâneo, 29932-540, São Mateus-ES, Brazil
e-mail: daniel.ribeiro@ufes.br

***Abstract.*** *Heavy oils and solid biomass are important sources of energy. In addition, heavy oil reservoirs and solid biomass burning reactors are composed of reactive porous media. Thus, the understanding of the combustion front propagation phenomena in these media, either for oil recovery or biomass combustion efficiency, is of interest from the energetic point of view. This way, the aim of the present work was to develop, by means of a thermal model, a thermally insulated combustion reactor to allow future studies about the in-situ combustion process in a laboratory scale. The design and construction of the reactor was based on principles of heat transfer, fluid mechanics, combustion, material selection and manufacturing. For this, it was based on literature in which similar devices were used. The reactor is composed of suitable materials for its thermal and mechanical requirements and it has the necessary instrumentation to carry out the small-scale in-situ combustion process. In order to verify the effectiveness of the equipment, a test was carried out in which the behavior of the materials to the imposed thermal regime, sealing and thermal insulation efficiency were verified. The results indicate that a satisfactory study of the process is possible, allowing a convincing perception of the variables that influence the stability, velocity of flame propagation and other in-situ combustion parameters.*

***Keywords:*** *Combustion reactor, In-situ combustion, Reactive porous medium, Solid fuels.*

## 1. INTRODUCTION

The world's growing demand for energy, the failure to provide it and the conditions under which new energy sources are developed have made the energy price rises dramatically in the last decades. As a result, the demand for fossil fuels has increased. The current drop in oil prices and the high supply of conventional oil are due to disputes for global market share between oil producing countries, and not because conventional oil reserves has increased. Thus, in the long term, the depletion of conventional oil reverse will cause the world supply demand to resort to fossil fuels such as heavy oils, coal and natural gas (Cai, *et al.*, 2017; Karimian *et al*., 2017; Monge *et al*., 2015). Moreover, to meet the world demand for energy and to reduce environmental pressure due to greenhouse gas emissions from fossil fuels, the development of renewable energy sources and the increase of energy consumption efficiency seem to be the way to solve both problems (Cai *et al.,* 2017). Among renewable energy sources, solid biomass, such as wood, agricultural production residue and municipal solid waste, has grown and gained prominence worldwide (Kaltschmitt and Janczik, 2015; Karim and Naser, 2016; Vassilev *et al*., 2017).

In addition to being an energy sources, heavy oils and some solid biomass may also have in common the combustion in reactive porous medium. In the case of heavy and extra-heavy oils, their recovery by conventional methods is often not possible due to their high viscosity. The thermal recovery method known as *in-situ* combustion (ISC) allows the recovery of heavy oils from various types of reservoirs. This method consists in the propagation of a combustion front through the reservoir. This front is sustained by burning part of the reservoir own oil and by an injection of air (de Araújo, 2012; Rahnema et al., 2017; Xu *et al*., 2017). Thus, it consists of a complex combustion in a reactive porous medium (Rezaei *et al*., 2013). Similarly, the process of burning solid biomass in a reactor for the purpose of energy generation is also complex due to factors such as: lower amount of carbon, lower heating value, greater amount of moisture, wide range of fuels and their properties and the complexities of combustion of solids. In this way, the development of equipment such as furnaces for steam generation and knowledge of their operating conditions are still limited (Karim and Naser, 2016; Vassilev *et al*., 2017).

The burning of fossil fuels causes environmental impacts such as the transfer of carbon that was stored underground to the atmosphere in the form of $CO_2$, besides others polluting gases. As for biomass, although many authors consider the net emission of carbon to the atmosphere as zero, it also causes impacts in the environment due to the emission of organic micro pollutants such as polycyclic aromatic hydrocarbons, polychlorinated dibenzo-p-dioxins and dibenzofurans (Wielgosinski *et al*., 2017). Thus, the understanding of the variables that influence the propagation of a combustion front in a reactive porous medium is important in order to minimize pollutant emissions in both, solid biomass burning and heavy oil recovery (Monhol, 2015).

The propagation of a flame in a reactive porous medium is a complex process since it involves mechanisms of thermal, chemical and fluid flow (Martins, 2008). To gain knowledge about these processes, the studies in combustion reactors in laboratory scales are an important step in the designing of an *in-situ combustion* project. With these devices, it is possible to evaluate a large number of variables and qualitative and quantitative data of the process (Castanier and Brigham, 2003; Sarathi, 1999).

There are basically two types of reactors, the thermally isolated and the adiabatic. Both consist of a thin-wall metal tube in which the material to be burned is inserted therein. In thermally insulated reactors, the metal tube is surrounded by an insulating material in order to avoid excessive heat losses to the medium during the run (Belgrave et al., 1990). The greater the amount of heat losses, the lower the amount of energy available for the flame propagates itself. Besides thermal insulation, adiabatic reactors also employ heaters, usually electric. As the flame propagates, the heaters release heat in an attempt to maintain the temperature on the outside and on the inside of the tube equal. Thus, since there is no temperature difference on the inner and outer sides of the tube walls, the combustion is said to be adiabatic. However, adiabatic reactors are more difficult to operate since the heaters may add heat to combustion rather than just keep it adiabatic, which would lead to erroneous results. Thus, thermally insulated reactors are easier to operate, although they require a greater flow of air than would be used in the field (Castanier and Brigham, 2003).

Several researchers have already carried out the ISC studies. Bagci and Kok (2001) used vertical combustion reactors filled with limestone saturated with crude oil and water to evaluate the performance of direct dry and wet combustion of heavy Turkish oils under different conditions. They observed that temperature was higher when stable combustion was achieved, and that it decreased as combustion approached the tube exit.

Castanier e Brigham (2003) carried out three tests on combustion reactors to analyze the *in-situ* combustion potential in improving the quality of recovered oil due to the removal of sulfur. In the test without additives, the original oil contained 6% sulfur and the oil produced contained 3% sulfur. In the test with additives, tin chloride and iron nitrate were dissolved in water at a concentration of 5% by weight. In the tests with additives, the combustion was more stable, with less fluctuation, and the amount of sulfur in the produced oil was less than 1% with the same initial concentration.

Belgrave e Moore (1992) proposed a model of a one-dimensional cylindrical adiabatic reactor dived in heating sections, which was developed based on computational simulations and experiments gained from other combustion reactors. The authors assessed in addition to adding energy to the combustion, the heaters may create a convective flow of the gas present in the insulation and add heat to the various parts of the reactor and not just in the region around the heater.

Kök and Ocalan (1995) used a one-dimensional model to assess the feasibility of implementing an ISC project for heavy oil recovery in southeastern Turkey. To do so, the authors combined the concept of combustion front propagation with mass and energy balance equations. Oil recovery histories from three reservoirs were determined, and thus the profitability of the *in-situ* combustion application was calculated.

Martins et al. (2010) created the model of a new one-dimensional combustion reactor to analyze the propagation structure of a combustion front. The authors chose the Timahdit shale oil as a porous medium to characterize the propagation structure of the combustion front. However, the first run was performed using charcoal as fuel to calibrate the reactor. Then, only after, a combustion run with shale was performed. The combustion front propagated almost horizontally. The maximum temperature was 1100 $^{o}$C and the heat loss, despite good thermal insulation, was about 42% of the heat released in the combustion. The thickness of the combustion front was evaluated with the aid of a new model of a micro-sample acquisition system.

Monhol (2015) mapped the effects of operating conditions in a one-dimensional tubular combustion reactor such as: influence of fuel composition, ignition and oxidation of the fixed carbon. The author verified that the combustion regime can be controlled by the reaction itself, or limited by the oxygen injection.

The objective of the present work was to design and manufacture a thermally insulated one-dimensional reactor for the analysis of the combustion front propagation in a reactive porous medium. In addition to the reactor itself, the project also includes the selection and assembly of auxiliary components in order to operate and to acquire data in a safe and accurate way. The auxiliary subsystems include compression and injection of air, flue gas wash and exhaustion, temperature monitoring, data acquisition and processing and ignition. Thus, the experimental bench will allow future studies on combustion in reactive porous media and improve the understanding of the variables involved in the process.

## 2. EXPERIMENTAL PROCEDURE

The design of the experimental bench for the analysis of the combustion process in a porous reactive medium consisted in the dimensioning of the components based on data published in the national and international literature. Figure 1 shows the schematic of the experimental devices proposed for the bench and how the assembling layout during a combustion run. The bench consists of several subsystems that operate together, in which the thermally insulated one-dimensional reactor is the main element developed to obtain data about the combustion process. based on the work of Martins et al (2010), the selection of materials and the design of the reactor were performed according to the maximum temperatures expected in the runs and based on a thermal resistance model for the reactor insulation. Table 1 presents the auxiliary subsystems and their basic requirements. Furthermore, to verify the apparatus ability to obtain data and its integrity a combustion run with a mixture of 5% charcoal and 95% sand by weight was performed.

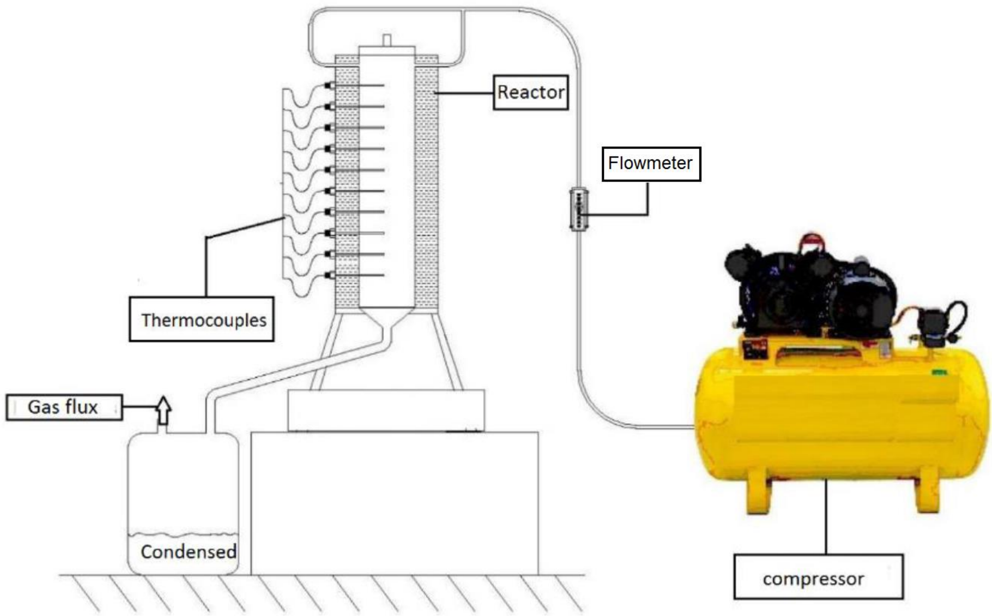


Figure 1. Schematic layout of experimental bench.

Table 1. Experimental bench subsystems, as well as their main components and requirements.

| Subsystem | Components | Requirements |
|---|---|---|
| Reactor | Steel tube | Withstand the experiments high temperatures (about 1200 $^oC$), and having a diameter large enough to reduce heat losses through its walls and small enough to minimize the amount of fuel used. |
| | Insulation | Withstand the experiments high temperatures, having a low thermal conductivity and a thickness that minimizes heat losses. |
| Ignition | Heat Source | It should be capable of initiating the combustion and then do not influencing the ability of the reactive porous medium to propagate the front combustion by itself. |
| Air Injection | Compressor | It must be able to supply air to the reactor in a continuous, controlled and uniform manner. |
| | Flowmeter | |
| Temperature Monitoring | Thermocouples | They should be able to measure the high temperatures reached at the center of the reactor during the runs and resist to its oxidizing medium. |
| Acquisition of Data | Microcontroller | They must process and record the temperature data measured by the thermocouples. |
| Exhaustion | Exhaust Pipe | It has to safely conduct the hot and toxic flue gases to the outside. It also can not clog easily, to prevent a pressure increase in the reactor. |
| | Gas Wash | It has to remove soot from de flue gases. |

## 3. RESULTS AND DISCUSSION

The reactor structure is composed of layer as shown in Fig. 2. Figure 2A shows its main steel pipe. The material selected for the pipe was the A310S steel. This material was chosen due to some of its properties, such as those pointed out by Chiaverini (1996): good stability at the welding temperature, resistant to oxidation in temperatures around 1100 $^{o}$C, can be used in chemical industry equipment and in furnaces. As for its diameter, according to Sarathi (1999), the diameters used in the majority of the experiments that use these devices are in the range of 50 mm to 100 mm. Thus, following the models of reactors proposed and calibrated by Martins (2008) and by Monhol (2015) for the ISC runs, the diameter chosen for the steel tube was 63 mm, its total length was 610 mm, and the height filled with fuel should be in the 450 to 500 mm range. The material to be burnt can not occupy a height greater than 500m due to the space required by the reactor covers.

The reactor proposed by Martins *et al* (2010) was the bases for this project. It allowed a heat loss of 42% of the released combustion heat. This percentage was considered high; therefore, it was proposed in this work that the insulation should not allow a loss greater than 15%. Equation 1 gives the percentage of heat losses, where $Q_{combustion}$ is the heat released in the combustion evaluated as a function of the mass of fuel and its LHV (lower heat value), and $Q_{losses}$ are the heat losses that corresponds to the sum of the heat lost to the environment and the heat absorbed by the insulation itself. Equation 2 gives the heat absorbed by the insulation, where $m_{ins}$ is the insulation mass, $c_{ins}$ is the insulation specific heat, $T_{ave}$ is the mean insulation temperature after the run, estimated by Martins *et al* (2010), and $T_o$ is the insulation temperature at the beginning of the run. Equation 3 gives the heat losses to the environment. For comparative purposes, the test duration time, $\Delta t$, the pipe inner wall temperature, $T_{int}$, the flame length, $L$, and the mean conductivity coefficient between the external insulation layer and the ambient air, $h$, were assumed equal to 7200 s, 900 $^{o}$C, 0,01 m and 15 W/m$^2$.K, respectively, as assumed by Martins *et al* (2010). In Eq. 3, $r$ represents the radius of the insulation layers and the steel tube, $k$ is the thermal conductivity of the materials, and the subscripts 1, 2, 3 and 4 represent, respectively, the radius of the inner and outer walls of the steel pipe, the outer wall of the first insulation layer and the outer wall of the second insulation layer, as show in Fig 3.

In order to minimize heat losses and based on Eq. 1, 2 and 3, the chosen insulations materials and dimensions are composed of a thermal blanket with a thickness of 3 mm, ($r_3 – r_2$, in Fig. 3) (Kaowool 700 E, Thermal Ceramics) with thermal conductivity of 0.14 W/mK at 816 °C and density of 176 kg/m$^3$, shown in Figure 2B, and a 47 mm ($r_4$ - $r_3$, Fig. 3) thick refractory fiber (Kaowool M 42 Board, Thermal Ceramics) with a thermal conductivity of 0.15 W/mK at 816 °C and density equal to 320 kg/m$^3$, as seen in Fig. 2C. The dimensions of the insulation were based on the thermal conductivity of the insulation and the mean convective coefficient between the air and the external wall of the reactor, according to Martins *et al* (2010), so that heat losses during the run were less than 15% of the heat released in the combustion. The amount of heat lost to the environment during the test influences the propagation of the flame, since the amount of energy available to propagate the flame depends on it. After the insulation installation, an aluminum tape was used to secure and maintain the integrity of the insulation, as shown in Figure 2D.

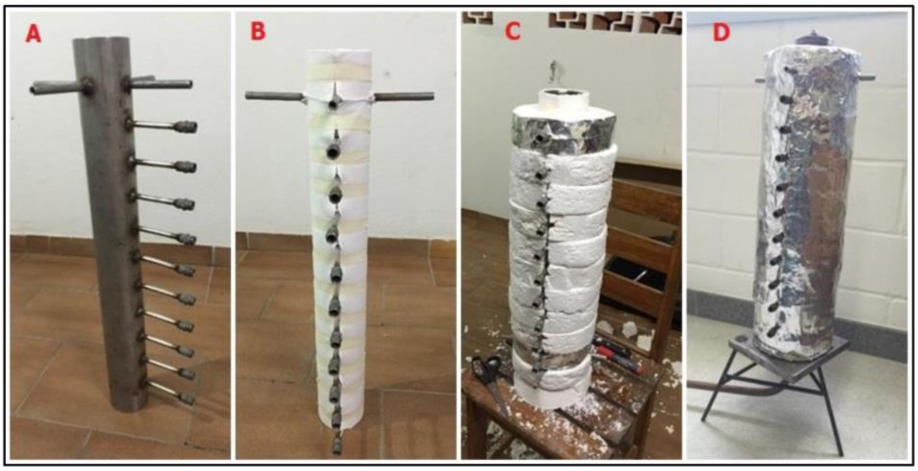


Figure 2. Isolation layers of the reactor. (A) Main tube with ten thermocouples guides tubes and four air inlet tubes. (B) Thermal blanket (first layer). (C) Refractory fiber (second layer). (D) Insulation fixing with aluminum tape.

$$\eta_{\text{insulation}} = \frac{Q_{losses}}{Q_{combustion}} \quad (1)$$

$$Q_{abs} = m_{ins} c_{ins} \left( T_{ave} - T_o \right) \quad (2)$$

$$Q_{env} = \frac{T_{int} - T_o}{\frac{1}{2\pi r_4 L h} + \frac{\ln(r_2/r_1)}{2\pi k_{1-2} L} + \frac{\ln(r_3/r_2)}{2\pi k_{2-3} L} + \frac{\ln(r_4/r_3)}{2\pi k_{3-4} L}} \times \Delta t \quad (3)$$

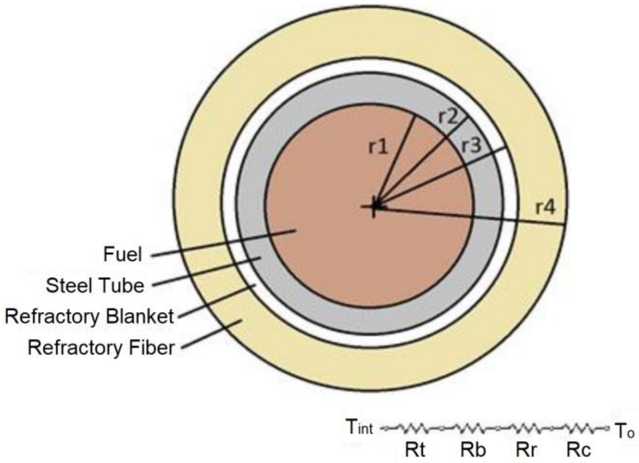


Figure 2. Schematic view of reactor cross-section with insulation layers, steel tube and fuel.

The ends of the tube are closed by screwed covers, which can be removed to allow introduction or removal of material and ignition. As the wall of the tube is reasonably thin, a tapered thread cover was not used to promote sealing. Then, the covers fencing was done by means of the o-ring 3018-70B manufactured by *Parke*®. This ring is recommended for sealing applications involving air up to 260 °C (Parker, 1997). After the test run, integrity and sealing capabilities of the rings were verified. The reactor covers as well as the sealing rings position can be seen in Fig. 4A. In addition, the top cover contains an access (threadable cap) to allow inner access for ignition. The bottom cover also has an opening, however its goals is to connect the reactor to the exhaust subsystem.

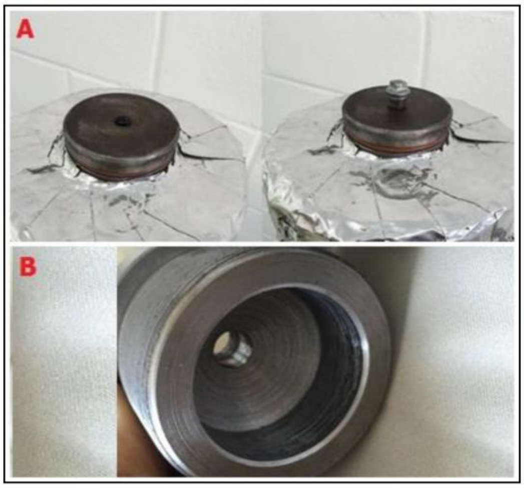


Figure 4. (A) Top cover screwed onto the reactor. On the left side, the cover without its cap to allow the torch flame to enter the reactor, and on the right side the cover with the its cap. (B) Inside view of top cover.

As can be seen in Figure 2A, there are 14 smaller diameter tubes welded to the sides of the main tube. The welds of these small diameter stainless steel tubes were made with MIG welding. The 10 tubes aligned in the vertical plane have the function of guiding the thermocouples to the center of the main tube. The temperature monitoring system consists of 10 metal K-type TCM thermocouples with 3.26 mm gauge from *Alutal*®. These thermocouples use are recommended for maximum temperature of 1260 °C that is in the range of maximum temperature expected in the runs. The ten thermocouples are aligned in a vertical plane and measure the temperature along the axial axis of the reactor center as shown in Fig. 5A. Figure 5B shows an example of a thermocouple, while Fig. 5C exemplifies the connection system of the thermocouples to the reactor. Washers were used to seal these connections. The first thermocouple is located 100 mm from the top of the reactor and the others 9 are located 50 mm below each other. During the test run, it was verified that the thermocouples were able to measure the temperatures and to generate valid results for the studies.

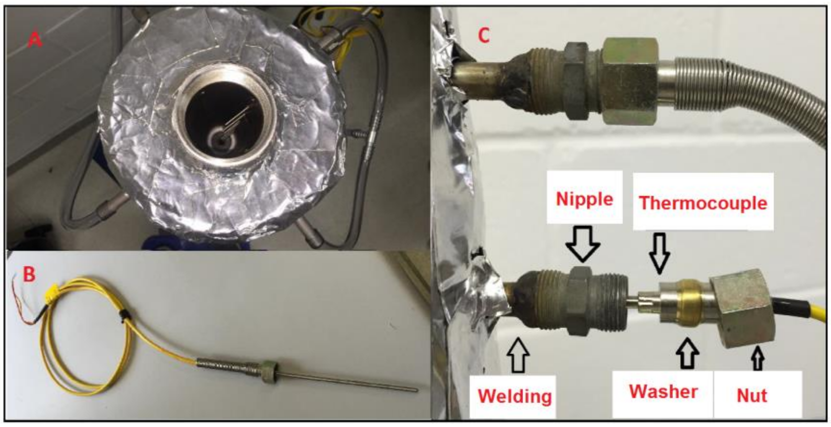


Figura 5. (A) Internal view of the reactor and the thermocouple tips in its center. (B) Thermocouple. (C) Connection of a thermocouple to the reactor by means of a guide tube using a system of washers, nipples and nuts in exploded view.

The 4 tubes on the top of the reactor that are on the same horizontal plane are the air inlets. The air injection system is composed of a compressor, a needle valve, a rotameter and 4 air intakes, according to Figure 6. The air exiting the compressor has its pressure controlled by a pressure regulator valve and a pressure gauge and its flow controlled by a needle valve also at the compressor outlet. Before arriving in the reactor, the air passes through a flowmeter in order to assess its velocity. Soon after, the air enters the reactor by four entrances, so that the air intake is evenly distributed. The air injection subsystem proved to be robust and easy to operate. In addition, it has the flexibility to provide different air flows and pressures in order to allow the study of the influence of air injection on combustion.

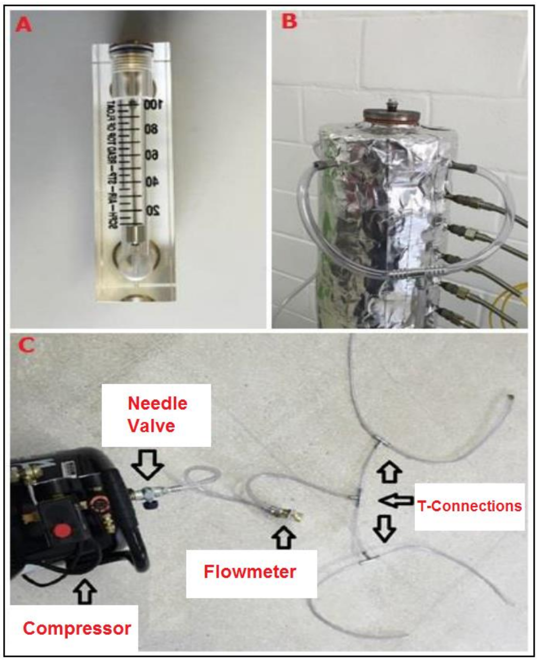


Figure 6. (A) Flowmeter. (B) Air hoses connected to the reactor through the four air inlet tubes. (C) Air injection subsystem with compressor, needle valve, rotmeter and three double outlet connections.

The ignition system consists of an oxyacetylene torch. The flame can be introduced through the opening in the top cover. After ignition, the torch flame is removed and the end covers is closed. To facilitate ignition, it is recommended to use a higher fuel concentration at the top. This extra amount of fuel should be small enough not to interfere with thermocouple temperature readings. During the validation test run, it was possible to verify that the flame of an oxyacetylene torch is an efficient and safe way of igniting the system.

The selected signals acquisition and processing used the *Arduino*®, Fig. 7, which is a platform development for boarded systems based on the ATmega microcontroller. It is a low cost solution in which the temperature sensors (thermocouples) can be connected for possible indication of the measured temperatures and processing of the data referring to such temperatures. The thermocouples are connected to the microcontroller via Max6675 modules.

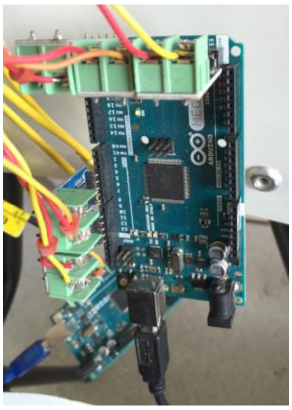

Figura 7. Signal acquisition and processing system.

The exhaust subsystem is shown in Figure 8. The exhaust tubing is comprised of a 19 mm diameter copper tube connected to a 19 mm diameter automotive (high temperature resistant) radiator hose. The diameter of the pipe was chosen equal to 19 mm, because this diameter allows a head loss of less than 500 Pa, which is the initial gauge pressure inside the reactor used by Martins (2010), besides big enough so that it is not easily clogged with any material that might come off the reactor.


Figure 8. (A) Gas outlet on the bottom cover and hole in the holder to allow the reactor fitting. (B) Copper exhaust gas pipe connected to the reactor outlet. (C) 19 mm copper tube flange to provide sealing. (D) Gas washer system with radiator hose connected to the inlet and outlet of the water wash tank.

Before the first combustion test was carried out in the reactor, a sealing test was performed. To do this, all inlets and outles ware closed, and, then, foam was used to check for leakings. It is recommended that a leakage test to be performed periodically in order to verify possible degradation or malfunction of the seals, be it the o-rings, the thermocouple conections, or the exustion pipes connections. After confirmation of the absence of leakage, a test to verify the capacity of the reactor for the *in-situ* combustion study was performed. The tests allowed to verify the integrity of the equipment after exposure to the high temperature of the test. In addition, the data indicate that the oxidation of the coal at high temperature (above 500 $^{o}$C) occured, thus validating the bench for future studies on the subject. Nowadays the bench is in operation and results from studies on combustion in reactive porous media are already showing up. One can cite among the studies in progress the analysis of the coconut shell combustion and of urban sludge waste for the energy generation. There are also ongoing projects of *in-situ* combustion using heavy oil rock reservoir samples.

The complete experimental bench is shown in Figure 9 during a run burning coconut shell. As can be seen in the figure, the temperature data are recorded on the laptop automatically according to the microcontroller's programming, which reduces the need for continuous presence of an operator.

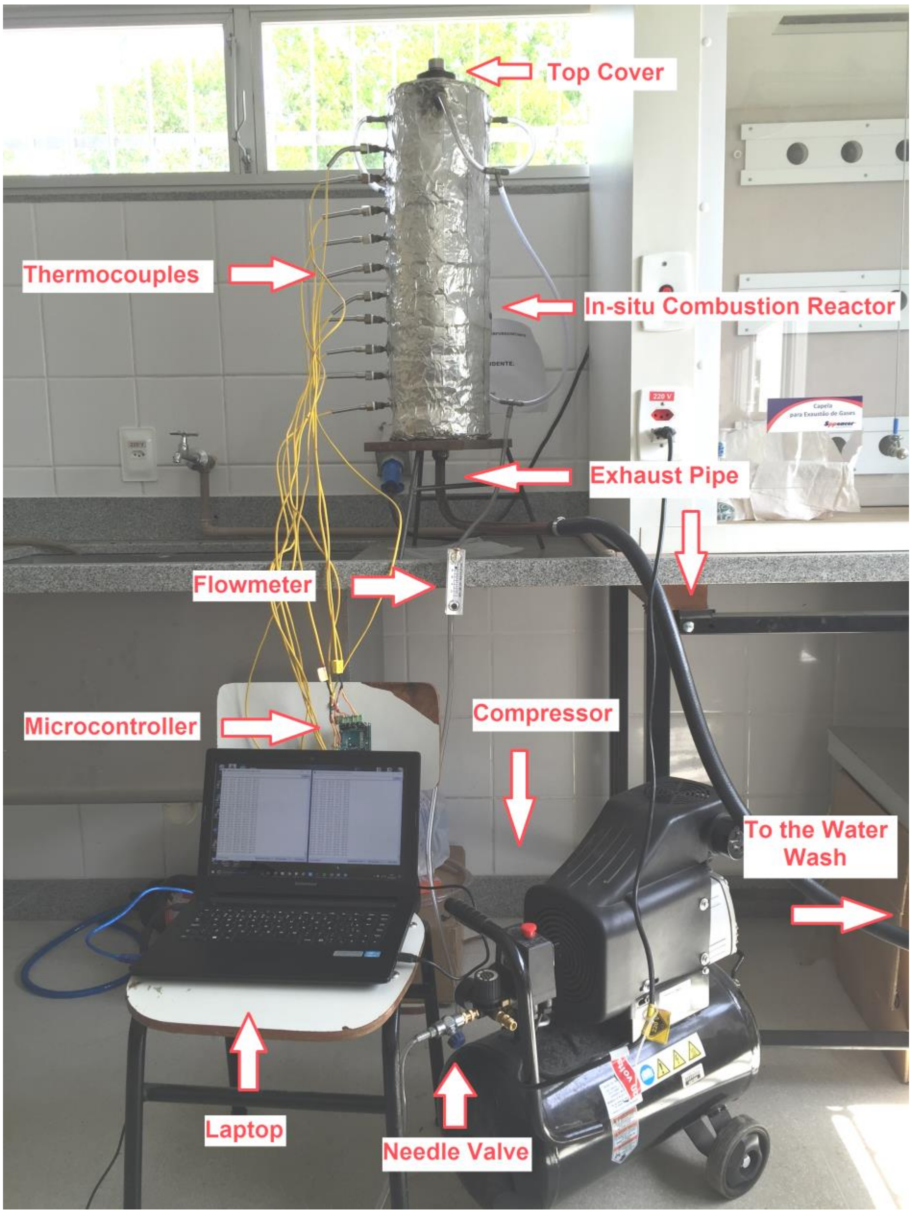


Figura 9. Complete experimental apparatus.

## 4. CONCLUSIONS

It was possible, based on the national and international literature, to construct not only a one-dimensional reactor thermally insulated for the analysis of the combustion in reactive porous medium, but also to select and to manufacture subsystems that are part of experimental bench as a whole. A test run with a mixture of 5% charcoal and 95% sand by weight allowed verifying the ability of the bench as a tool by which researchers can study the phenomena involved in the propagation of a flame in a reactive porous medium. Several subsystems were coupled to the reactor in order to safely and reliably operate and obtain data on the combustion process. Auxiliary subsystems include air injection and compression, exhaust and gas wash, temperature monitoring, data acquisition and processing, and ignition. A leakage test was performed and no leaks were verified. After the test, the integrity of the components and the data obtained were analyzed. The obtained data will be presented in a separate paper. Thus, it was found that the seals and other components were in good condition and that the reactor was able to propagate a stable flame within it without allowing gas leakage.

The selected materials were chosen based on the temperatures estimates for the tests based on works on combustion in unidimensional reactors published in the literature. The insulation allowed a heat loss of less than 15% of the total heat released in the combustion, lower than that of other reactors found in literature. This implies a better approximation of the adiabatic conditions required for the combustion processes. The air injection system proved to be capable of supplying the air demand efficiently. The ignition with the torch flame was done quickly, safely and without influencing the thermocouple readings. The thermocouples were able to measure and withstand the high process temperatures. The temperature readings were processed and registered automatically by a microcontroller.

## 5. REFERENCES

Bagci, S and Kok, M. V., 2001. "In-situ combustion laboratory studies of Turkish heavy oil reservoirs". *Fuel Processing Technology*, Vol. 74, n. 2, p. 65-79. DOI: http://dx.doi.org/10.1016/s0378-3820(01)00213-2.

Belgrave, J. D. M. et al., 1990. "The thermal behavior of vertically-operated near-adiabatic in-situ combustion tubes". Journal of Petroleum Science and Engineering, Vol. 5, n. 1, p. 51-65. DOI: https://doi.org/10.1016/0920-4105(90)90005-N.

Cai, W. et al., 2017. "A tool for assessing the energy demand and efficiency of machining systems: Energy benchmarking". *Energy*, Vol. 168, p. 332-347. DOI: https://doi.org/10.1016/j.energy.2017.07.039.

Castanier, L.M. and Brigham, W.E., 2003. "Upgrading of crude oil via in situ combustion". Journal of Petroleum Science and Engineering, Vol. 39, n. 1-2, p. 125-136, DOI: http://dx.doi.org/10.1016/s0920-4105(03)00044-5.

Chiaverini, V., 1996. *Aços e ferros fundidos*. ABM, São Paulo: Abm, 7th edition,. 599 p.

de Araújo, J. S., 2012. Estudo paramétrico do processo de combustão in situ como método de recuperação avançada de petróleo. Ph.D. thesis (Doctorate in Petroleum Engineering), Universidade Federal do Rio Grande do Norte, Natal.

Kaltschmitt, M. and Janczik, S., 2015. "Biomass to power is on the rise globally". *Renewable Energy Focus*, Vol 16, n. 5-6, p. 174-176.

Karim, M. R. and Naser, J., 2016. "Numerical modelling of solid biomass combustion: difficulties in initiating the fixed bed combustion". In *1st International Conference on Energy and Power, ICEP2016*, 14-16 Dec., RMIT University, Melbourne, Australia.

Karimina, M. *et al*., 2017. "Estimation of the kinetic triplet for in-situ combustion of crude oil in the presence of limestone matrix". *Fuel*. Vol. 209, p. 203-210. DOI: https://doi.org/10.1016/j.fuel.2017.07.098.

Martins, M. F., 2008. *The Structure of a Combustion Front Propagating in a Fixed Bed of Crushed Oil Shale: Co-Current Configuration*. Ph.D thesis, University of Toulouse, Toulouse.

Martins, M.F. *et al*., 2010. "Co-current combustion of oil shale – Part 2: Structure of the combustion front". *Fuel*, Vol. 89, n. 1, p. 133-143, DOI: 10.1016/j.fuel.2009.06.040.

Monhol, F. A. F., 2015. Uma contribuição experimental aos fundamentos da propagação de uma frente de combustão em meio poroso. Dissertation (Master Degree in Mechanical Engineering), Universidade Federal do Espírito Santo, Vitória.

Monge, M. *et al*., 2015. "U.S. Shale Oil Production and WTI Prices Behaviour". *Energy*, Vol. p. . DOI: 10.1016/j.energy.2017.09.055.

Parker, 1997. *Manual de o'ring: seals. São Paulo: Parker Hannifin*. 104 p. 12 mar. 2016 http://www.parker.com/parkerimages/br/download/seal/pdf/5700_br.pdf.

Rahnema, H. et al., 2017. "Combustion assisted gravity drainage – Experimental and simulation results of a promising in-situ combustion technology to recover extra-heavy oil". Journal of Petroleum Science and Engineering, Vol. 154, p. 513-520. DOI: http://dx.doi.org/10.1016/j.petrol.2017.01.044.

Rezaei, M. et al., 2013. "Thermocatalytic in situ combustion: Influence of nanoparticles on crude oil pyrolysis and oxidation". Fuel, Vol. 113, p. 516-521. DOI: http://dx.doi.org/10.1016/j.fuel.2013.05.062.

Sarathi, P. S., 1999. In-Situ Combustion Handbook - Principles and Practices. National Petroleum Technology Office: Tulsa, Oklahoma. Report DOE/PC/91008-0374, OSTI ID 3174.

Vassilev, S. V. *et al*., 2017. "Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion". *Fuel*, Vol. 208, p. 377-409. DOI: https://doi.org/10.1016/j.fuel.2017.07.036.

Wielgosinski, G. *et al*., 2017. "Emission of some pollutants from biomass combustion in comparison to hard coal combustion". Journal of the Energy Institute, Vol. 90, p. 787-796. DOI: https://doi.org/10.1016/j.joei.2016.06.005.

Xu, Q. et al., 2017. "Chemical-structural properties of the coke produced by low temperature oxidation reactions during crude oil in-situ combustion". Fuel, Vol. 207, p. 179-188.

## 6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.