Effects of High Temperature in the Combustion Chamber of a Drop Tube Furnace (DTF) for Different Thermochemical Processes

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Abstract

Thermochemical and biochemical processes are used to convert biomass into useful and sustainable energy. Thermoconversion processes comprises the biomasses burning in an oxygen-rich environment or in the absence of this, where types and fuel properties, process conditions, particles size, air flow rate and fuel moisture affect directly the combustion characteristics, altering the generation and heat transfer and the reaction rates. The combustion chamber temperature is an important factor for the biomasses combustion or other material, because this exerts large influence in the thermal processes efficiency, products yield and composition of the generated products. For this reason, this paper aims to investigate the temperature behavior in the combustion chamber of a Drop Tube Furnace (DTF) for the thermochemical processes (conventional combustion, pyrolysis and two typical oxy-fuel combustion atmospheres), when five Brazilian biomasses (pine sawdust, sugarcane bagasse, coffee and rice husks, and *tucumã* seed) are employed. Such monitoring *in situ* was performed using two thermocouples located inside the furnace: one in the upper and other in bottom part. Results showed for the different biomasses and atmospheres used, a trend in the combustion chamber temperature variations (measured by thermocouples) and residence times, which can be related to the biomasses feeding system, moisture samples and specific furnace operation conditions.

Keywords: biomasses, efficiency, gases composition, performance, thermal processes.

1. INTRODUCTION

Brazil, compared to other countries, uses more alternative energy sources and is a major producer of sugarcane and coffee worldwide [1,2].

At last 20 years, it was highlighted a crescent consensus worldwide of that fossil fuels are main responsible for promoting environmental damages and, as consequence, climate changes in the Planet and still interfere directly in the human health, animals and plants [3,4].

The new technologies developing for the sequestration and CO_2 capture, aims to mitigate this situation, for example, a promising alternative is the use of renewable fuels for the energy production [5]. Several studies have been conducted to elucidate the various thermal conversion processes using biomasses [3,5-10].

However, for a perfect understanding of the central point of this research, a brief literature review of some studies about the combustion of different lignocellulosic materials and atmospheres in a DTF will be necessary.

According to Adams *et al*. (1999) [11], Drop Tube Furnaces (DTFs) are commonly used for obtaining of kinetic parameters from pyrolysis processes or oxidation of different concentrations, and gases composition. DTF also presents information about temperatures, oxygen concentrations and residence times.

The reactivity of the sawdust char combustion in a DTF was investigated by Meesri and Moghtaderi (2003) [12]. The study involved experimental determination of the global kinetic parameters of the oxidation reaction of the sawdust char. Results indicated that large part of the oxidation reaction of the sawdust char occurred at second regime, *i.e*, the heterogeneous chemical reaction rates and oxygen diffusion in the internal pores are comparables.

Biagini *et al*. (2005) [13] developed a drag flux reactor or Drop Tube Furnace (DTF) in lab-scale for characterizing a biomass (hazelnut shell) and bituminous coal (Kema). Some experimental techniques were applied for determination of the conversion degree, reactivity and morphology of the solid fuels. A special attention was given by authors to the feeding device in order to understand the DTF versatility for different materials or biomasses.

The combustion of a brown coal under N_2/O_2 and CO_2/O_2 mixtures was developed in a Drop Tube Furnace (DTF) of laboratory scale as studied by Zhang *et al*. (2010) [14]. Results indicated that replacing of CO_2 with N_2 significantly affected the coal combustion behavior by the CO_2 physical-chemical influence and CO_2 interaction with char. Changes were also observed in the coal pyrolysis behavior by means parameters as ignition point, volatile materials temperature and char particles size, which were reduced by CO_2 atmosphere, eliminating all coal oxidation.

Haykiri-Açma *et al*. (2013) [15] evaluated the combustion process efficiency of hazelnut husks in a Drop Tube Furnace (DTF), when these were tested to average temperatures (600 to 900 ºC), commonly in this furnace type are used equal temperatures or superior at 1000 ºC. The authors showed that some biomass properties, such as functional groups distribution, quantities of cellulose and lignin, heating rate and ignition point were not affected. However, variations in the other properties were noted, for example, remaining volatiles amount, total organic materials, morphologies and reactivities.

For Wang *et al*. (2014) [16], the biomass particles yielded combustion values comparable to coals, which can be explained by the high volatile materials content in the biomasses, which are released during combustion process. The high moisture amount and large size of the biomass particles caused the combustion effects to be decreased. It was also noted that residence time of the solid fuels (coal, rice and coffee husks, pine branches, straw and residue derived fuels) in the DTF was strongly affected by particles size.

Álvarez *et al*. (2014) [17] studied the co-firing of olive residues with coal fractions in a Drop Tube Furnace (DTF) under typical oxy-fuel combustion and synthetic air atmospheres. In all cases the co-firing of biomass with coal found synergetic effects favorable, improving significantly the combustion and reducing the NOx emissions. The samples temperatures were reduced during co-firing, this decrease contributed to assuage the ash formation and deposition in the furnaces bottom.

The combustion chamber temperature has an important role in the biomasses combustion, because this exerts great influence in the thermal processes efficiency, products yield and gases composition generated [18]. This study aims to investigate the temperature behavior inside the combustion chamber of a Drop Tube Furnace (DTF) for the different thermo-conversion processes: conventional combustion (synthetic air, 80% N_2), pyrolysis (100% nitrogen) and two typical oxy-fuel combustion atmospheres (60 and 80% CO_2), when Brazilian biomasses (pine sawdust, sugarcane bagasse, coffee and rice husks, and *tucumã* seed) are employed.

2. MATERIALS AND METHODS

2.1 Biomasses Origin

The five *in natura* biomass samples used in this study were collected from different regions of Brazil, namely: sugarcane bagasse, pine sawdust and coffee husk samples (São Paulo State, Southeast region); rice husk (Maranhão State, Northeast region) and *tucumã* seed (Pará State, North region). It is interesting to mention that each Country region exhibits a vegetation and climate that are clearly defined and differentiated; these features facilitate the planting of several native species, which require very specific natural conditions.

2.2 Biomasses Preparation

The biomass samples have been received *in natura* from their respective regions and underwent pretreatments that comprised: washing in running water to remove impurities, grinding in laboratory knives mill to decrease particles size and subsequent sieving for separation in the required granulometric range. The *in natura* biomass samples have been pulverized using a household blender and thereafter sieved. For all the biomass samples, average sizes of 0.46 mm particles were selected. The biomass samples used in this research were prepared according to the procedures established by standard ASTM (D 2013-72) [19].

2.3 Drop Tube Furnace (DTF)

A Drop Tube Furnace (DTF) electrically heated (3.5 kVA maximum power) (Figure 1) was used for all the thermal processes of the biomasses. The basic dimensions of the experimental apparatus are 60 mm outer diameter, 400 mm uniform zone and 200 mm heated zone. The biomass particles were introduced into the reactor (DTF) by a feeding system with vibratory mechanical transport and controlled by PWM (Pulse Wide Modulation), where the optimal rotational velocities and frequencies were achieved for each material. The sample mass used was 3.0±0.5 g for a 10-minute experiment. An air primary flow rate of 1.5 L min^{-1} with 20% oxygen concentration was applied to keep the biomass particles in suspension, during the combustion process in DTF. Such monitoring *in situ* was performed using two encapsulated K-type thermocouples, located inside the furnace - one in the upper and other in bottom part, which are positioned at 107 mm and 310 mm, respectively, regarding as reference an thermocouple that is located in the heated zone at 200 mm [2,18].

2.4 Feedind System for the biomass combustion in a DTF

The DTF feeding system, which was developed by our research group, is composed of a mechanical conveyor of threaded screw, with proportional holes and equidistant along their entire surface and a small air injection system on one side, for assisting in the samples removal from the surface of the threaded screw. Such system allows a continuous feeding for the five lignocellulosic materials. The maximum rotational velocity for this system was 15 rpm or 12 V provided by PWM (Pulse-Wide Modulation) and, the optimum rotational velocities (from 30 to 70%) were reached for each biomass [18].

3. RESULTS AND DISCUSSION

Figure 2 presents the temperature variations in the DTF combustion chamber for the pine sawdust samples in the thermochemical processes from conventional combustion (synthetic air - N_2/O_2: 80/20%), pyrolysis (100% N_2) and two typical oxy-fuel combustion atmospheres (CO_2/O_2: 80/20% and 60/40%).

By means of the temperature profiles determined by two thermocouples (upper and bottom part) some differences were observed for the pine sawdust samples in the various thermal processes. For example, for the conventional combustion the ignition time (burning start) and residence time (experimental measure), around 20 and 900 s, respectively, were lower than for other atmospheres. In this same condition were observed the higher fluctuations and maximum temperature peaks (966, 985 and 967 ºC), which can be an indicative of the combustion process effectiveness at determined moments and also is related to sample feeding in the DTF.

These increase sudden were caused to sample reactivity and solid-gas mixtures, released heat for the high and fast volatiles release and, an environment more oxidative promoted by the O_2 concentration, which accelerate and facilitates the burning [16,20,21]. A decrease in the furnace temperature was observed from 962 to 950 °C and between 385 and 468 s, which may have been caused by biomass feeding problems. Another possible explanation for this effect can be high moisture proportions in gases inside furnace, whose result in elevated gaseous emissions, due to high capacity of water vapors formation via radiation heat transfer [22].

For the oxy-fuel combustion conditions (60 and 80% CO_2) no significant effect on the temperature gradients was observed. The processes started at higher temperatures from 961 and 960 ºC, and reached the maximum temperatures from 970 and 968 ºC, respectively. After that, both temperatures showed a stable behavior throughout the process, mainly for the lower temperatures.

However, for the inert atmosphere condition (100% N_2), simulating pyrolysis, is interesting note that temperatures close to 390 s were overlapped. The temperature measured by bottom thermocouple increased from 948 to 961 ºC, while the upper thermocouple temperature decreased from 963 to 960 ºC, after which both temperatures presented some homogeneity, but followed in opposite directions from the beginning to the experiment end.

Probably, this effect of gradual decay of the system temperature can be explained, because when the pyrolysis temperature reached ≈ 900 ºC, a higher restriction in the char devolatization is caused to mass transfer for diffusion [23]. On the other hand, in the region between 40 and 400 s occurred an increase in temperature from 957 to 963 ºC (upper thermocouple), and may be an effect of the volatiles released from the biofuel. For Molina and Shaddix (2007) [20] is expected that volatiles released under N_2 atmosphere burn faster than those released in other oxidizing atmospheres and, consequently, increase the temperature.

Figure 3 present the temperature variations in DTF combustion chamber for the sugarcane bagasse samples in the different thermal processes. For all the atmospheres used for the burning of this sample, mainly noted by bottom thermocouple, temperature profiles presented a practically homogeneous behavior, indicating burning processes in favorable conditions and stables.

For the conventional combustion (synthetic air) and oxy-fuel combustion (60 and 80% CO_2) conditions for the coffee husk samples (Figure 4) were observed fluctuations regions between 100 and 1000 s, with maximum peaks temperature ranging from 965 to 970 ºC. These fluctuations can be an effect from a batch feeding of the biomass pulverized, non-uniformity of burning in the combustion zone, increase rotation velocity and biofuels random distribution [24,25].

A biomass feeding with continuous flux was planned and it was expected that, by means of several adjusts in the feeding system parameters, for example, rotation velocities could be obtain a homogeneous demand of the samples mass. However, optimal conditions in feeding system are not always obtained and, the temperature curves are good diagnostics for this verification. Another possible explanation for the temperature variations during the thermal processes can be due to fast volatiles release and the occurrence of successive exothermic reactions, which can also promote temperature increase [26].

In the pyrolysis ambient for the coffee husks between 100 and 200 s was verified for both thermocouples a decrease in the process temperature (962 and 947 ºC, respectively). This decrease can be attributed to the devolatilization process, which is an endothermic process [9]. Among the biomasses studied, the coffee husk presented the highest moisture content (≈ 8%), which can make the ignition poorer and delay the volatiles release [27]. This moisture can also result in capacity of water vapor formation inside the furnace, via radiation heat transfer, which contributes strongly to the decrease in temperature [22]. It is interesting to note that of all the biomasses of this study, for the N_2 atmosphere the coffee husk samples presented the lowest initial temperatures (≈ 948 ºC).

The temperatures variations inside DTF for the rice husk samples for the various thermochemical processes are presented in Figure 5. The behaviors from thermal profiles presented for this biomass are similar to other biomasses and already were mentioned previously (pyrolysis condition). However, it is convenient to highlight that all oxidizing atmospheres had large fluctuations between 100 and 600 s. This time interval can be considered as a region inside DTF of effective combustion, with maximum temperatures of approximately 950 to 970 °C, which were registered by both thermocouples.

For the *tucumã* seed, temperature variations inside DTF for the different atmospheres are presented in Figure 6. Among the oxidizing atmospheres, the higher effects in temperature gradients were observed for the 60% CO_2 condition, probably provoked by increase in O_2 concentration and, consequently, fast elimination of volatile materials [18,28]. These large fluctuations occurred in a short time period (between 50 and 200 s), with maximum temperatures from 950 and 970 °C. This abrupt temperature variation for the combustion process from the tucumã seed was confirmed by bottom thermocouple and, indicates that combustion process was completed in the DTF inferior part (residues collection region). Other possible justification for this phenomenon can be that in the delimited region for this thermocouple, the biomass particles were still incandescent [29]. For the 100% N_2 environment was observed a decrease in the temperatures (≈ 945 °C) close a 100 s, sample moisture or oiliness can be responsible for such situation [30], after this a behavior considered homogeneous was verified.

According to Toftegaard *et al*. (2010) [31], in high partial pressures and temperatures the CO_2 can be dissociated in CO and O_2, by means of strongly endothermic reactions. For our specific case, in the reactor flame zone under oxy-fuel combustion processes, only one condition can be observed, *i.e*., high temperature (> 950 ºC) and such information was verified and confirmed in a previous study developed by Cruz (2015) [18]. However, in specific of the CO_2 gas, their high partial pressure is an inherent characteristic [31]. The biomass burning process carried out in a combustion chamber hermetically closed, in which CO_2 gas is directly injected, can exist shocks between the molecules gas and biomasses, and so the internal system pressure can be further increased by physicochemical properties of the dioxide carbon and samples reactivity.

4. CONCLUSIONS

This research aimed to investigate the thermal behavior inside the combustion chamber of a Drop Tube Furnace (DTF) for the different thermoconversion processes (conventional combustion, pyrolysis and two typical oxy-fuel combustion atmospheres), when five *in natura* Brazilian biomasses (pine sawdust, sugarcane bagasse, coffee and rice husk, and *tucumã* seed) are employed.

Results showed that for the different biomasses and atmospheres, a certain trend in the internal temperature variations and residence times measured by two thermocouples inside the DTF was observed, which can be related to biomass feeding system, furnace operation conditions, samples moisture, large fluctuations of maximum temperatures, higher and faster release of volatile materials, O_2 and CO_2 concentrations and heat transfer inside DTF, such parameters can indicate the effectiveness of the thermal process in a DTF.

Our findings can assist in projects elaboration of new thermochemical conversion systems in lab-scale or same industrial for the biomasses burning or other materials with purpose bioenergy generation. The utilization of green fuels in thermoconversion processes can help in the construction of a Planet with a great eco-friendly and environmental awareness.

5. ACKNOWLEDGEMENTS

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Figures Legends

Figure 1. Schematic representation of the Drop Tube Furnace (DTF) and feeding system for the biomasses combustion.

Figure 2. Temperature average profiles in the combustion chamber of the DTF for the **pine sawdust** samples in different thermal conversion processes.

Figure 3. Temperature average profiles in the combustion chamber of the DTF for the **sugarcane bagasse** samples in different thermal conversion processes.

Figure 4. Temperature average profiles in the combustion chamber of the DTF for the **coffee husk** samples in different thermal conversion processes.

Figure 5. Temperature average profiles in the combustion chamber of the DTF for the **rice husk** samples in different thermal conversion processes

Figure 6. Temperature average profiles in the combustion chamber of the DTF for the ***tucumã* seed** samples in different thermal conversion processes.

Figure 1

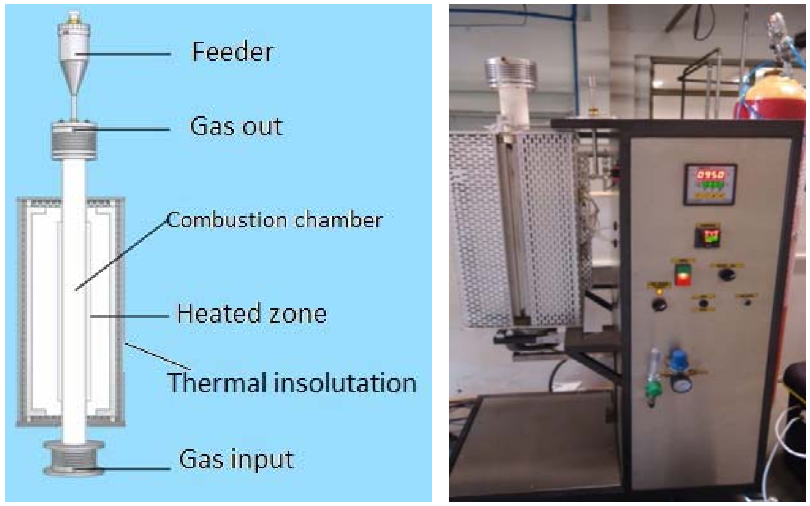
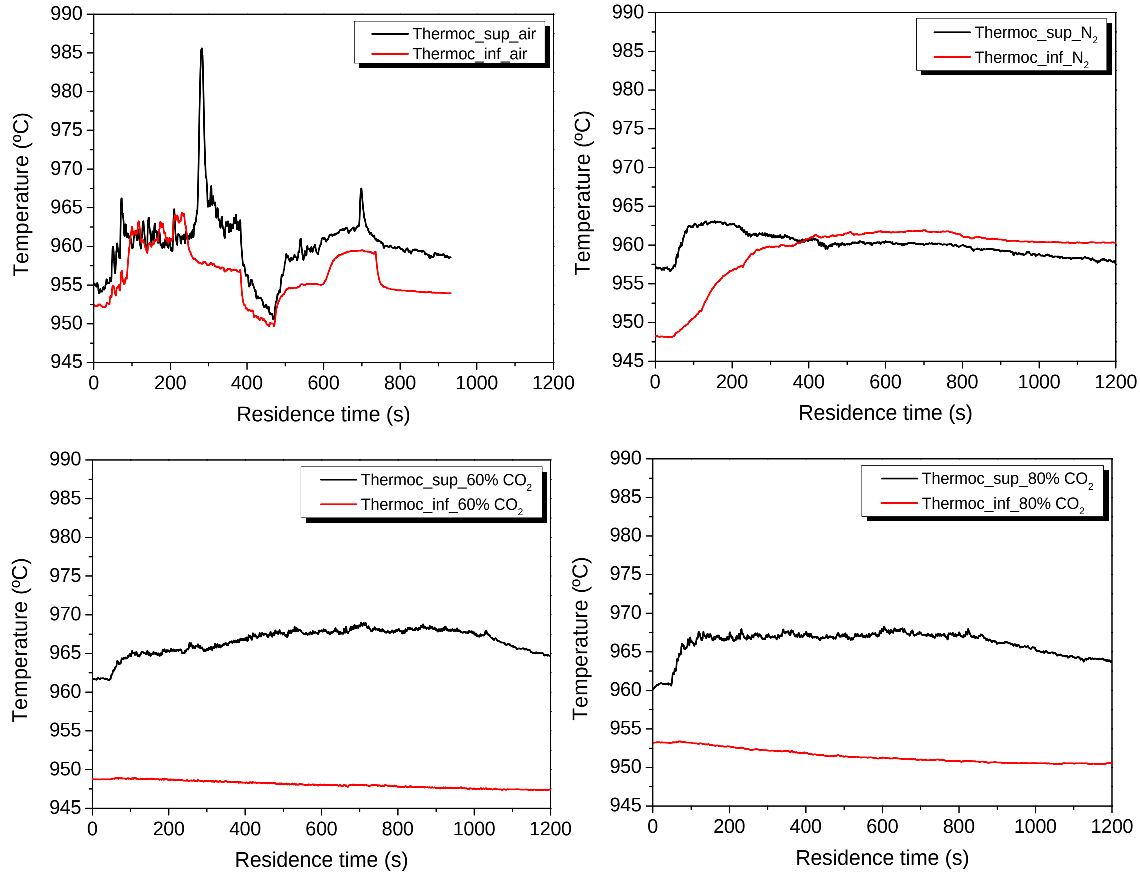

Feeder
Gas out
Combustion chamber
Heated zone
Thermal insolutation
Gas input

Figure 2



Thermoc_sup_air
Thermoc_inf_air
Temperature (ºC)
Residence time (s)
Thermoc_sup_N2
Thermoc_inf_N2
Temperature (ºC)
Residence time (s)
Thermoc_sup_60% CO2
Thermoc_inf_60% CO2
Temperature (ºC)
Residence time (s)
Thermoc_sup_80% CO2
Thermoc_inf_80% CO2
Temperature (ºC)
Residence time (s)

Figure 3

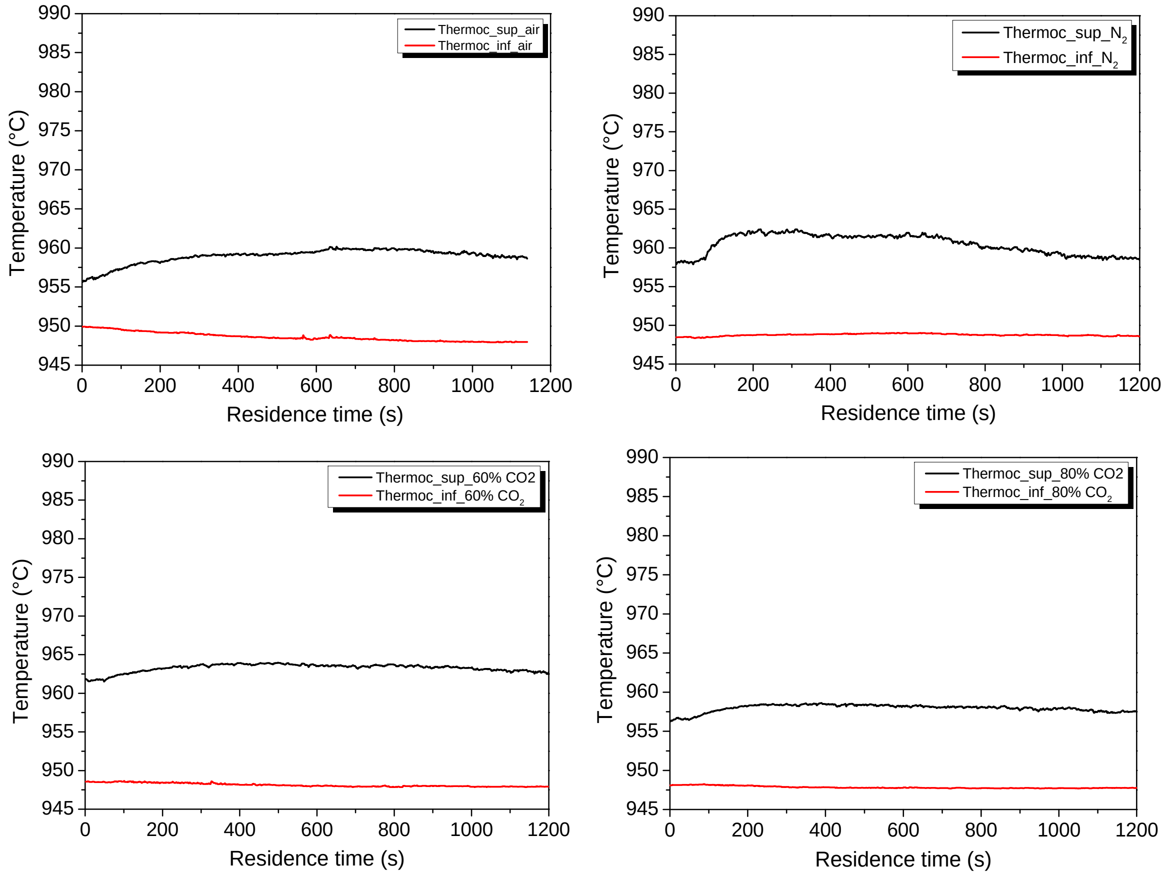

Thermoc_sup_air
Thermoc_inf_air
Temperature (°C)
Residence time (s)
Thermoc_sup_N2
Thermoc_inf_N2
Temperature (°C)
Residence time (s)
Thermoc_sup_60% CO2
Thermoc_inf_60% CO2
Temperature (°C)
Residence time (s)
Thermoc_sup_80% CO2
Thermoc_inf_80% CO2
Temperature (°C)
Residence time (s)

Figure 4

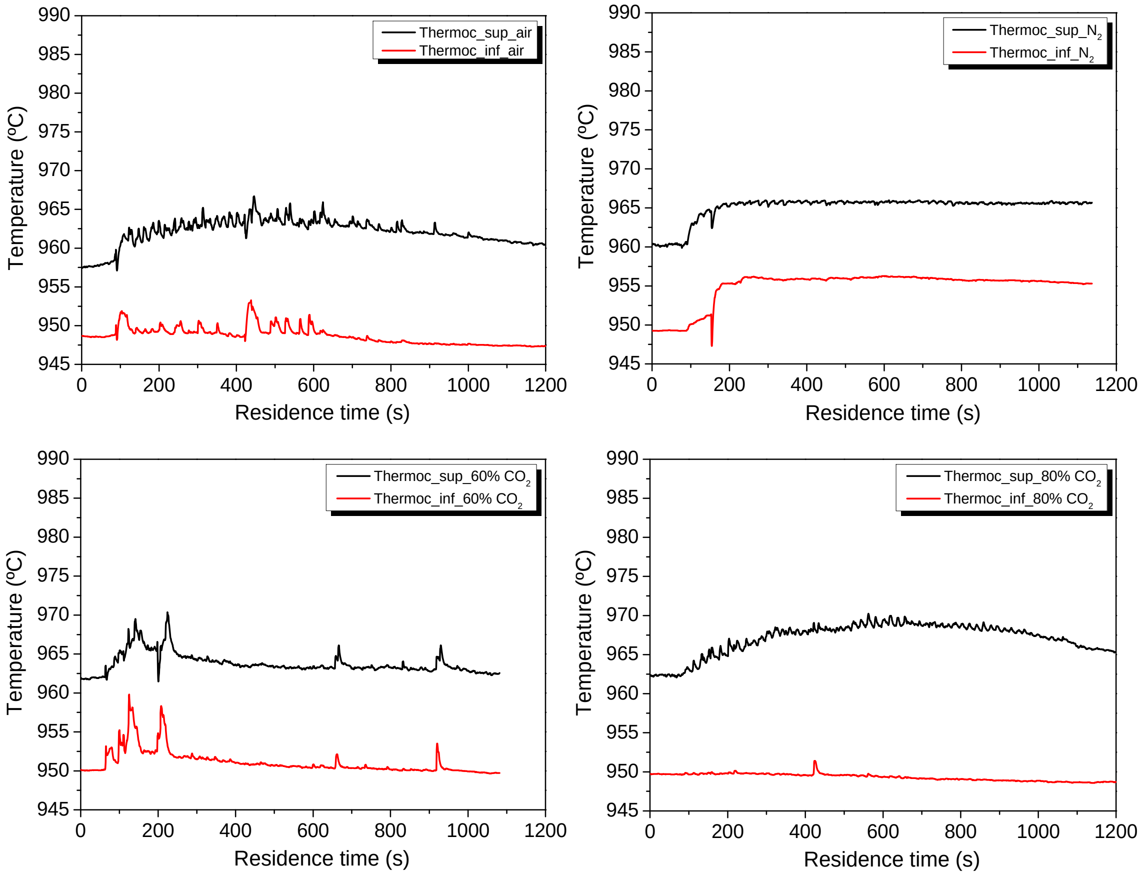
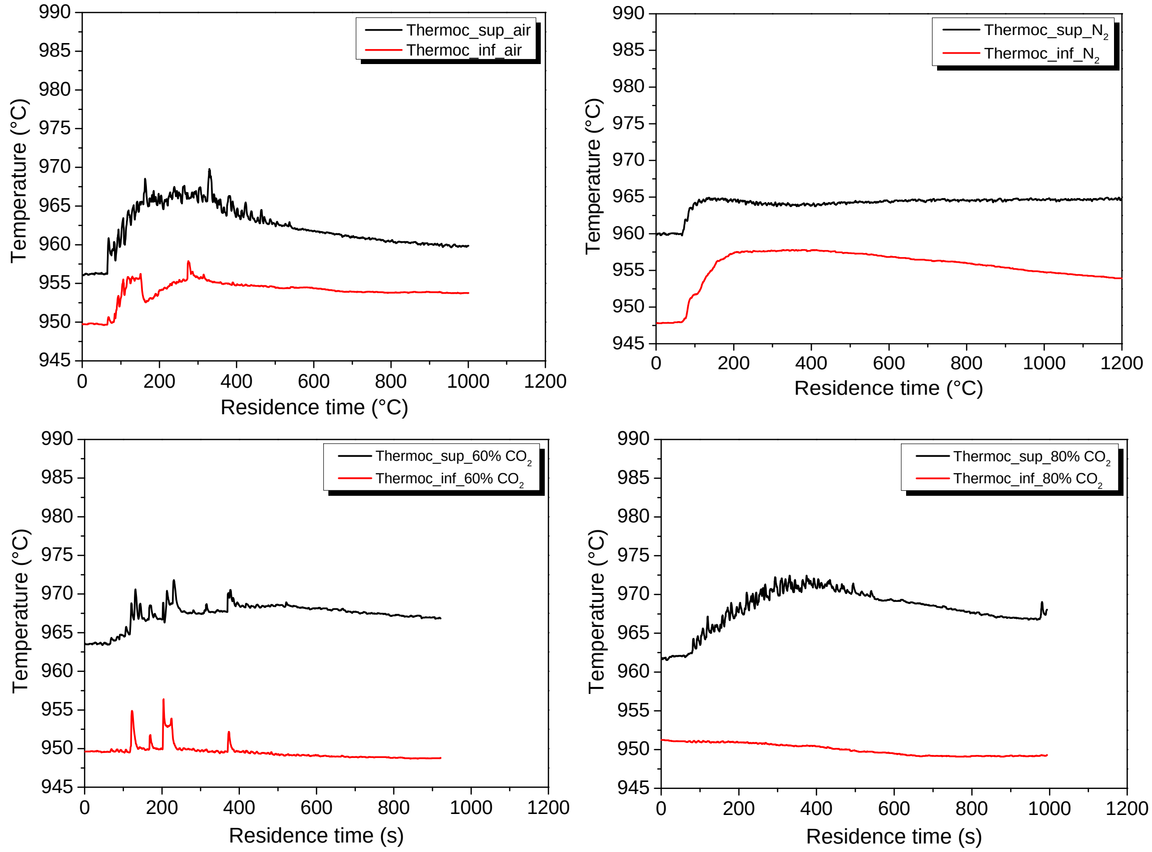
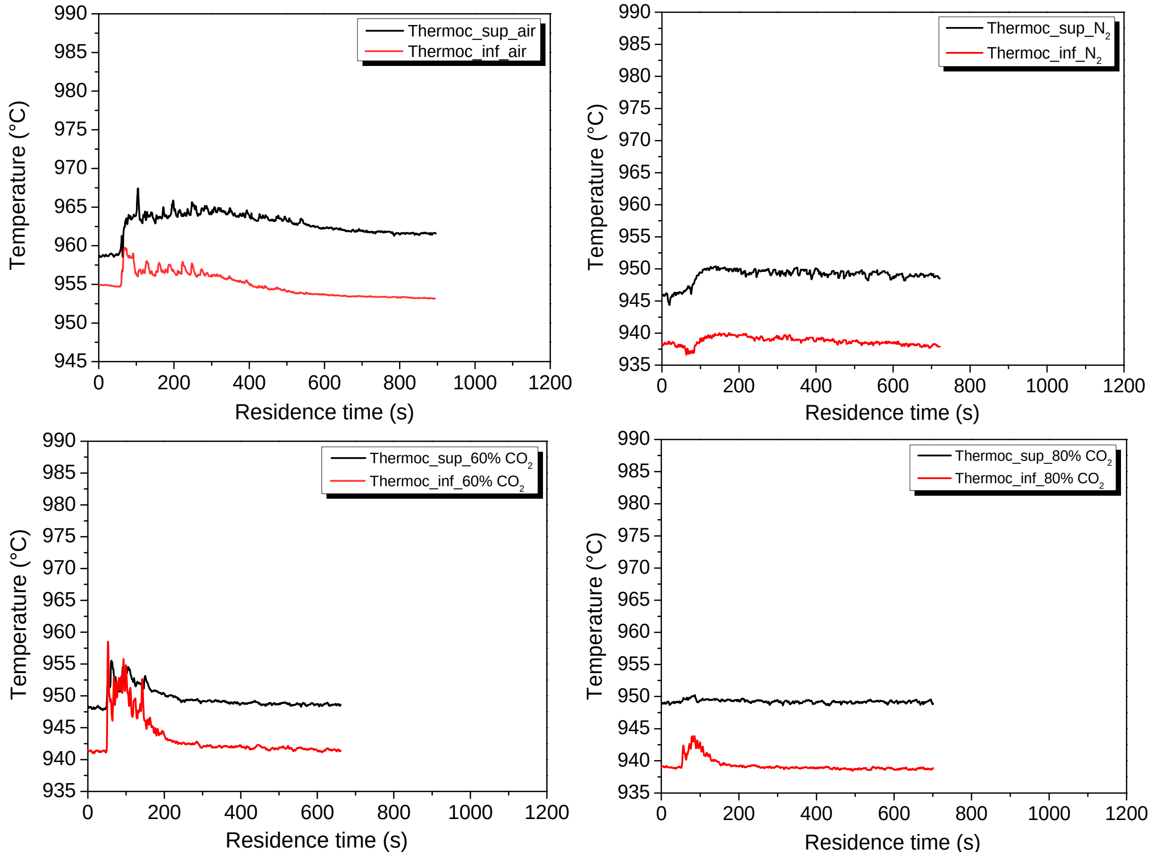

Thermoc_sup_air
Thermoc_inf_air
Thermoc_sup_N2
Thermoc_inf_N2
Thermoc_sup_60% CO2
Thermoc_inf_60% CO2
Thermoc_sup_80% CO2
Thermoc_inf_80% CO2
Temperature (ºC)
Residence time (s)

Figure 5



Thermoc_sup_air
Thermoc_inf_air
Temperature (°C)
Residence time (°C)
990
985
980
975
970
965
960
955
950
945
0
200
400
600
800
1000
1200
Thermoc_sup_N2
Thermoc_inf_N2
Temperature (°C)
Residence time (°C)
Thermoc_sup_60% CO2
Thermoc_inf_60% CO2
Temperature (°C)
Residence time (s)
Thermoc_sup_80% CO2
Thermoc_inf_80% CO2
Temperature (°C)
Residence time (s)

Figure 6


Thermoc_sup_air
Thermoc_inf_air
Temperature (°C)
Residence time (s)
Thermoc_sup_N2
Thermoc_inf_N2
Temperature (°C)
Residence time (s)
Thermoc_sup_60% CO2
Thermoc_inf_60% CO2
Temperature (°C)
Residence time (s)
Thermoc_sup_80% CO2
Thermoc_inf_80% CO2
Temperature (°C)
Residence time (s)