Oxy-fuel combustion kinetics and morphology of coal chars obtained in N₂ and CO₂ atmospheres in an entrained flow reactor

M.V. Gil, J. Riaza, L. Álvarez, C. Pevida, J.J. Pis, F. Rubiera *

Instituto Nacional del Carbón, INCAR-CSIC, Apartado 73, 33080 Oviedo, Spain

Abstract

The thermal reactivity and kinetics of four coal chars (HVN, UM, SAB and BA) in an oxy-fuel combustion atmosphere (30%O₂-70%CO₂) were studied using a thermobalance. The coal chars were obtained by devolatilization in an entrained flow reactor (EFR) at 1000 °C for 2.5 s under 100% N₂ and CO₂ atmospheres. The reactivity tests were carried out by isothermal thermogravimetric analysis at different temperatures in a kinetically controlled regime. Three *n*th-order representative gas-solid models -the volumetric model (VM), the grain model (GM) and the random pore model (RPM)- were employed in order to describe the reactive behaviour of the chars during oxy-fuel combustion. From these models, the kinetic parameters were determined. The RPM model was found to be the best for describing the reactivity of the HVN, UM and BA chars, while VM was the model that best described the reactivity of the SAB char. The reactivities of the chars obtained in N₂ and CO₂ in an oxy-fuel combustion atmosphere with 30% of oxygen were compared using the kinetic parameters, but no differences were observed between the two devolatilization atmospheres. The apparent volatile yield after the coal devolatilization under CO₂ in the EFR was greater than under N₂ for all the coals studied. According to the scanning electron microscopy

* Corresponding author. Tel.: +34 985 118 975; Fax: +34 985 297 662

E-mail address: frubiera@incarcsic.es (F. Rubiera)

(SEM) images of the chars, those obtained in the CO₂ atmosphere experienced a greater degree of swelling, some particles showing partially reacted surfaces indicative of reaction between the char and CO₂.

Keywords: Coal; Char; Isothermal TG; Oxy-fuel combustion; Kinetics models; Entrained flow reactor

1. Introduction

The use of coal in power plants generates a large amount of CO₂, which is the chief contributor to global climate change. However, coal is the most abundant and geographically the most widely distributed fossil fuel. The stability of its supply and its relatively low cost will ensure its inclusion in the energy mix in the foreseeable future [1]. Several strategies for the reduction and capture of CO₂ from large-scale stationary power plants are being studied. The main problem is that the concentration of CO₂ in a conventional coal-air combustion flue gas stream is low (typically 15% by volume), rendering it unsuitable for direct sequestration in a supercritical state via compression which requires a high concentration of CO₂ [2]. As an alternative, the oxy-fuel combustion process has been proposed as a promising technology for CO₂ capture from fossil fuel power plants. This technology involves the combustion of coal in a mixture of oxygen (instead of air) and recycled flue gas (RFG), which consists mainly of CO₂ and H₂O [3]. In this process, the net volume of flue gas is reduced and a highly concentrated CO₂ (95%) flue gas is produced, which after purification [4,5] can be directly stored in a supercritical state by means of compression.

The combustion of coal in the O_2/CO_2 atmosphere of an oxy-coal combustion boiler can be expected to be different from that of an O_2/N_2 atmosphere of a conventional coal-air combustion boiler, because CO_2 has a larger specific molar heat than N_2 , and the coal may be gasified by the CO_2 [6]. The use of CO_2 instead of N_2 may also cause a reduction in the propagation speed, stability of the flame and gas temperature profile or lead to an increase in the unburned carbon content. During the oxy-fuel combustion process, these problems can be overcome by increasing the oxygen concentration in the oxidizer (up to approximately 30%) in order to match the combustion performance achieved in air.

In addition, oxy-coal combustion can be used as retrofit technology in conventional pulverized coal boilers to capture and store carbon. However, the successful implementation of O_2/CO_2 technology in conventional pulverized coal boilers requires a full understanding of the changes that occur when N_2 is replaced by CO_2 in a combustion atmosphere [7]. A precise knowledge of char reactivity and kinetics under a CO_2 atmosphere is essential for designing and modelling oxy-fuel combustion at industrial scale. In modelling studies related to oxy-coal combustion, coal pyrolysis during oxy-coal combustion is usually assumed to be the same as in air [8]. According to Naredi and Pisupati [9], it is necessary to establish whether the pyrolysis of coal particles in CO_2 will produce different results from pyrolyzing them in an inert gas medium. Knowledge of coal pyrolysis under a CO_2 atmosphere is essential for understanding the process of oxy-fuel combustion [10].

The aim of the present work is to study the oxy-fuel combustion ($30\%O_2$ - $70\%CO_2$) reactivity and kinetic behaviour of four coal chars obtained under N_2 and CO_2 atmospheres. For this purpose, three mathematical models -the volumetric model (VM),

the grain model (GM) and the random pore model (RPM)- were used to determine the kinetic parameters which best represent the oxy-fuel combustion characteristics of the coal chars obtained in N₂ and CO₂ under an oxygen-carbon dioxide atmosphere. The morphology of the coal chars was compared by scanning electron microscopy (SEM).

2. Experimental

2.1. Fuel samples

Four coals of different rank were used: a semi-anthracite (HVN), a medium-volatile bituminous coal (UM) and two high-volatile bituminous coals (SAB and BA). The samples were ground and sieved to obtain a particle size fraction of 75-150 µm. The results of the proximate and ultimate analyses and high heating values of the samples are shown in Table 1.

2.2. Char preparation

The chars were prepared by devolatilizing the raw coals in an electrically heated entrained flow reactor (40 mm internal diameter, 1400 mm length) in streams of 100% N₂ or 100% CO₂ (4.79 NL min⁻¹). The experimental device has been described elsewhere [11,12]. The devolatilization experiments were carried out at a reactor temperature of 1000 °C and a particle residence time of 2.5 s. After the experiments, the chars were cooled down under a flow of nitrogen to room temperature. A water-cooled collecting probe was inserted into the reaction chamber from below to collect the char samples. The external morphology of the coal chars was examined by means of scanning electron microscopy (SEM).

2.3. Oxy-fuel combustion reactivity tests of the chars

Thermogravimetric analysis (TGA) is one of the most commonly used techniques to investigate and compare thermal events and kinetics during the combustion and pyrolysis of solid raw materials, such as coal, woods, etc. [13-17]. The reactivity tests were conducted in a thermobalance (Setaram TAG24) at atmospheric pressure. Approximately 5 mg of char sample was placed in a crucible of height 2 mm with a circular base 5 mm in diameter. A thermocouple was located close to the platinum basket to monitor the temperature and to close the control loop. In this work, all the experiments were performed under isothermal conditions at different temperatures (400-600 °C). These temperatures were chosen in order to avoid diffusion problems and consequently apply the Arrhenius plot for calculating the kinetic parameters. The total flow rate of the reactive gas introduced into the thermobalance during the oxy-fuel combustion experiments was 50 NmL min⁻¹, the gas consisting of 30% O₂ and 70% CO₂. The char conversion, X , and the reaction rate, dX/dt , were calculated.

3. Kinetic models

A general kinetic expression for the overall reaction rate in gas-solid reactions can be expressed as follows [18]:

$$dX/dt = k(P_g, T)f(X) \quad (1)$$

where k is the apparent combustion reaction rate, which includes the effect of temperature (T) and the effect of the reactive gas partial pressure (P_g), and where $f(X)$ describes the changes in the physical or chemical properties of the sample as the combustion proceeds. Assuming that the partial pressure of the reactive gas remains

constant during the process, the apparent combustion reaction rate will be dependent on the temperature and can be expressed using the Arrhenius equation, as follows:

$$k = k_0 \exp^{-E/RT} \quad (2)$$

where k_0 and E are the pre-exponential factor and activation energy, respectively.

In this work, three n th-order models were applied in order to describe the reactivity of the chars studied: the volumetric model (VM), the grain model (GM) and the random pore model (RPM). These models give different formulations of the term $f(X)$, with X representing the degree of char conversion on a dry ash-free basis.

The VM assumes a homogeneous reaction throughout the particle and a linearly decreasing reaction surface area with conversion [19]. The overall reaction rate is expressed by:

$$dX/dt = k_{VM} (1-X) \quad (3)$$

The GM or shrinking core model, proposed by Szekeley and Evans [20], assumes that a porous particle consists of an assembly of uniform nonporous grains and that the reaction takes place on the surface of these grains. The space between the grains constitutes the porous network. The shrinking core behaviour applies to each of these grains during the reaction. In a regime of chemical kinetic control and, assuming that the grains have a spherical shape, the overall reaction rate can be expressed as:

$$dX/dt = k_{GM} (1-X)^{2/3} \quad (4)$$

This model predicts a monotonically decreasing reaction rate and surface area because the surface area of each grain is receding during the reaction.

The RPM model considers the overlapping of the pore surfaces, which reduces the area available for reaction [21]. The basic equation for this model is:

$$dX/dt = k_{RPM} (1-X) [1-\psi \ln(1-X)]^{1/2} \quad (5)$$

This model is able to predict a maximum value of reactivity as the reaction proceeds, as it considers the competing effects of pore growth during the initial stages of combustion and the destruction of the pores due to the coalescence of neighbouring pores during the reaction. The RPM model employs two parameters, the apparent combustion reaction rate, k_{RPM} , and ψ , which is utilized to represent the pore structure of the unreacted sample and was used as a fitting parameter.

In order to evaluate these models using the experimental results, Eqs. 3-5 were linearized, giving Eqs. 6-8, respectively:

$$-\ln(1-X) = k_{\text{VM}}t \quad (6)$$

$$3[1-(1-X)^{1/3}] = k_{\text{GM}}t \quad (7)$$

$$(2/\psi)[(1-\psi \ln(1-X))^{1/2}-1] = k_{\text{RPM}}t \quad (8)$$

The values of the apparent combustion reaction rates (k_{VM} , k_{GM} , k_{RPM}) and ψ were calculated using the experimental data obtained in the isothermal thermogravimetric runs, from the slope of the plots of Eqs. 6-8. The Arrhenius plot ($\ln k$ vs. $1/T$) was then employed to calculate the activation energy, E , and the pre-exponential factor, k_0 , for each of the char samples and models according to Eq. 2.

The conversion-time relationships for the three models are:

$$X = 1 - \exp(-k_{\text{VM}}t) \quad (9)$$

$$X = 1 - (1 - k_{\text{GM}}t/3)^3 \quad (10)$$

$$X = 1 - \exp[-k_{\text{RPM}}t(1 + k_{\text{RPM}}t\psi/4)] \quad (11)$$

The k values were calculated by introducing the estimated E and k_0 values into Eq. 2. $X_{\text{calc},i}$ was obtained by introducing the k values, and the ψ value in the case of the RPM model, into Eqs. 9-11. The X calculations were performed in order to assess the quality of the fit and verify the capacity of the kinetic models to describe the degree of char

conversion. By comparing the experimental and calculated X values, the kinetic model may be further tested and verified. The deviation (DEV) between the experimental and calculated curves was calculated using the following expression:

$$\text{DEV } X (\%) = 100 [\sum_{i=1,N} (X_{\text{exp},i} - X_{\text{calc},i})^2 / N]^{1/2} / \max X_{\text{exp}} \quad (12)$$

where $X_{\text{exp},i}$ and $X_{\text{calc},i}$ represent the experimental and calculated data of X , N is the number of data points, and $\max X_{\text{exp}}$ is the highest absolute value of the experimental curve.

In order to compare the oxy-fuel combustion reactivity of the chars obtained under the N_2 and CO_2 atmospheres, the reactivity index at 500 °C, R_{500} , was calculated as follows:

$$R_{500} = 0.5 / \tau_{0.5} \quad (13)$$

where $\tau_{0.5}$ represents the time required to reach 50% of carbon conversion. High reactivity indices indicate high reactivities.

4. Results and discussion

4.1. Kinetic parameters

The linearized form of the three models studied, Eqs. 6-8, was used to represent the experimental data obtained during oxy-fuel combustion at all the temperatures studied in order to find the parameters k_{VM} , k_{GM} , k_{RPM} and ψ of best fit. As an example, the plots of the VM, GM and RPM linearized models for the HVN- CO_2 and BA- N_2 char samples are shown in Fig. 1. The parameter ψ was calculated assuming that its value is constant for each char sample at all the temperatures, since it is related to the initial pore structure.

The Arrhenius plot ($\ln k$ vs. $1/T$) was then employed to calculate the activation energy, E , and the pre-exponential factor, k_0 , for each of the char samples (Eq. 2). As an

example, Fig. 2 shows the Arrhenius plots for the HVN-N₂, HVN-CO₂, BA-N₂ and BA-CO₂ char samples, using the reaction rates calculated with the three models studied. Only the results obtained under the chemical controlled regime were included in the calculations. The change from chemical to diffusion-controlled regime can be detected from the change in slope on the Arrhenius plots.

Table 2 shows the values of the activation energy, E , and the pre-exponential factor, k_0 , that allow the best fit of the experimental data to the different models. In the case of the RPM model, the ψ value was also included.

In order to assess the ability of the kinetic models to predict conversion during oxy-fuel combustion, the experimental conversion values, $X_{\text{exp},i}$, were compared with the calculated values, $X_{\text{calc},i}$, at the different temperatures selected. The calculated conversion values of the chars during oxy-fuel combustion were obtained by introducing the previously estimated k (calculated from k_0 and E) and ψ values into Eqs. 9-11. As an example, the results for the HVN-N₂, HVN-CO₂, BA-N₂ and BA-CO₂ char samples are shown in Fig. 3. In addition, the errors produced by the kinetic models in predicting the values of conversion were quantified by means of Eq. 12, which compares the experimental and calculated X values taking into account the deviation, $\text{DEV } X (\%)$, between the experimental and calculated curves. Table 3 shows the results of the average deviation for all the char samples.

The best model for describing the reactivity of the HVN, UM and BA coal chars proved to be RPM, which presented the lowest deviation values. VM was the model that best described the reactivity of the SAB chars, although in this case the $\text{DEV } X$ value was similar to that of RPM model. This was due to the ψ value being very close to zero and, when this occurs, the RPM model predicts an almost constant decrease in reactivity

with conversion, like the VM model, which assumes a homogeneous reaction throughout the particle [19].

Using the models of best fit, the activation energy for the coal chars under oxy-fuel atmosphere (30% O₂) was 117-127 kJ mol⁻¹ (Table 2). Niu et al. [22] obtained activation energy values for pulverized coals in an oxy-fuel atmosphere (20% O₂) that ranged between 109 and 248 kJ mol⁻¹. Similarly, Liu [6] achieved activation energy values for coal chars in an oxy-fuel atmosphere (10% O₂) that ranged between 115 and 147 kJ mol⁻¹.

Table 4 shows the reactivity index, R_{500} , calculated from Eq. 13. As can be seen, the reactivity index values obtained for the coal chars in N₂ and CO₂ were similar, although there is a slight trend towards higher reactivity values in the case of the N₂-chars. Table 2 shows that the activation energy values and pre-exponential factors for the chars obtained under CO₂ and N₂ are also very similar. From these data, it can be concluded that no differences in the kinetic parameters are produced by using these different devolatilization atmospheres. The reaction rate of a char under an oxygen atmosphere is usually very high and in the present study the reactivity was measured in a high oxygen content (30%) atmosphere, which may have concealed possible differences in reactivity between both chars and may explain why no differences were observed between the chars obtained under N₂ or CO₂. The results obtained by Naredi and Pisupati [9] also suggest that the reactivity of the coal char generated in CO₂ was similar to that of the coal char generated in an Ar gas medium. These authors were led to conclude that the properties of the char obtained in both atmospheres differed only at high temperatures (>1300 °C), which they attributed to the effect of char gasification resulting from the reaction between the char and CO₂.

4.2. Properties of the chars

The apparent volatile yields of the four coals studied after devolatilization in N_2 and CO_2 at 1000 °C in an entrained flow reactor are presented in Table 5. The apparent volatile yields (V^*) of the UM, SAB and BA coals calculated from the EFR experiments were higher than their respective volatile matter contents (VM) obtained by proximate analysis, indicating an enhanced devolatilization at the higher temperature and heating rate in the entrained flow reactor. However, in the case of the HVN coal, the V^* yields measured after coal devolatilization in N_2 and CO_2 in the EFR were lower than the coal VM content, probably due to the high rank of this coal together with the short residence time in the EFR during the devolatilization experiments compared to that of the proximate analysis.

Furthermore, the apparent volatile yields measured after coal devolatilization under CO_2 were greater than those obtained under N_2 for all the coals studied (Table 4). The greater mass loss observed under CO_2 was probably caused by char- CO_2 gasification occurring at high temperatures during the devolatilization experiments in the EFR. Rathnam et al. [2] and Li et al. [23] also observed higher apparent volatile yields under CO_2 than under N_2 after devolatilization in a drop tube furnace. These authors attributed the higher values to the gasification of the chars by CO_2 . Jamil et al. [24] observed a lower char yield in CO_2 than in He after the pyrolysis of a brown coal at 900 °C in a wire-mesh reactor, which they attributed to gasification of the char by CO_2 . In contrast, Brix et al. [25] noted that the devolatilization of coal in N_2 and CO_2 in an entrained flow reactor gave rise to a similar char morphology and volatile yield. Naredi and Pisupati [9] reported a higher weight loss during pyrolysis in CO_2 than in Ar in a drop tube reactor

at temperatures above 900 °C, which they also ascribed to the reaction between char and CO₂. Gasification of the coal would seem a reasonable explanation for the higher volatile yield in CO₂ in the present study in view of the residence time and temperature used. Brix et al. [25] concluded that at high temperatures (>1227 °C) the low residence times required for devolatilization to occur limit the access of CO₂ to the surface of the particle. These authors did not observe any differences between devolatilization in N₂ and CO₂ at temperatures over 1300 °C when the heating and devolatilization process was completed between 150 and 200 ms.

The chars obtained from coal devolatilization under N₂ and CO₂ in the entrained flow reactor were also examined using a scanning electron microscope (SEM), images of which are shown in Figs. 4-7. It can be observed that the HVN-N₂ coal consists of solid particles with an external angular profile, whereas the HVN-CO₂ char is composed of solid particles with a more rounded shape (Fig. 4). Both types of char particle have a similar mean particle size.

Both the UM-N₂ and the UM-CO₂ char particles show significant signs of swelling after devolatilization, but both have a similar particle size distribution and external appearance (Fig. 5). They also have a network-type char structure (Figs. 5b,c,f), although the proportion of this type of char is lower in the case of UM-CO₂, while the proportion of thick-walled particles with wide blow holes (Fig. 5g) is higher in the UM-CO₂ char than in the UM-N₂ char. The particles exhibited intense bubbling and grew larger during the plastic stage to form larger and more hollow char particles due to the growth of the bubbles. These bubbles grow thanks to the generation of volatiles and, if they swell to a sufficiently large extent, the particles appear almost transparent. On the other hand, the bubbles may rupture at an early stage and the holes may not close again

if the release of volatiles through the holes is intense [26]. This might explain the larger amount of char particles with large blow-holes on their surface in UM-CO₂ (Fig. 5g), resulting from more intense release of volatiles under CO₂ than under N₂.

A more noticeable swelling is observed in the case of the SAB-CO₂ and BA-CO₂ particles than in the case of the chars obtained under N₂, since the mean particle size of the SAB-CO₂ and BA-CO₂ char particles is larger than that of the SAB-N₂ and BA-N₂ chars, respectively (Figs. 6 and 7). The SAB-N₂ char exhibits both solid and irregular particles with very small holes, while the SAB-CO₂ particles are more spherical with wider holes and thick walls. This could be due to the high vitrinite content (43.5 wt.% mineral-matter-free basis) in the SAB coal. In general, particles containing liptinites or vitrinites generate a porous char, while those containing inertinites generate relatively dense char structures [26].

The BA-N₂ char has both solid particles and particles with holes, while the BA-CO₂ char exhibits more spherical particles with thinner walls, bigger holes and a network structure (Fig. 7). This diversity in morphology in the case of the BA char particles seems to indicate a multiplicity of maceral components, possibly due to the fact that the BA coal is a mixture of bituminous coals and anthracites (> 90% high-volatile bituminous coal).

In general, from the SEM images (Figs. 4-7) of the coal chars, it can be concluded that devolatilization under CO₂ causes a more pronounced swelling in the char particles than under N₂. Furthermore, some particles in the UM and BA CO₂-chars show partially reacted surfaces (Figs. 5h and 7h), which could be indicative of a reaction between the char and CO₂. This would accord with the higher volatile yield obtained after CO₂-devolatilization.

5. Conclusions

Chars obtained from four coals were subjected to oxy-fuel combustion in a thermobalance in order to evaluate their thermal reactivity and kinetics under a 30%O₂-70%CO₂ atmosphere. The isothermal thermogravimetric technique was employed at different temperatures in a kinetically controlled regime to analyze the gas-solid reactions and three models -the volumetric model (VM), the grain model (GM) and the random pore model (RPM)- were applied to describe the reactive behaviour of the chars during oxy-fuel combustion. The best model for describing the char oxy-fuel combustion of the HVN, UM and BA coals was found to be the RPM model, whereas the most efficient model for describing SAB char reactivity was VM. The kinetic parameters did not show an evidence of the chars obtained under CO₂ and N₂ showing different reactivities in a typical oxy-fuel combustion atmosphere (30%O₂-70%CO₂). The reactivity indices would appear to indicate a slightly higher reactivity in the case of the N₂-chars over the CO₂-chars. Finally, the comparatively higher apparent volatile yields and certain features in the SEM images of the chars obtained under CO₂ may indicate that the char has undergone gasification by CO₂, which would accord with the lower reactivity displayed by the CO₂-chars.

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Figure captions

Fig. 1. VM, GM and RPM linearized models for the HVN-CO₂ (a-c) and BA-N₂ (d-f) char samples during oxy-fuel combustion at different temperatures.

Fig. 2. Arrhenius plot for the VM, GM and RPM models of the HVN-N₂ (a), HVN-CO₂ (b), BA-N₂ (c) and BA-CO₂ (d) coal chars during oxy-fuel combustion.

Fig. 3. Experimental conversion curves for HVN-N₂ (a), HVN-CO₂ (b), BA-N₂ (c) and BA-CO₂ (d) coal chars and those calculated with the RPM model during oxy-fuel combustion at different temperatures.

Fig. 4. SEM images of the HVN coal char particles obtained under N₂ (a-d) and CO₂ (e-h) in an entrained flow reactor (EFR) at 1000 °C.

Fig. 5. SEM images of the UM coal char particles obtained under N₂ (a-d) and CO₂ (e-h) in an entrained flow reactor (EFR) at 1000 °C.

Fig. 6. SEM images of the SAB coal char particles obtained under N₂ (a-d) and CO₂ (e-h) in an entrained flow reactor (EFR) at 1000 °C.

Fig. 7. SEM images of the BA coal char particles obtained under N₂ (a-d) and CO₂ (e-h) in an entrained flow reactor (EFR) at 1000 °C.

Table 1. Proximate and ultimate analyses and high heating value of the coals

Sample	HVN	UM	SAB	BA
Origin	Spain	Mexico	South Africa	Spain
Rank	sa	mvb	hvb	hvb
Proximate Analysis ^a				
Moisture content (wt.%)	1.1	0.4	2.4	1.2
Ash (wt.%, db)	10.7	21.1	15.0	6.9
<i>VM</i> (wt.%, db)	9.2	23.7	29.9	33.9
<i>FC</i> (wt.%, db) ^b	80.1	55.2	55.1	59.2
Ultimate Analysis (wt.%, daf) ^a				
C	91.7	86.2	80.8	88.5
H	3.5	5.5	5.0	5.5
N	1.9	1.6	2.0	1.9
S	1.6	0.8	0.9	1.1
O ^b	1.3	5.9	11.3	3.0
<i>HHV</i> (MJ/kg, db)	31.8	27.8	27.8	33.1

sa: semi-anthracite; mvb: medium-volatile bituminous coal; hvb: high-volatile bituminous coal.

db: dry basis; daf: dry and ash free bases.

^a The proximate analysis was conducted in a LECO TGA-601, and the ultimate analysis in a LECO CHNS-932.

^b Calculated by difference.

Table 2. Kinetic parameters that allow the best fit of the experimental data from oxy-fuel combustion (30%O₂-70%CO₂) to the VM, GM and RPM models

Char	Volumetric model (VM)		Grain model (GM)		Random pore model (RPM)		
	E (kJ mol ⁻¹)	k_0 (s ⁻¹)	E (kJ mol ⁻¹)	k_0 (s ⁻¹)	E (kJ mol ⁻¹)	k_0 (s ⁻¹)	ψ
HVN-N ₂	128	1.64E+05	128	1.21E+05	127	5.09E+04	15.9
HVN-CO ₂	118	3.55E+04	118	2.51E+04	117	8.10E+03	29.4
UM-N ₂	125	1.90E+05	123	1.12E+05	123	5.89E+04	6.7
UM-CO ₂	126	2.03E+05	123	8.86E+04	119	2.37E+04	12.2
SAB-N ₂	121	1.36E+05	120	8.15E+04	120	9.48E+04	0.7
SAB-CO ₂	125	2.50E+05	125	1.88E+05	125	2.31E+05	0.2
BA-N ₂	127	4.09E+05	126	2.66E+05	126	2.82E+05	0.9
BA-CO ₂	122	1.57E+05	121	1.10E+05	121	1.11E+05	1.0

Table 3. Average deviation (%) between the experimental and calculated conversion (X) data

Char	DEV X (%)		
	VM	GM	RPM
HVN-N ₂	8.5	5.7	2.5
HVN-CO ₂	9.3	6.4	2.9
UM-N ₂	8.5	5.5	3.8
UM-CO ₂	9.8	8.3	6.3
SAB-N ₂	6.2	7.4	6.4
SAB-CO ₂	5.1	5.9	5.2
BA-N ₂	5.3	4.9	4.0
BA-CO ₂	6.8	7.2	5.8

Table 4. Reactivity index at 500 °C of the coal chars obtained in N₂ and CO₂

	HVN		UM		SAB		BA	
	N ₂	CO ₂	N ₂	CO ₂	N ₂	CO ₂	N ₂	CO ₂
R_{500} (h ⁻¹)	0.76	0.69	1.25	1.19	2.68	2.08	2.94	2.78

Table 5. Apparent volatile yield of the coal chars obtained under N₂ and CO₂ in entrained flow reactor experiments at 1000 °C

	HVN	UM	SAB	BA
<i>V</i> <i>M</i> proximate analysis (wt.%, daf)	10.3	30.1	35.2	36.4
<i>V</i> * (N ₂)	6.0	40.6	44.9	49.9
<i>V</i> * (CO ₂)	7.2	65.3	53.1	62.2

daf: dry and ash free bases.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.