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Burnout synergic or inhibiting effects in combustion of coal-sawdust blends

Efectos sinérgicos o inhibitorios en la combustión de mezclas de carbón y aserrín

C. Ulloa¹ and X. García²

ABSTRACT

The co-firing of coal and biomass was studied using DTG assays. Blends of coal of different ranks and pine charcoal (obtained through pyrolysis of biomass at 1000°C) were prepared. Combustion profiles and characteristic temperatures (IT, PT and BT) were obtained and compared. To detect deviations, the experimental burnout curves for each blend were compared with weighted averages calculated from the conversion profiles obtained for the individual fuel samples and the blend composition. Positive and negative deviations were obtained which can be predicted from the differences in the reactivity of the blend components and their relative proportions.

Keywords: Coal-biomass co-firing, Biomass, Coal, DTG.

RESUMEN

Se estudia la combustión de mezclas de carbones de diferente rango con carbonizados de pino (pirolizados a 1000°C) mediante ensayos DTG. Se registraron perfiles de combustión y temperaturas características (IT, PT y BT). Para detectar desviaciones en el quemado de las mezclas, se compararon las curvas experimentales de conversión con aquellas obtenidas a partir del promedio ponderado calculado a partir de la conversión de los combustibles individuales y la composición de la mezcla. Estos ensayos revelaron que existen tanto desviaciones positivas como negativas en la conversión. Los factores clave en la predicción de estas desviaciones corresponden a las diferencias de reactividad entre los componentes de la mezcla y su proporción relativa.

Palabras clave: Co-combustión carbón-biomasa, Biomasa, Carbón, DTG.

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Introduction

The steady incremental increase in fossil fuel prices, concerns about the effect of CO₂ emissions on global climate change, and the growing demand for energy have generated an ever-greater interest in alternative energy sources. Although Chile only contributes with 0.2% of the world's greenhouse gas emissions, it has recently made a commitment to reduce these emissions by 20% by 2020. Furthermore, Chile is in the process of strengthening its environmental standards through the enactment of the Standard for atmospheric emissions from thermoelectric power plants. Finally, national energy expansion plans indicate strong growth of the coal-based thermoelectric sector.

Given this new scenario, coal-based power plants should invest in efficient systems for emission reductions. Additionally, power plants should test new alternative technologies that would allow them to partially replace coal feedstock with other energy resources, specifically forest biomass resources. As these resources abound in Chile, the co-firing of residues, especially those from the lumber industry (sawdust), constitutes an excellent short-term

alternative for the thermal valorization of residues in thermoelectric plants that currently use pulverized coal as the fuel source.

Despite the irrefutable advantages of generating energy through co-firing coal-biomass blends, some technical issues remain unresolved. In particular, the burnout of the blend may deviate from the expected average value. Negative deviations (lower burnout of the organic matter) result in undesired increments of unburnt fuel in the ashes, thus reducing their quality, causing operational difficulties in those systems designed to reduce particulate matter, and heightening the risk of non-compliance with environmental standards.

Three successive steps are involved in coal and biomass combustion: fuel devolatilization (pyrolysis), homogeneous volatile matter combustion, and heterogeneous char/charcoal combustion. Of these, the latter is known to be the limiting step of the whole process and its extent is directly responsible for the unburnt fuel present in combustion residues. The study of each of these stages, for pure components as well as blends, will allow the determination of possible interactions as well as any synergic or inhibiting effects.

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A previous study by Ulloa et al. [2005] showed that deviations in the burnout of blends made with coals of different ranks were produced during the heterogeneous combustion stage. The different levels of reactivity of the chars remaining after pyrolysis compete for the available oxygen to the detriment of the less reactive char.

Several authors have studied the interaction of coal and biomass during pyrolysis and combustion. Biagini [2002] concluded that no interactions occur during the pyrolysis of coal-biomass blends, as weight losses, obtained using a thermogravimetric balance, were easily predicted from the average weighted losses of the pure components. Two years later, Moghtaderi et al. (2004) arrived at the same conclusion using volatile yield determinations, obtained during the pyrolysis of coal-biomass blends in a DTF reactor. Ulloa et al. [2009] concluded that volatile yields increased in the last stages of pyrolysis, particularly for blends of biomass and low-ranking coal. This phenomenon was attributed to the occurrence of demethoxylation reactions in the presence of aliphatic compounds and inorganic elements, favoring the formation of volatiles and diminishing the formation of char. Consequently, it is logical to expect this phenomenon to influence the following stage of the process – the heterogeneous firing of the char – which is studied herein.

In the last few years, several authors have considered the effect of mixing different types of biomass with coal, obtaining diverse results in terms of how the blend affects the burnout.

Kastanaki and Vamvuka [2006] studied the firing of char from different types of biomass with coals of different ranks using non-isothermic thermogravimetric analysis. They found that, in general, chars derived from biomass were more reactive than those from coal. Moreover, these authors reported that the burnout in the blend depended fundamentally on the rank of the coal and, consequently, on its reactivity, and the proportion of biomass in the blend. In a later study, also using thermogravimetric techniques, Haykiri and Yaman [2009] determined that the higher or lower burnout obtained when mixing lignites with two different types of biomass, was heavily dependent on the type of biomass in the blend. Finally, Sahu et al. [2010] corroborated earlier hypotheses regarding the importance of the different levels of reactivity of the blend components. In effect, these authors determined that mixing chars of biomass (highly reactive) with coal (less reactive) would not necessarily result in better burns (increased burnout). They concluded that blends with less than 50% biomass had greater yields in terms of the conversion of the organic matter during firing. In recent work, Vamvuka and Sfakiotakis [2011] showed that combustion characteristics of different coal/biomass blends followed those of parent fuels in regards to both additives and non-additives.

Chile is a net importer of coals of different ranks from a variety of geographic origins; it is also a producer of sub-bituminous coal used in electricity production. At the same time, the Chilean forestry industry produces some biomass residues, especially from *Pinus radiata*, on an appropriated scale for use as a partial replacement fuel in coal-based power plants. Therefore, it becomes relevant to evaluate the combustion behavior of this residue when blended with different types of coal and to establish the occurrence of interactions between the blend components that may result in positive or negative deviations from the typical burnout rate.

Experimental

Three coals of different rank and geographical origins (B, L, and LD) and one type of biomass (pine sawdust, S) were selected for the study. All samples were sieved, dried at 105°C, and pulverized to 53-75 µm (coal) or 125-177 µm (sawdust). Proximate analysis was carried out, according to ASTM standards, and ultimate analyses were performed using a LECO CHN-2000 analyzer. Petrographic analyses of coals were carried out according to ISO standards.

Binary blends containing 5, 10, and 20 wt% sawdust were prepared and subjected to pyrolysis in a drop tube furnace (DTF) reactor (see Ulloa et al., 2005 for device details) at 1200°C and 250 ms residence time. Pyrolysis was carried out under N₂ with trace O₂ (2%) concentrations to avoid volatile condensation and to reproduce the conditions existing in a flame burner. The chars produced from pure coals, sawdust, and blends of the two were collected in the water-cooled sample probe and kept for further characterization.

Char and charcoal samples underwent a differential thermogravimetric (DTG) analysis in a Mettler Toledo TGA/SDTA 51. Combustion profiles of chars were obtained by heating approximately 15 mg of each sample in air (100 ml/min) up to 1000°C at a heating rate of 5°C/min. and recording the initial temperature (IT) at 10% conversion (daf); the peak temperature (PT), when the reaction rate was maximal; and the burnout temperature (BT) at 95% conversion (daf).

Results and Discussion

The characteristics of studied fuels are shown in Table 1. Clear differences can be observed between them, especially in terms of fixed carbon content, volatile matter, and calorific value; the tendencies of these are related to material type and coal rank. Petrographic analysis indicated that coal B was lignite, a low-rank coal (Ro= 0.22%) rich in vitrinite, whereas coal L (Ro= 0.71) was bituminous, high in volatiles and having a considerable content of inertinite (28.1%), which is considered to be less reactive than vitrinite during combustion. Finally, the rank of coal LD was higher (Ro= 1.87%). According to these characteristics, the expected behavior in terms of the reactivity of the corresponding chars is B>L>LD and, consequently, the final conversion obtained will be LD<L<B.

Table 1. Fuels characterization

Analysis	Coal B	Coal L	Coal LD	Sawdust S
Ash (% w/w, db)	14.48	11.16	6.05	0.13
VM (% w/w, daf)	53.56	41.33	17.66	81.64
FC (% w/w, daf)	46.44	58.67	82.34	18.36
HCV (kcal/kg, db)	5314	6997	7338	4919
Vitrinite (% vol.)	95.4	70.0	78.8	-
Liptinite (% vol.)	2.0	1.9	0.0	-
Inertinite (% vol.)	2.6	28.1	21.2	-
Ro (%)	0.22	0.71	1.87	-

VM: Volatile matter, FC: Fixed carbon, HVC: High Calorific Value, db: dry basis, daf: dry ash free

As expected, the contents of volatile matter were higher in the sawdust than in the coals studied. This favors the use of blends with thermal coals which have low volatile matter contents, as the volatile matter has a positive effect on flame stability and ignition

characteristics in the furnace. Another aspect to note is the low presence of ash, which reduces required post-process disposal of residues (ashes) compared to burning just coal. The most important advantage of sawdust over coal was its expected high reactivity. However, as is already known, biomasses possess a lower caloric value and higher moisture content than coal, what could affect the firing process, hindering the burning of the particles and decreasing the overall efficiency of the process. Moreover, due to its high moisture content, the biomass must be subjected to a drying process prior to the furnace to avoid problems with feeding and excess moisture.

Thermogravimetric assays

Combustion profiles of coal chars (Table 2) exhibited a single peak (PT) whereas two peaks were formed during combustion of the sawdust charcoal (S). Several authors (Liu et al. 2002; Haykiri-Açma, 2003) have reported that the first of these peaks for sawdust (323°C) was caused by the combustion of remaining volatiles (i.e., homogeneous combustion) and the second peak (440°C) by charcoal combustion (heterogeneous step). Complete devolatilization of sawdust did not occur under the pyrolysis conditions applied in this work in the DTF due to the high volatiles content of the sawdust.

Table 2. Thermogravimetric parameters from combustion profiles of pure chars, charcoal and their blends

Char/charcoal blend	IT (°C)	PT (°C)	BT (°C)
S-100	270	324-440	500
B-100	371	553	596
B/S-95/5	357	329-537	579
B/S-90/10	348	327-446	574
B/S-80/20	325	326-424	549
L-100	439	560	618
L/S-95/5	404	325-564	613
L/S-90/10	374	325-568	616
L/S-80/20	322	325-578	628
LD-100	445	562	630
LD/S-95/5	411	324-569	651
LD/S-90-10	401	323-568	662
LD/S-80/20	328	324-576	660

IT: Initial Temperature, PT: Peak Temperature, BT: Burnout Temperature

A comparison of peak temperatures (PT) showed the following reactivity order for the assayed chars and charcoal: sawdust (charcoal) > char B > char L ≈ char LD. This order agrees with the increasing rank (%Ro) of the parent coals.

For the blends, a comparison of their characteristic temperatures (Table 2) showed that as the sawdust content in the blend increased, its ignition temperature (IT) decreased with respect to that of pure charcoal. This result could be explained by the greater content of volatiles in the blend with respect to char. In practice, this result should translate into improved ignition of the fuels mixed in the furnace.

On the other hand, parameters PT and BT obtained for the blends behaved differently depending on the char present in the blend. For the BS blends, both parameters tended to decrease as the charcoal content in the blend increased.

The behavior of the S blends with the higher-rank coals (L, LD) was different. In these cases, the thermogravimetric parameters, PT and BT, increased with the increment of the content of S in the blend, indicating that the combustion of the charcoal retarded the

combustion of the charcoal present in the blend. This could have implications at the operational scale: the blending of higher-rank (bituminous) coals with sawdust could translate into greater unburnt coal in the ashes because coal requires more combustion time to burn completely. This result agrees with that expressed some years ago by other authors, who recommended not using coal-biomass blends with over 20% biomass (Hughes and Tillman, 1998; Spliethoff and Hein, 1998) because of this operational consequence.

To more precisely elucidate any interactions between the components of the different blends, the evolution of the actual conversion of each blend over time was compared with the corresponding weighted average, determined from the conversions of the single components. In particular, the real conversion was compared with the weighted average at 450°C, the temperature at which the velocity of charcoal burning achieved its highest value. This would be the condition at which interactions between the blend components will be favored, as was observed for the case of coal blends during the heterogeneous firing (Ulloa et al., 2005). Moreover, at this temperature, co-firing of the different components of the distinct blends was verified. Therefore, for each blend, the average deviation relative to the weighted average for the conversion (daf) was calculated according to the following equation:

$$D(\%) = 100 \cdot \frac{X_{real} - X_{wa}}{X_{wa}}$$

where:

D: Deviation of real conversion with respect to the weighted average

X_{real} : Experimental conversion of the blend at 450°C

X_{wa} : Weighted average conversion calculated from the conversion of the individual components of the blend and its composition.

Figure 1 shows the deviations calculated for the conversion of blends at 450°C, and Figure 2 provides an example of the experimental and average weighted conversion curves for the B/S-80/20 blend with higher biomass content.

Two types of behavior were observed in Fig. 1. In the first, experimental burnouts of the blend BS-80/20 were shown to be higher than those expected from the pure components, i.e., positive deviations were observed, shown in figure 2. These began at approximately 400°C, meaning that, from the initial temperature (these chars have similar ignition temperatures) up to this temperature, just below the peak temperature (PT) for charcoal, char B and charcoal burned simultaneously at similar rates (parallel combustion). As the temperature exceeded approximately 500°C, the charcoal burnt completely, leaving more favorable conditions for burning off the remaining of char B, thereby promoting its combustion, resulting in positive deviations of conversion.

The results obtained for this blend are very interesting for the coal based thermoelectric sector, as they indicate that the mixing of low-rank coal with sawdust would not only decrease losses due to unburnt coal in the ashes, but would also improve the yield for energy plants through savings on fossil fuels (coal). This will also allow for the valorization of a waste product (sawdust), and shrink the country's carbon footprint through the partial substitution of fossil fuels in the electricity production.

The second type of behavior was observed for the blends L-S and LD-S. Real burnouts of L-S blends (with 10% and 20% biomass material) were lower than expected from the individual fuels. This

observation agrees with the behavior observed for the thermogravimetric parameters PT and BT, which evidenced a delay in combustion due to the presence of charcoal. Combustion was also delayed in the case of the L-S and LD-S blends containing 10 and 20% biomass, especially for the blend with the higher charcoal content. No significant deviations were observed in the conversion, nor were any large displacements found in the thermogravimetric parameters of blends containing 5% charcoal. Thus, according to these results, sawdust blends with higher-rank (bituminous) coals cannot be recommended for power plants due to the risk of lower burnout.

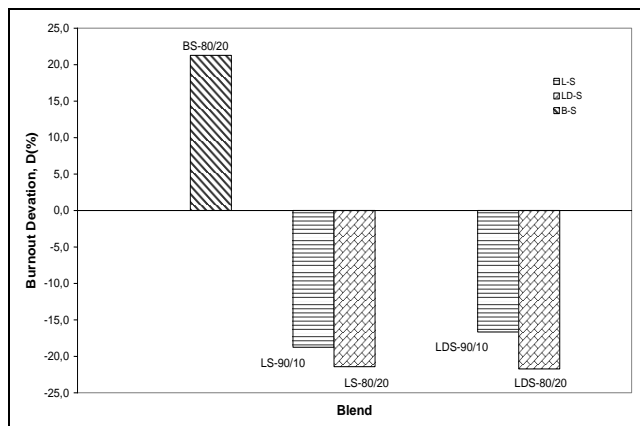


Figure 1. Observed deviations on conversion of blends at 450°C

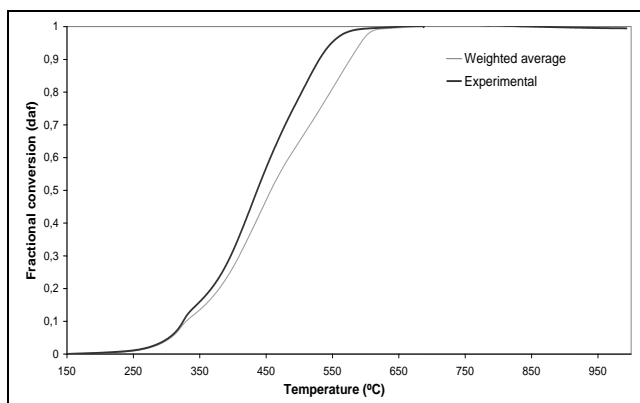


Figure 2. Conversion curves for B/S-80-20 blend. Comparison with weighted average

These results indicate that the different levels of reactivity of the blend components and their relative proportions are the key factors for predicting eventual deviations in the burnout of coal-biomass blends, and thus avoiding efficiency losses due to high contents of unburnt coal in the residual ashes.

Conclusion

The thermogravimetric assays for the combustion of coal-sawdust blends presented herein demonstrated that, in fact, positive and negative deviations occur in the burnout. The key factors that allow forecasting the deviations are the different levels of reactivity of the blend components and their relative proportions. Thus, the results obtained do not support blending sawdust with bituminous coal, as their widely different reactivity rates would cause competition for the available oxygen during the heterogeneous stage. On the contrary, blends with low-rank coals were not at risk of increased unburnt coal in the ashes and may even result in higher burnout with respect to the expected weighted average.

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