CO-COMBUSTION OF COAL AND BIOMASS IN FB BOILERS: MODEL VALIDATION WITH EXPERIMENTAL RESULTS FROM CFB PILOT PLANT

A. Bahillo[1], A. Cabanillas[1],P. Gayán[2], L. De Diego, J. Adanez[2],

[1] CIEMAT, Avda. Complutense, 22. 28040 Madrid (Spain)

[2] CSIC, Miguel Luesma Castán, 4. 50015 Zaragoza (Spain)

ABSTRACT

Circulating fluidized bed technology is developed for the combustion of mixtures of different coals and wood-based waste to operate in an environmentally friendly way. Biomass waste has combustion characteristics which improve the combustion behaviour of low quality coals due to high volatile content and low sulphur, nitrogen and ash contents. In this work, the objective is to improve co-combustion of coal and wood-based biomass waste in CFB by pilot plant experiments, modeling and validation. The new CFB model can be effectively used to optimise co-combustion of coal and biomass from the point of view of the carbon combustion efficiency and the sulphur retention.

INTRODUCTION

Circulating fluidized bed (CFB) is a technology for combustion of solid fuels. It was first used for combustion of coal due to its unique ability to handle low quality, high sulphur coals. The size of the largest boilers has increased, based on the experiences gained and is now around 300 MWe. CFB combustion (CFBC) has increased its market share of biomass combustion during recent years. The main reasons are high burnout of the fuel, wide fuel span, high thermal efficiency, low emissions of harmful gases and a competitive price. Co-combustion with coal can be utilized for exploitation of wastes that otherwise would be landfilled or incinerated alone. (Davidsson, 1999) (Hein, 1996)

Extensive experimental investigation has been carried out to date on the feasibility and performance of the CFBC of different alternative fuels. However, the modeling effort of biomass co-combustion in CFB has received little attention. One of the first works on co-combustion was that of Leckner and Karlsson (1993) who measured experimental emissions of NO, N_2O, SO_2 and CO from combustion of mixtures of bituminous coal and wood in a CFB.

They concluded that emissions from the combustion of mixtures are approximately proportional to the mixing ratio of the fuels and to the emissions properties of the respective fuels.

Reviews on CFB reactors modeling can be found in Grace et al. (1997) and Basu (1999). Most of the models have been developed for coal combustion. The modelling effort of biomass combustion in CFB has received little attention. Modelling attempts of the last few years (Leckner, 1998; Eaton et al., 1999; Yam and Zhang, 2000) have focused on the details of the hydrodynamic, relegating the combustion to simple chemical reactions, which are inadequate for phenomena such as CO oxidation or NO_x formation. Recent works (Kilpinen et al. 1999 and Wargadalam et al., 2000) incorporated detailed reaction schemes. Desroches-Ducarne et al. (1998) developed a one-dimensional model for CFB waste incineration with a simple hydrodynamic submodel but including instantaneous waste devolatilisation, char and volatiles combustion and pollutant gas emissions.

EXPERIMENTAL

The nominal capacity of the CIEMAT circulating fluidised bed (CFB) reactor is 0.3 MW_{th}. The process scheme is shown in figure 1. Riser diameter was 0.2 m and length 6.5 m. The inner parts of the reactor were made of ceramics. Solid circulation is carried out through the cyclone, return leg and solid valve. They are lined with refractory ceramic as well. The connection between the riser and the return leg is made with solid valve. The combustion air is preheated in an electrical heater. The secondary air is divided in two currents: the air used in the pneumatic transport and the air introduced at 2,25 m. The feeding system has two fuel hoppers mounted on a balance. The biomass and coal are fed simultaneously to a third screw feeder system leading to the boiler. The rotation speed of this screw feeder is kept constant and high. Coal and biomass mass flows are controlled separately. The pilot plant is also equipped with a gas burner, which may be used for faster pre-heating during the star-up. The plant is instrumented for measurement of pressures, temperatures and gas flow rates. The plant has an adaptive-predictive control system. All process variables are recorded in continuous form and processed by the control system. Composition of dry flue gas was measured with traditional on-line analyzers (O_2, CO_2, CO NO, SO_2) and wet and hot (180 ^{o}C) flue gas with FTIR (CO_2, CO, NO, NO_2, CH_4, SO_2, H_2O, HCl).
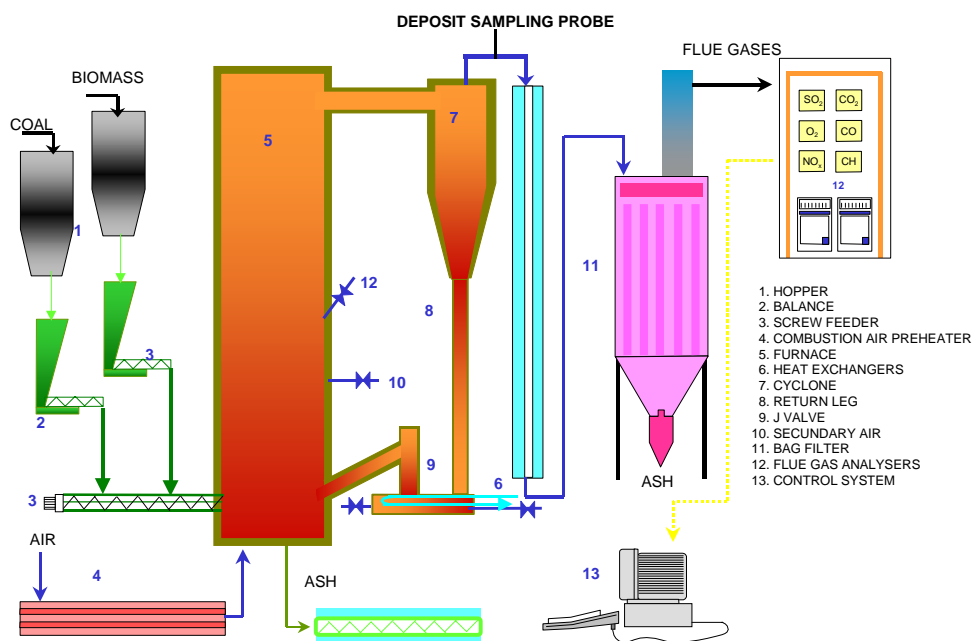
Figure 1 Circulating fluidised bed pilot plant scheme

FUELS AND THEIR COMPOSITIONS

Two different coals were selected for the combustion tests: one bituminous, South African (SA) coal and one Teruel lignite (LT). Pine bark (PB) was sampled from UPM Kymmene OYJ's Rauma mills (Finland), South African coal from PVO's Tahkoluoto power plant (Finland) and Teruel lignite from SAMCA's mine. Fuels composition has been compared in Table 1 and table 2. The main characteristics of the pine bark are high volatile matter, low ash and sulfur contents. Initially, the moisture content of pine bark was 34.5%. During the storage and grinding the moisture content of the biomass decreased from 34.5% (a.r.) to 10.7%. Besides, it is important to make stand out high sulphur content and high ash content of the Teruel lignite. Some test runs were carried out with limestone.

Sulphur contents varied between 0.05 (pine bark) and 6.5**%** (LT), aluminium contents between 5.1 (PB) and 26.6 wt% (SA) and silicon contents between 17.1 (PB) and 44.1 wt% (LT). Wood-based fuel (PB) contained highest concentrations of potassium. Sodium contents were relatively low. Synergetic effects were expected to be discovered due to large differences between the fuel compositions.

Table 1. Proximate and ultimate analysis of fuels

Parameter	PB	SA	LT
Proximate analysis			
Moisture (%)	10.7	6.6	11.0
Volatile Matter (%)	72.9	37.6	38.1
Ash, 815ºC (%)	2.6	13.32	26.5
Fixed Carbon (%)	24.5	49.08	35.4
ULTIMATE ANALYSIS			
Carbon (%)	52.9	70.3	49.2
Hydrogen (%)	6.3	4.4	4.6
Nitrogen (%)	0.5	2.0	0.6
Sulphur (%)	0.05	0.6	6.5
Chlorine (%)	0.01	0.02	0.02
Oxygen (%)	37.6	9.3	12.5
HEATING VALUE			
GHV (MJ/kg)	20.2	28.5	21.7
LHV (MJ/kg)	18.8	27.5	20.7

Table 2- Fuel ash analysis

	PB ash, wt, %	SA ash, wt, %	LT ash, wt, %
SiO_2	17,1	49.3	44.1
Al_2O_3	5,1	26.6	17.4
CaO	34,2	7.8	3.7
Fe_2O_3	2,3	4.8	17.4
MgO	4,2	2.7	0.8
MnO	1,2	0.2	0.1
P_2O_5	4,0	0.9	0.2
TiO_2	0,2	1.4	0.7
K_2O	6,7	1.1	1.1
Na_2O	2,3	0.6	0.2

Figure 2 shows the particle size distribution of the pine bark (PB), S.A. coal (SA1 and SA2), Teruel lignite (LT) and limestone.
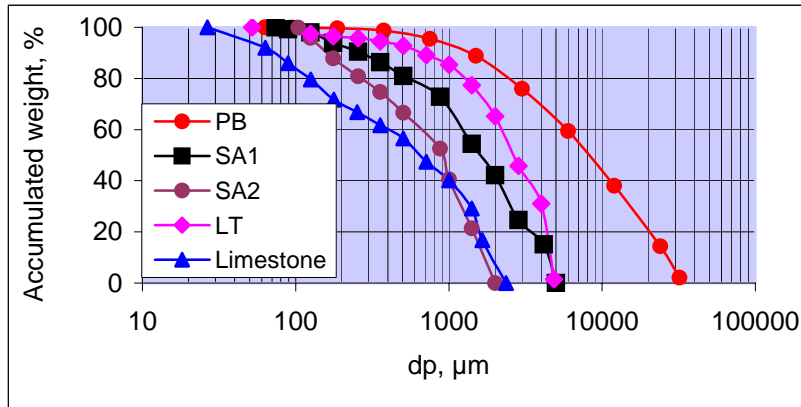

Figure 2: Cumulative particle size distributions

RESULTS AND DISCUSSION

PB and SA coal blends were burned in the CFB pilot plant. Different variables have been studied: the share of pine bark in fuel blend (0-100 % LHV db), combustion temperature (800 - 900ºC), fluidizing velocity (4 – 6 m/s), secondary air/total air ratio (24 – 50%), air excess (1,1 – 1,3 %), two SA coal particle size and the effect of the limestone.

Some results of the test runs done at Ciemat pilot plant are analysed here. The influence of the variables on the emission in the flue gases has been studied.

Temperature profiles

Figures 3 and 4 illustrate the temperature profiles along the height of the furnace in the co-combustion test runs with SA-PB and LT-PB blends. The tests were carried out with different percentages of pine bark in the mixture. The distribution plate is located at 0 m.

The effect of amount of pine bark in the mixtures on the temperature profiles is significant when the coal used is SA coal. The higher is the share of biomass in the fuel mixture, the higher is the temperature at the top of the furnace. Because of the high volatile matter content in the pine bark the release of volatiles and its subsequent combustion was observed to take place mainly at heights between 1 to 3 m. Besides, the slope in this area is more pronounced when the share of biomass is higher.
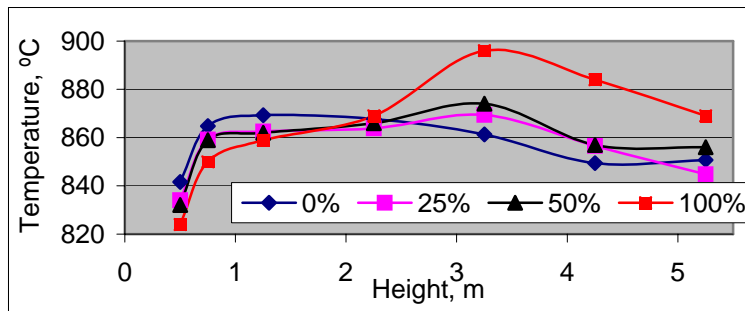
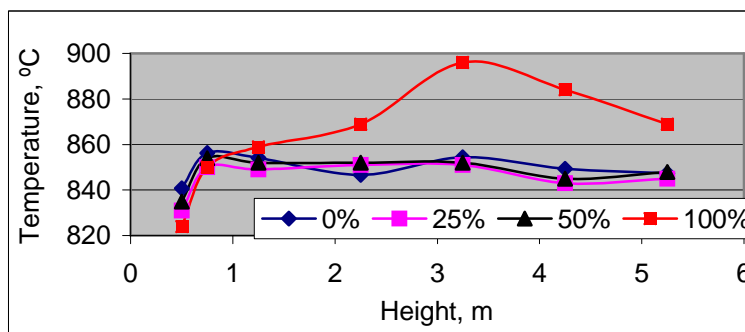Figure 3: Temperature profiles in the furnace of pine bark and SA bituminous coal

Figure 4: Temperature profiles in the furnace of pine bark and Teruel lignite

CO emissions

Figure 5 shows CO emissions in all test runs carried out with PB-SA and PB-LT blends.
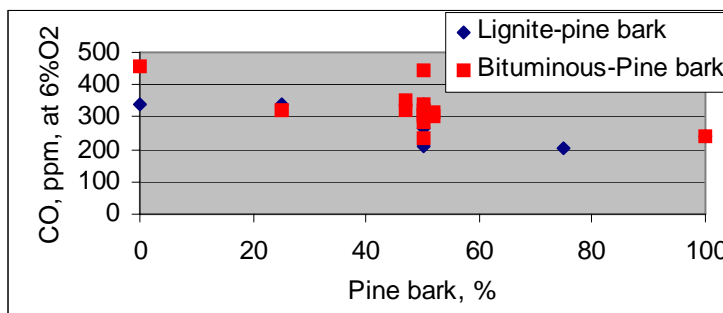

Figure 5: CO emissions from mixtures of pine bark with SA coal and Teruel lignite.

CO emission increases when SA coal share in the mixture increases. In general, when the volatile matter content is low the reactivity is low too and the combustion of this fuel is more difficult (Carpenter, 1988). The SA coal has reactivity lower than pine bark and lignite and, as a consequence of this, the presence of unburned particles in the ash is higher resulting a decrease of the combustion efficiency. The high reactivity of the pine bark compared to that of coal char results in a rapid burn-out of pine bark particles in case such particles would have survived the

passage through the combustion chamber to burn in the cyclone together with the combustible gases.

SO$_2$ emissions

Figure 6 shows SO$_2$ emission during co-combustion of pine bark and South African coal. SO$_2$ emission also increases in proportion to the amount of coal burned, since the sulphur content of the wood is negligible and all the sulphur is contained in the coal.

This is due, not only, to the fact that foot cake has lower sulphur content in comparison to coal, but also due to the calcium and potassium content in the foot cake ashes. Alkalies and alkaline earths in biomass ash bind sulphur from coal in the furnace. In consequence, decrease of SO$_2$ emissions in co-firing can be clearly larger than reduction of sulphur content of the feedstock after mixing biomass to coal (Wang, 1999 and Sami, 2001). The maximum value corresponds at 100% coal. Fuel-S conversion to SO$_2$ is the sulphur content of the coal minus self-absorption of 10-20% of sulphur in the coal ash, figure 7. It can observe that the fuel-S conversion to SO$_2$ is hardly influenced by pine bark share.

Some test runs were realized with limestone. SO$_2$ emission decreases 32% as a consequence of reaction with CaO. However, the effect of the limestone is little compared with the expected results.
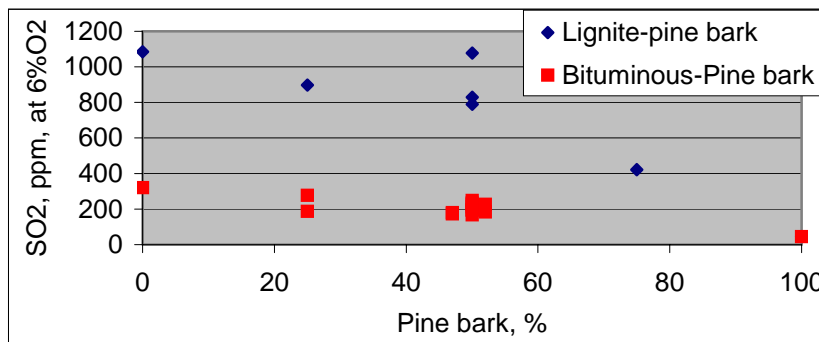

Figure 6: SO$_2$ emission during combustion of SA coal and LT with pine bark

Co-combustion test runs with pine bark-LT blends were carried out with limestone. The Ca/S ratio was 3. As a consequence of it, SO$_2$ emissions with lignite are lower than with bituminous coal but it is not possible to compare the results.
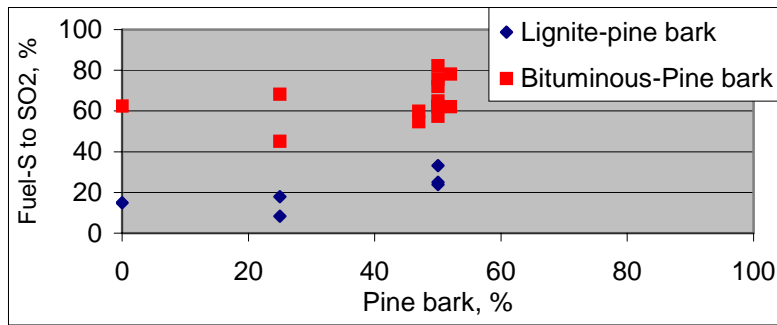
Figure 7: Fuel-S conversion to SO_2

Nitrogen oxides emissions

NOx emission decreases slightly increasing the pine bark share in the mixture with SA coal. The increase of volatile matter in the mixture is responsible of NOx emission decreasing. The relatively fast release of this volatile matter causes the presence of high levels of hydrocarbon radical to give rise to a reduction in the amount of NOx (Sami, 2001). In case of LT/PB mixtures no clear influence on NOx emission can be detected, as its reactivity is similar, figure 8.
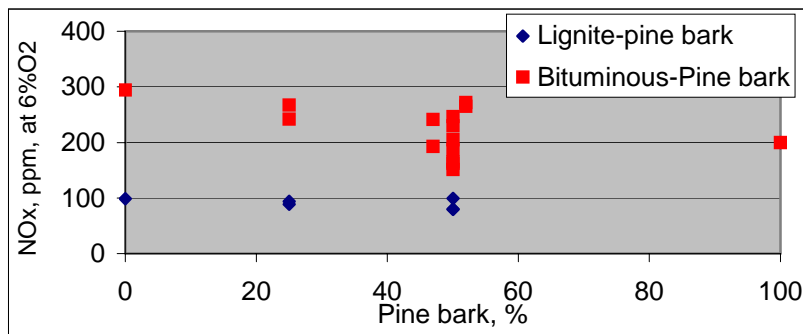
Figure 8: NOx emissions during co-combustion pine bark and coal mixtures

Figure 9 represents the conversion of fuel nitrogen to NO. It is seen that the conversion of fuel-N to NO is slightly higher when SA coal is used. These values agree with the results obtained by Wang (1994), which indicates that, the conversion of coal-N to NO increases with the coal rank.
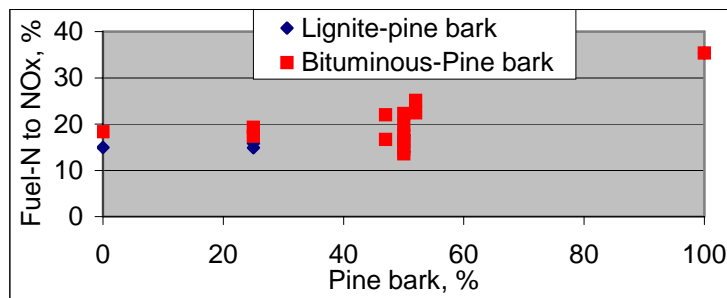
Figure 9: Fuel-N to NOx conversion at different pine bark share

It can be explained according to the char in the combustion chamber. The higher is the percentage of coal the higher is the char content in the furnace. Therefore, the conversion of fuel nitrogen to NO is lower in coal combustion tests than pine bark combustion tests. However, NOx emissions are the same magnitude because, although the coal has higher nitrogen content than pine bark, the reduction of NO with char is higher in the coal combustion tests. As figure 10 shows, the N_2O emission by co-combustion of bituminous coal and pine bark decreases with increasing the ratio of the biomass to coal. At the same time, there is no effect of lignite on N_2O emission.
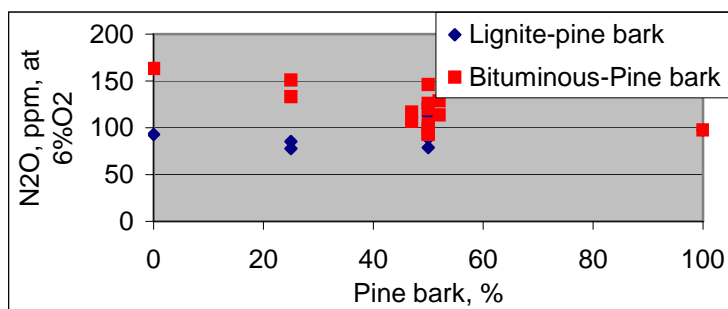

Figure 10: N_2O emission from mixtures of pine bark and coal

Studies carried out by some authors (Wang, 1999; Davidson, 1999; Sami, 2001) show that co-combustion of coal and biomass can reduce N_2O emission. This reduction is due to that the biomass contains a very high volatile matter; the release and combustion of these volatiles creates a reducing atmosphere that decreases the fraction of N_2O. Also the biomass have very small amounts of fuel-N, and this, is generally released as NHi compounds, leading to the formation of N_2O to be suppressed. The relative distribution of nitrogen to volatiles and char and to HCN and NH_3 depends on the content of volatile matter. In general, bituminous and anthracite coals released more HCN than NH_3, whereas subbituminous and lignite coals tend to released larger quantities of NH_3 than HCN. There is general agreement that HCN is the most

important precursor in the formation of N_2O in the temperature range of FBC, whereas NH_3-based compounds tend to react towards NO.

N_2O emissions are higher when SA bituminous coal is used in the place of LT. The conversion to N_2O increases with decreasing volatile matter content in the fuel (Carpenter, 1988 and Pels, 1995) but in this case both coals have similar volatile matter but different nitrogen content.

Finally, the effect of the combustion temperature is appreciable on N_2O emission as fuel-nitrogen conversion to N_2O decreased with increasing temperature (Pels, 1995; Feng, 1996; Liu, 1999).

MODEL VALIDATION WITH EXPERIMENTAL RESULTS FROM CFB PILOT PLANT

Figures 11, 12, 13 and 14 show the effect of the percentage of biomass added in the fuel, the combustor temperature, the air velocity and the excess air on E_c. As can be seen, for both coals the carbon combustion efficiency increased when the percentage of biomass, the temperature or the excess air increased. However, an increase in the linear gas velocity gave a decrease on E_c. To analyse the effect of the particle size distribution of the fuel on E_c, the bituminous coal was sieved to obtain a different particle size distribution with a lower amount of fine particles. An increase on E_c was obtained for all gas velocities due to this coal had here fewer amounts of fine particles. We have to emphasize the high values of carbon combustion efficiencies obtained with the lignite, being lower for the bituminous coal due to its lower reactivity.
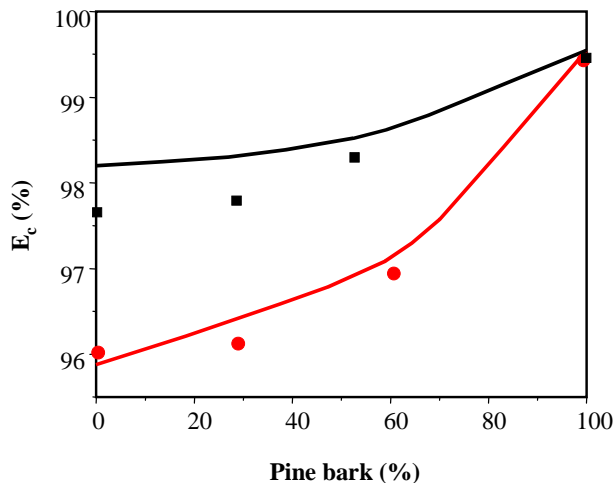

Figure 11. Effect of percentage of biomass added in the fuel on carbon Ec with two different coals: T = 850°C, u = 5 ms^{-1}, excess air = 25%, secondary air = 24 %. ■ LT/PB, ● SA/PB.
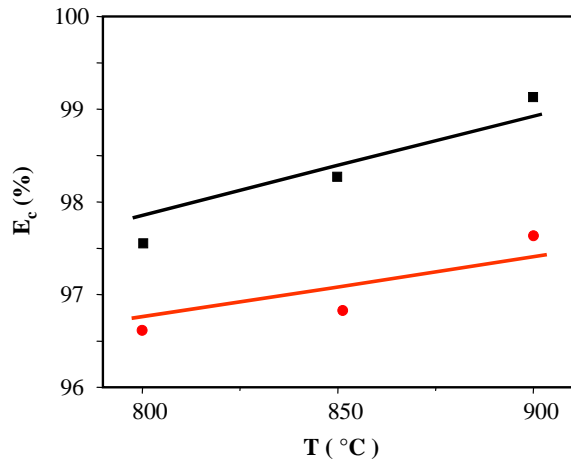
Figure 12. Effect of temperature on carbon combustion efficiency with two different coals: u= 5 ms^{-1}, excess air= 25 %, secondary air= 24 %. ■ LT/PB, ● SA/PB.
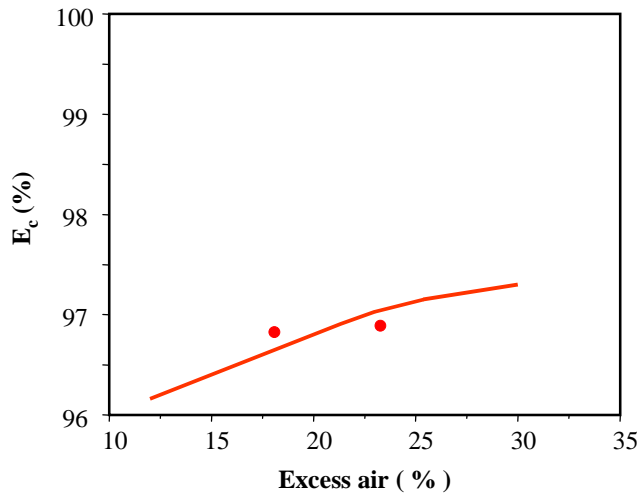

Figure 13. Effect of excess air on carbon combustion efficiency with SA coal: T= 850°C, u= 5 ms^{1}, secondary air= 24 %.
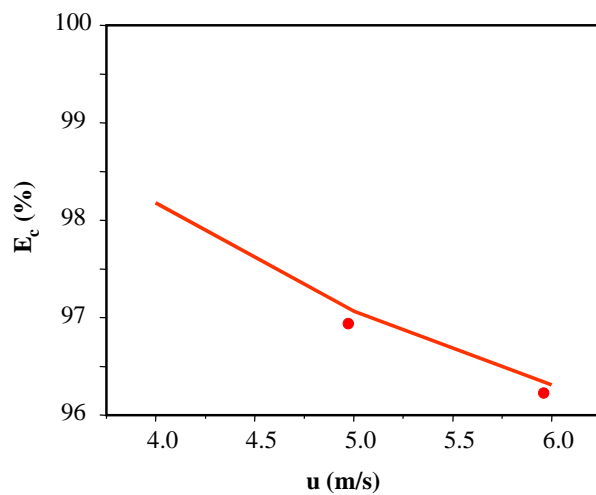

Figure 14. Effect of linear gas velocity on carbon combustion efficiency with SA coal: T= 850°C, excess air= 25 %, secondary air= 24 %.

Figure 15 shows a comparison between the experimental E_c and those predicted by the model, including all the experimental results. To validate the model with respect to the sulphur retention, some tests were carried out in the CIEMAT pilot plant. The effect of the percentage of biomass added, the Ca/S molar ratio and the coal type on the SO_2 emissions were studied using a limestone. Figure 16 shows a comparison between the experimental SO_2 retentions (R_s) and those predicted by the model when using PB with SA and LT. In general, it can be observed a good agreement in the whole range of operating conditions used.
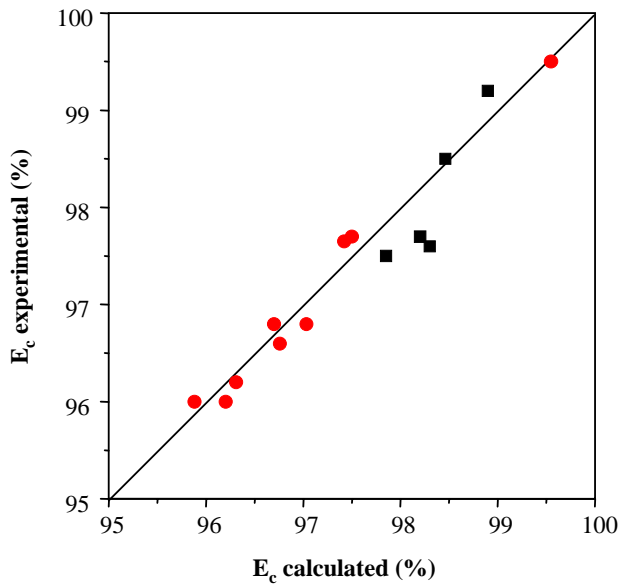

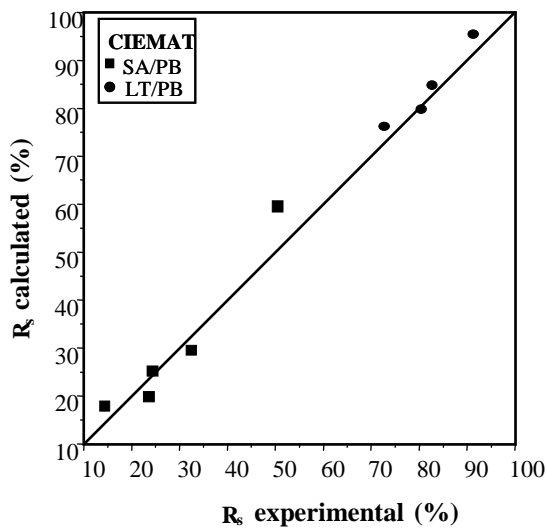Figure 15: Comparison between predicted by the model and experimental carbon combustion efficiencies

Figure 16: Comparison between predicted by the model and experimental sulfur retention

CONCLUSIONS

Pilot-scale atmospheric circulating fluidised bed co-combustion test runs were performed using two types of coal (lignite and bituminous coal) and a biomass (pine bark) to validate the model for co-combustion of coal and biomass. The main findings are:

- The model shows a good agreement between the experimental Ec and SO_2 retention (Rs) and those predicted in the whole range of operating conditions studied.

Different variables have been studied analysing their influence about combustion efficiency and flue gas composition. Other remarks are:

- CO emissions were slightly lower when lignite was used. This is due to higher volatile matter content.
- SO_2 emission decreased with increasing of the pine bark share in SA coal-pine bark blends. Not only is SO_2 concentration in flue gases reduced because the lower sulphur content of pine bark but also due to alkali metals in the pine bark ash. SO_2 emissions with bituminous-pine bark blends cannot be compared with lignite-pine bark blends because co-combustion test runs with Teruel lignite were carried out with limestone.
- NOx and N_2O emissions in lignite-pine bark blends are lower than in bituminous coal-pine bark blends as a consequence of lower nitrogen content. NOx emission is hardly influenced by the percentage of pine bark in the mixtures. However, N_2O emission decreased with increasing the pine bark share especially in SA coal-pine bark blends. The conversion of fuel nitrogen to NO is slightly higher when bituminous coal is used.

REFERENCES

Carpenter, A.M., 1988. IEA CR/12 IEA Coal Research

Davidson, R.M., Experience of cofiring waste with coal. 1999. 63 p. IEACR LIB. IEA coal Research, London (United Kingdom). ISBN: 90-9029-322-5

Feng, B. et col. 1996. International Journal of Energy Research 20, 1015-1025.

Gulyurtlu I., 1995. A comparison of NOx levels from R&D studies with values measured at different plants. Fuel 74, 2 pp 253-257

Hein, K.R.G., Heinzel, T., Kicherer, A., Spliethoff, 1996. H. Deposit formation during the co-combustion of coal-biomass blends. Proceedings: Applications of advanced technology to ash-related problems in boilers. Editors: Baxter, L. and deSollar, R. Plenium Press, New York, 1996.

Helmer, W.A.; Stokke, D.D. A case study of fluidized-bed combustion of wood/coal mixtures. Part B. The effect of wood moisture content. Forest Products Journal, Volume: 48, Part: 4, p.51-54, Apr 1998.

Johnsson, J.E., 19994. Fuel 73 (9).

Leckner, B., Karlsson, M. Emissions from circulating fluidized bed combustion of mixtures of wood and coal. 12. International conference on fluidized-bed combustion, San Diego, CA (USA), 9-13 May 1993.

Liu, de Chang et col. 1999 15th Int. Conf. on FBC ASME, Paper Nº FBC99.

Pels, J.R., Ph.D. Thesis, Technical University of Delft, 1995

Sami, M., Annamalai, K., Wooldridge, M., 2001. Progress in Energy and Combustion Science 27 171-214

Tillman D.A, Hughes E, Plasynski S. Commercializing biomass-coal cofiring: the process, status, and prospect. Proceedings of the Pittsburg Coal Conference, Pittsburgh, PA, October 11-13, 1999.

Wang, J., Liu, H., Lu, J., 1999. Dev. Chem. Eng. Mineral Process 7 (5/6): 501-511.

Wang W., Brown S.D., Thomas K.M., Crelling J., 1994. Fuel 73: 341-347