Title: Investigation on co-firing of coal mine waste residues in pulverized coal combustion systems

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Abstract

Every year millions of tones of coal mines waste residues are piled up causing serious environmental problems. These residues are mainly composed of inorganic matter and have a low calorific value. Among the alternatives for the energy utilization of these by-products, combustion or co-combustion processes in facilities based on fluid bed technology is the most widespread alternative worldwide. However, even though more than 90% of the installed coal-fired capacity is based on the pulverized coal combustion technology, there are no reported experiences of co-firing coal mine residues under this combustion technology. This work proves the technical feasibility of co-firing coal mine wastes residues and coal in pulverized fuel combustion systems up to 20% shares in energy basis and investigates the impacts of transferring this co-firing alternative into a commercial pulverized fuel unit in terms of plant efficiency, increase in auxiliary equipment power consumptions and pollutants emissions. First, experimental co-firing tests of coal mine wastes were conducted on a 500 kWth semi-industrial pulverized fuel pilot plant, varying the co-firing ratio in energy basis from 0% (only coal) to 20%. Finally, the impact analysis of co-firing coal mine waste residues in a full scale pulverized fuel plant, was performed by simulating the power cycle and combustion process in a 160 MW_e pulverized coal combustion unit.

Highlights

- Experimental co-firing tests of CMWR and coal were conducted in a PCC pilot plant
- Lower combustion efficiency but stable conditions are achieved as CMWR share increases
- An impact analysis of co-firing CMWR in a full scale PCC plant was performed
- Plant efficiency reduction and emissions levels for CMWR co-firing are acceptable

Keywords: Coal mine waste residues, co-firing, pulverized coal combustion

Abbreviations

CCD – Charge coupled device
CFBC – Circulating fluidized bed combustion
CMWR – Coal mine waste residues
FC – Fixed carbon
FWH – Feed water heater
HHV – High heating value
HPT – High pressure turbine
MPT – Medium pressure turbine
LPT – Low pressure turbine
NDIR – Non dispersive infrared
OECD - Organization for Economic Co-operation and Development
PCC – Pulverized coal combustion
SAC – South African coal
VM – Volatile matter

1. Introduction

Coal is one of the main sources of energy in our society, with a global consumption of 5.500 millions tones in 2015 representing more than 19 % of the primary energy in the world. Despite of the fact that in the last years coal consumption has drastically decreased in OECD countries, in the same proportion it has increased in non-OECD countries, specially in China, overtaking USA as the world's biggest producer [1].

However, coal mining and energy production have significant impacts to the environment and human health which jeopardize its sustainable use as primary source of energy without efficient waste management strategies [2]. One of these problems is the production and stockpiled at waste dumps of coal mining waste residues (CMWR). Coal mining wastes are mainly composed of inorganic matter (SiO_2, Al_2O_3, Fe_2O_3 and impurities) and present a low calorific value. Materials from recent coal bed sites present carbon contents in the order of 5 %, but this value can increase up to 30% in the case of ancient sites, while ash content can vary from 2% to 90%. In any case, the ash yield, carbon content and in general the elemental composition of these samples are extremely conditioned from the site [2].

Coal mining waste represents about 10 to 15% of the total coal production, which results in millions of tons of new solid wastes piled every year [3-5]. These coal wastes disposals may cause a serious environmental problem in the vicinity of the mines where they are generally piled. On the one hand, acid lixiviates lead to soil and underground water pollution by leaching, drainage, natural weathering and rainwater drenching and consequently affect the environment of the biosphere. On the other hand, the spontaneous combustion of waste piles produce a harmful atmospheric pollution due to the dispersion of particles, contaminants and trace metals (As, Be, Cd, Co, Cr, Cu, Mn, Ni, Se, Pb , Sn, V, Zn) [2,5-8] and impede soil and vegetation regeneration. These noxious effects are particularly harmful if the coal mining wastes presents high sulfur content, since spontaneous combustion leads to sulfur dioxide emissions, which gives raises to acid rain formation and soil and groundwater acidification besides of other human health affections.

Therefore, it exists a necessity to recover soil and reduce these impacts as far as possible reusing this waste material. There are different ways of using these materials [9]. Main use of coal mine waste materials are in the building sector, as filling material in road base and granular materials. This use allows reusing the residue without adding new/additional environmental charges in comparison to the use of conventional materials. Main disadvantage of this use is related to the transportation cost to the final construction point, which makes distance a determinant factor in the profitability of the process.

Alternatively, other uses try to recover it calorific value as fuel in combustion systems for power generation while reducing the adverse impacts of coal gangue disposal [10]. With the fuel flexibility advantage of circulating fluidized bed combustion (CFBC) technology and increasing demand for electricity, coal gangue is widely used in CFBC power plants firing low calorific value fuels. Moderate operation temperature and the use of lime in the process can help to limit the discharge of air pollutants such as SO_x and NO_x [11]. In addition, co-firing can also off-set carbon dioxide emissions [12].

Thus, co-firing of coal gangue and coal or biomass is considered as an alternative effective method for coal gangue utilization and pollution control. The use of biomass or coals with high volatiles and low ash content would also provide stable combustion conditions and improve the thermal behavior of CFCB. Therefore, co-firing of coal gangue not only facilitates clean utilization of solid wastes but also increase its combustion efficiency [10].

Circulated fluidized bed combustion technology developed for co-firing coal gangue with coal have been steadily increasing in both quantity and capacity over the past decade [4]. Generally, the mixed fuel contains coal gangue and coal with a blending ratio of 2-3:1. According to statistics collected up to 2010, there are more than 120 coal gangue circulated fluidized bed co-

combustion power plants in China and around 30 waste coal burning power plants in the United States, most of them based on circulating fluidized bed technology.

Although, pulverized coal combustion (PCC) is the most commonly used technology in coal-fired power plants, there are thousands of units around the world accounting for well over 90% of coal-fired capacity, there are not reported experiences of co-firing coal mine residues under this combustion technology. It is well known that PCC can be used to fire a wide variety of coals, although it is not always appropriate for those with a high ash content [13].

This CMWR/coal co-firing technology in pulverized fuel combustion systems, not commercially exploited and not widely reported in the scientific literature, focus the interest of this research work. The first goal was to demonstrate experimentally the viability and stability of the co-firing of CMWR and coal in pulverized fuel swirl burners. To this purpose, a full co-combustion test campaign has been conducted at different co-firing ratios in a 500 kW_{th} pulverized fuel swirl burner showing the stability of the combustion process and the impact over the pollutant regulated emissions. Boiler performance impacts due to corrosion, slagging and fouling produce by the very high ash content of CMWR have been already published [14], and are not included in this work.

Reached this objective, and in order to transfer these results analyzing the impact of co-firing CMWR on the operation in a large scale power plant, simulations of the power cycle and of the co-combustion process of a pulverized fuel combustion unit of 160 MW_e were carried out, covering the full operation regulation regimen (full load and partial load conditions), and evaluating the influence of the co-firing ratio on plant efficiency, increase in auxiliary equipment power consumptions and pollutants emissions.

2. Materials and methodology

2.1 Materials

Coal mine residues samples from different stockpiles spread in the region of Teruel (Spain) were collected, homogenized, milled (mean diameter under 50 μm) and sieved for the test campaign in the 500 kW_{th} pulverized fuel swirl burner. Table 1 presents proximate and ultimate analyses of the coal mine residues. The high ash content, the low carbon content as well as its low calorific value, dismiss an stable combustion of this residue in an isolated way in a pulverized fuel burner, being necessary the use of an additional co-fuel that in a co-firing process act as supporter and permit to self-maintain the flame stability. To this purpose, a typical blend of South-African subbituminous coals (SAC), with low ash and sulfur content, which is usually fired in the pulverized fuel power plants of this region, was selected for the co-firing study.

Table 1 is completed with the characterization analysis corresponding to the subbituminous coals blend.

Proximate analysis, dry basis (% wt)	Moisture	Ash	VM	FC	HHV (kJ/kg)
CMWR	16,81	55,51	28,94	15,54	7.392
SAC Blend	2,90	15,40	25,91	58,69	27.940
Ultimate Analysis, dry basis (% wt)	**C**	**H**	**O**	**N**	**S**
CMWR	23,07	1,15	16,46	0,56	3,25
SAC Blend	71,44	3,81	7,13	1,82	0,40

Table 1: Proximate and ultimate analysis of the study fuels (SAC: South-Africa coal, CMWR: coal mine waste residue)

2.2 Experimental tests

Experimental tests were all performed in a 500 kW_{th} semi-industrial pulverized fuel pilot plant (Figure 1). This facility is composed of a premixed fuel swirl burner on top of a cylindrical combustion chamber vertically disposed, a loss-in-weight feeding system which allows a precise dosage of coal and coal mine waste residue, and a preheating secondary air system (up to 250 ºC). Coal and coal mine waste were dosed by the feeding system and transported to the combustion chamber by the primary air. Preheated secondary air coming from the wind box was swirled using movable radial vanes and then entered the secondary air duct that goes coaxially around the primary air pipe. Finally, CO, CO_2, SO_2 and NO_x emissions were monitored at stack using a standard ABB NDIR-absorption analyzer and signals were collected by an automatic acquisition system and sent to a computer. Combustion efficiency and stability was monitored during the test, registering the visible flame radiation with an image acquisition system composed by a CCD camera (CM-030PMCL-RH) [15].

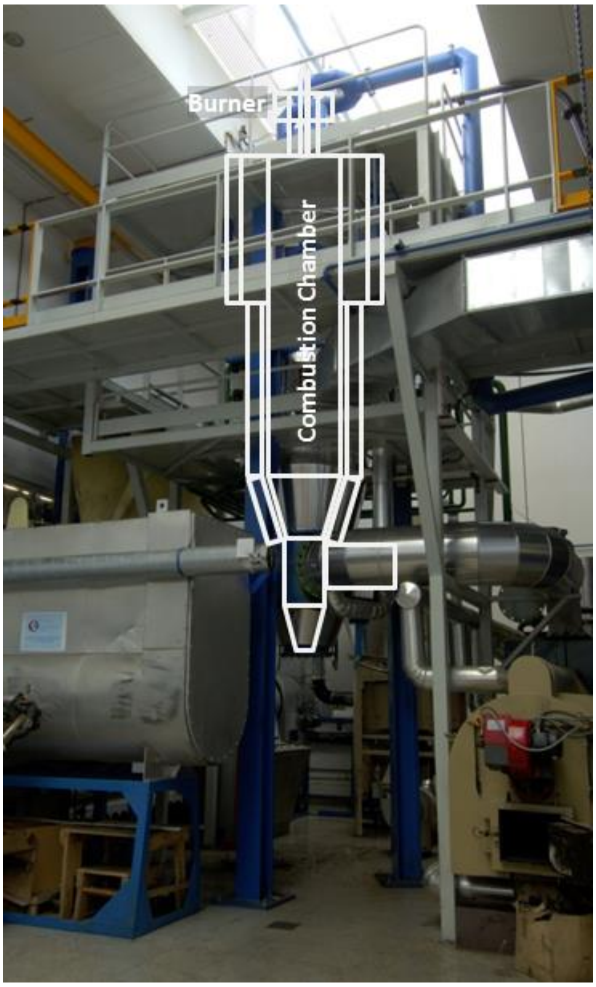

Figure 1: 500 kWth pulverized fuel co-firing laboratory

The goal of the experimental test campaign was to prove the technical viability of stable and efficient combustion of coal mine waste materials in pulverized swirl burners. In order to ensure flame stability and SO_2 emissions under the saturation limit of the gas analyzer (5000 ppm), the maximum co-firing ratio was set to 20% (substitution percentage on energy basis). Test campaign under nominal operation conditions in terms of fuel share contribution, thermal power and mass flows, primary and secondary air mass flows are summarized in Table 2.

Test	**CMWR (%)**	**SAC (%)**	**Thermal Power [kW]**	**CMWR [kg/h]**	**Coal [kg/h]**	**Primary air [kg/h]**	**Secondary air [kg/h]**
0 (Ref)	0%	100%	496,97	0	68,66	157,70	660,25
1	5%	95%	546,84	14,94	71,75	207,89	565,06
2	10%	90%	497,19	27,14	61,79	204,99	614,62
3	20%	80%	497,36	54,16	54,94	251,22	605,87

Table 2: 500 kW_{th} co-firing test campaign conditions

In all the tests the same experimental procedure was conducted in order to ensure stable conditions and repeatability of the results for its comparison. The experimental procedure consists of the following phases:

1. Preheating of the combustion facility. This stage takes about three hours. During this period of time, the combustion chamber and the refractory wall are preheated with the combustion of natural gas injected though the inner pipe of the burner and with the introduction of preheated secondary air at 250 ºC through the windbox.

2. Setting test conditions, stabilization and combustion optimization. This stage takes about two hours. First, at nominal conditions (500 kW_{th}) only coal (SAC) was fed into the burner. Once the temperature in the flue gases after the flame region exceeds 900 ºC and acceptable CO levels are reached and remain stable, the coal mine waste residue is gradually introduced, substituting the corresponding coal mass flow, until the co-firing ratio defined in the present test is reached. Finally, in order to optimize and stabilize the combustion process the secondary air vanes tilt, primary to secondary air ratio and swirl is adjusted.

3. Stationary operation. During this stage, which takes about two hours, emissions measurements, temperatures inside the furnace and other control variables of the facility are gathered for its further analysis. Also during this period of time, different videos of the combustion flame are recorded using a CCD camera in order to analyze the influence of the operating conditions on the flame stability and combustion efficiency.

2.3 Modelling approach

To analyze the impact of the use of coal mine residues on a power plant performance in terms of boiler, cycle and plant efficiency, pollutant emissions and other operation parameters, a full simulation of the cycle and combustion process of a full scale power plant has been performed.

For this study, a 160 MW_e pulverized fuel power plant located in the coal mining region of Teruel (Spain) has been selected. This selection hold in the fact that this plant has been previously used for demonstration projects involving a complete campaign of direct co-firing tests, which have provided us with enough and accurate plant data information of its operation under different load conditions required in the simulation model [16,17].

Figure 2 shows the simplified layout diagram of the regenerative power cycle. This cycle includes the reheating of the steam after its expansion in the high pressure turbine and six steam bleedings to five closed shell and tubes counter-flow heaters (FWH1, 1, 3, 5 and 6 in Figure 2) and to one open mixing heater (FWH4 in Figure 2) in order to preheat the feed water before it reaches the boiler. Resolution of main thermodynamic variables, net power output and cycle thermal efficiency have been completed based on thermodynamics calculations and energy and mass balances of the cycle. Real plant data under different operation conditions, full load (100 %) and partial load (80 %, 60 % and 50 %), has been used as inputs to the model.

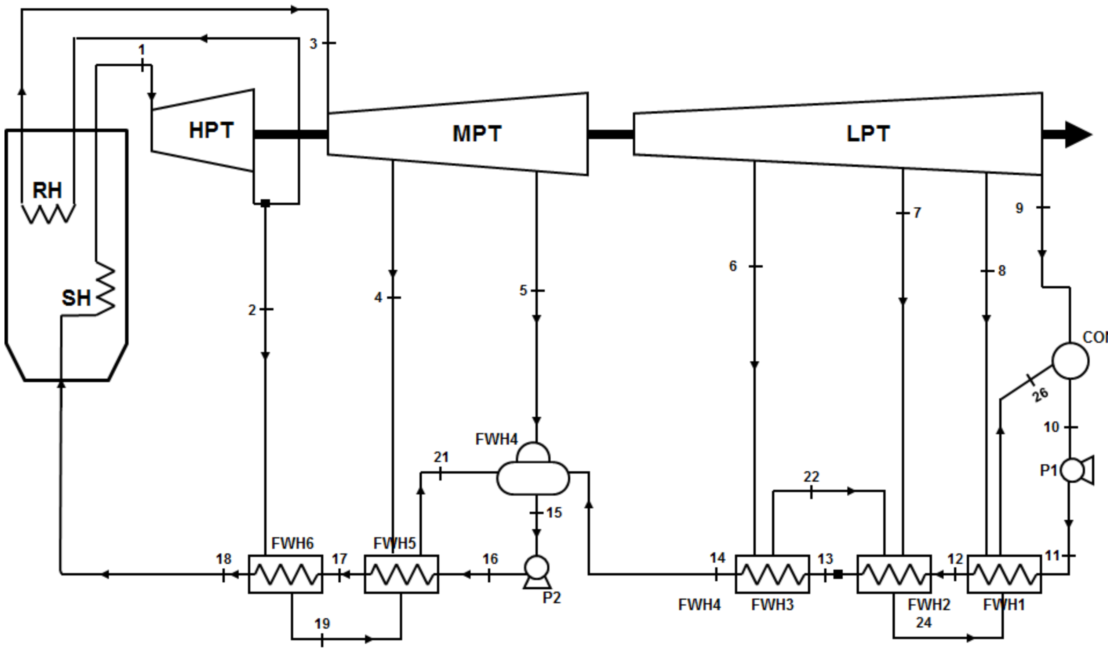

Figure 2: Simplified layout of the power cycle power plant

Table 3 summarizes the inputs to the simulation model for each load case considered, where m is the steam mass flow to the high pressure turbine (HPT), P and T are respectively the pressure and temperature of the corresponding thermodynamic states in the diagram (Figure 2) and η_{iso} the isoentropic efficiency of the different expansion sections determined according to the Spencer et al. expressions [18].

Load	**100%**	**80%**	**60%**	**50%**
m[1] (kg/s)	146,2	120,4	90,47	73,95
P[1] (bar)	165,5	137,3	104,5	86,41
T[1] (ºC)	512,8	506,3	503,9	507,7
P[2] (bar)	46,69	38,68	29,39	24,32
P[3] (bar)	40,68	33,69	25,61	21,18
T[3] (ºC)	511,4	505,3	502	506,2

P[4] (bar)	18,69	15,45	11,74	9,74
P[5] (bar)	8,8	7,29	5,57	4,64
P[6] (bar)	2,81	2,33	1,79	1,49
P[7] (bar)	1,208	1,002	0,7708	0,6453
P[8] (bar)	0,3737	0,3044	0,2364	0,2005
P[9] (bar)	0,0997	0,0459	0,056	0,0901
P[18] (bar)	246,6	201,6	149,1	120,2
HPT η_{iso}[1]	0,822	0,8	0,745	0,697
MPT η_{iso}[3]	0,8162	0,8163	0,8163	0,8163
MPT η_{iso}[4]	0,8484	0,8483	0,8482	0,8481
MPT η_{iso}[5]	0,8429	0,8429	0,8429	0,8428
MPT η_{iso}[6]	0,8191	0,8191	0,819	0,819
MPT η_{iso}[7]	0,8175	0,8177	0,8177	0,8177
MPT η_{iso}[8]	0,7604	0,6139	0,6768	0,717

Table 3: Power cycle operation data for different operation loads [17]

Results from the simulations under coal combustion conditions have been validated against nominal plant data in terms of gross power output, cycle efficiency and mass flow balances at the pre-heaters extractions (Table 4).

		100%	**80%**	**60%**	**50%**
Gross power output (kW$_e$)	npd	160.000	130.000	100.000	80.000
	sr	156.466	131.396	98.343	78.242
Cycle efficiency (%)	npd	42,23%	41,95%	40,87%	39,87%
	sr	41,61%	41,58%	40,31%	38,44%
Bleeding fraction to FWH1	npd	0,0991	0,1203	-	-
	sr	0,1208	0,1107	-	-
Bleeding fraction to FWH2	npd	0,0419	0,0509	-	-
	sr	0,0455	0,0449	-	-
Bleeding fraction to FWH3	npd	0,0566	0,0687	-	-
	sr	0,0512	0,0501	-	-
Bleeding fraction to FWH4	npd	0,0386	0,0468	-	-
	sr	0,0379	0,0367	-	-
Bleeding fraction to FWH5	npd	0,0366	0,0445	-	-
	sr	0,0424	0,0420	-	-
Bleeding fraction to FWH6	npd	0,0288	0,0349	-	-

	sr	0,0506	0,0662	-	-

Table 4: Nominal plant data (npd) and simulation results (sr) for gross power output (kW), cycle efficiency (%) and mass bleeding fraction at turbine extractions (%)

Simulation of the combustion process has been completed by means of basic calculation of main oxidation reactions together with mass and energy balances. Nominal plant data under different operation conditions have been used as inputs to the model (Table 5). Coal and CMWR mass flow inputs are determined according to the share ratio in energy terms defined for each simulation case, while oxygen supplied for the combustion, provided by the primary and secondary air streams and the oxygen content of both fuels, has been determined according to the excess air conditions presented in Table 5.

For the determination of NO_x emissions, which unlike SO_2 or CO_2 cannot be solved from simple mass conservation balances, a specific tailored fit correlation has been developed that accounts for the contributions of the NO_x formed from the nitrogen contained in the fuel and the NO_X of thermal origin related to the excess of air and the calorific value of the fuel.

$$\begin{aligned} NO_x(mg/m^3N) = {} & (135 - ([O_2] - 3) \cdot 75) \cdot (LHV/16000) \\ & + (400 + (N_{fuel} - 0{,}0855) \cdot 1837{,}75) \end{aligned}$$

where $[O_2]$ is the oxygen concentration at the boiler exit in % dry basis, LHV the low heating value (mass average for both fuels under co-firing conditions) in kJ/kg and N_{fuel} the nitrogen content of the fuel (mass average for both fuels under co-firing conditions) in parts per unit.

Load	Excess air (%)	Primary air to fuel ratio	Primary Air Temp. (ºC)	Secondary Air Temp. (ºC)	Unburned carbon in ash (%)	Combustion Gases Temp. (ºC)
100%	25	2,3	75	300	3	190
80%	23	2,3	75	300	3,5	190
60%	21	2,3	75	300	4,5	190
50%	20	2,3	75	300	5	190

Table 5: Boiler operation data for different operation loads [17]

Boiler efficiency has been determined by the indirect method calculating the different losses originated by the energy loss from sensible heating of the flue gases, flying ash and slag, assuming that 80% of the total ash fraction of the parent fuels exits the boiler as flying ash [19], and energy loss from unburnt carbon losses. Other fixed losses such as heat transferred to the ambient by radiation and convection of the outer surface of the boiler and other unaccounted losses has been estimated representing in the model a 2% of the total energy input [20].

3. Results and discussion

The combustion efficiency and stability were investigated, during the experimental tests campaign conducted in the 500 kW_{th} pulverized fuel pilot plant, through the records of the visible flame by a CCD camera together with the registered variables of the plant.

From this analysis it is concluded that once the parameters are adjusted, the combustion flame is stable, obtaining regular flicker level and flame brightness intensity. On the other hand, and according to previous works, lower flicker levels and flame brightness intensity are obtained as the co-firing ratio of CMWR is increased, revealing lower local temperatures and the presence of a higher concentration of slower inert particles [14].

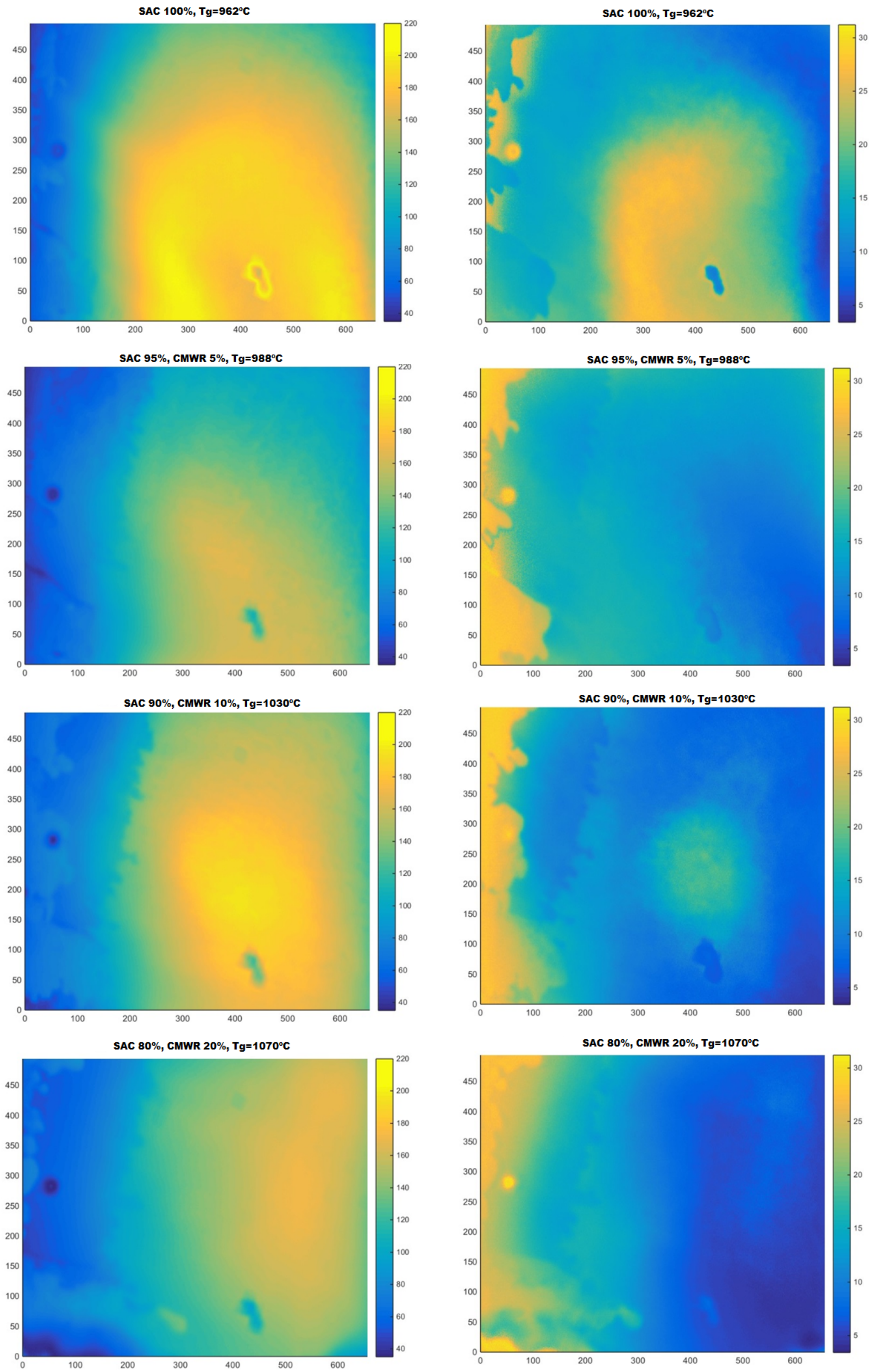

Figure 3: Flame brightness (left) and flicker level (right) at different co-firing ratios corresponding to the experimental test campaign (Test 0, 1, 2, 3)

Such results are corroborated by obtaining acceptable emissions levels for CO (200 mg/m^3N) and for NO_x (700 - 800 mg/m^3N). However, special attention should be paid to SO_2 emissions which increase notably with the substitution percentage due to the high sulfur level in the coal mine residues.

Test	Co-firing ratio	CO (6%O_2)	NO (6%O_2)	SO_2 (6%O_2)
0 (Ref)	**SAC 100%**	91,04	786,63	418,00
1	**SAC 95%, CMWR 5%**	125,77	741,55	1447,17
2	**SAC 90%, CMWR 10%**	66,47	812,23	2726,58
3	**SAC 80%, CMWR 20%**	225,69	722,64	5333,30

Table 6: CO, NO and SO_2 emission (normalized at 6% O_2) during the tests (mg/m^3N)

The feasibility of the co-firing process, even for high substitution levels (20%), is even more important taking into account factor scale considerations. Main key variables of the combustion behavior in the region close to the burner such as temperature, vorticity, recirculation velocities, etc. are more difficult to control and keep at stable conditions in a pilot burner when compared with a full scale plant burner. Therefore, although coal mine residues are traditionally burnt in CFBC technologies, its application, depending on the parent waste composition, may be extended to retrofitted pulverized fuel units.

In order to implement a CMWR co-firing experience in a commercial pulverized fuel unit, a simulation-based analysis of the impact on the plant operation, efficiency and pollutants emissions is conducted at different load conditions (100%, 80%, 60% and 50%) varying the CMWR substitution percentage in terms of energy (0 – 20%). Otherwise, in this study the impacts due to corrosion, slagging and fouling or abrasion produce by the high concentration of flying ash particles in the flue gases and their impacts in the performance and maintenance of the plant have not been tackled. However, it is an aspect that should not be ignored since the very high ash content of CMWR produces high levels of fouling and sintering of the deposits, which may make it necessary to install auxiliary cleaning measures such as steam blowers [14].

Results of the simulation cases, using the modelling approach described in section 2.3, are presented. First, the influence of the coal mine waste substitution percentage on the boiler efficiency is analyzed for different load conditions. Figure 3 shows two prevailing tendencies. On the one hand, the higher is the CMWR substitution percentage the lower is the combustion efficiency. This result has been already confirmed during the experimental tests. Despite the fuel energy input is the same in all the cases, the high ash content of the CMWR notably increases sensible heating losses related to them. On the other hand, at partial load conditions, temperature in the near burner region and in the furnace is lower, thus reducing the combustion efficiency and increasing unburned carbon losses. The combination of these effects results in that at full load conditions or even at high load partial conditions (80%), the reduction in the boiler efficiency is less than 3% for CMWR co-firing ratios under 10% (Full load conditions: from 89.91 to 87.71%, Partial load conditions 80%: from 89.7 to 87.4%). However, as the CMWR substitution percentage is increased up to 20%, the reduction in the boiler efficiency reaches 4% at full load conditions, and above 7% if the plant is operating at low partial load conditions (< 60%).

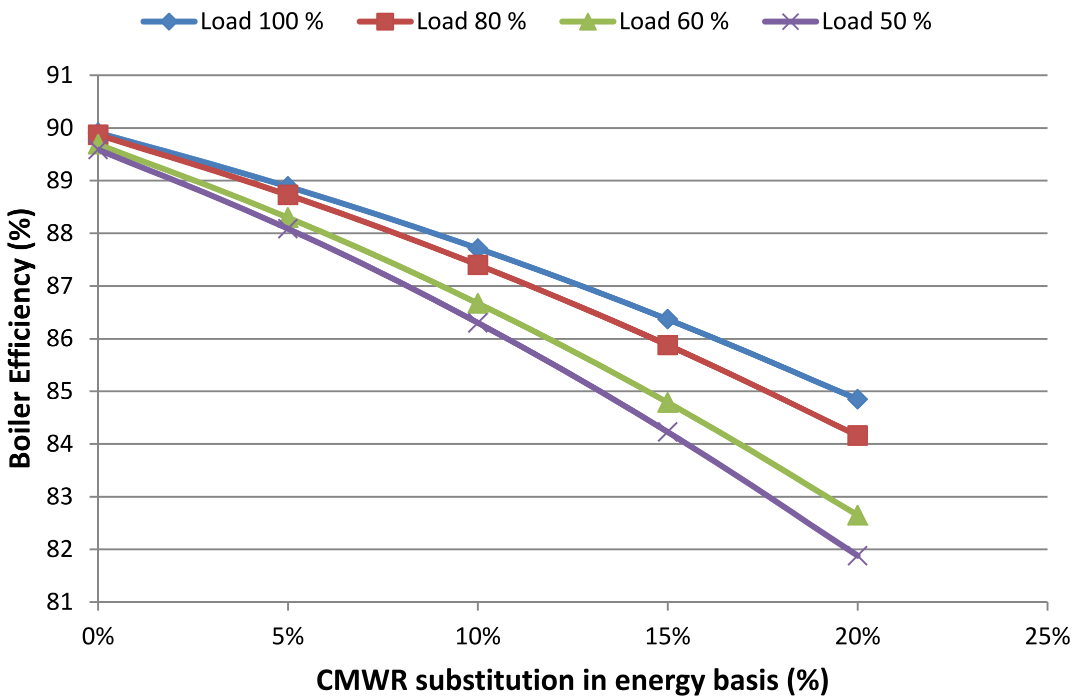

Figure 4: Influence of coal mine waste residue co-firing ratio (%) on the boiler efficiency

In order to go deeper into this analysis, and to determine the impact on the overall efficiency of the plant, it is necessary to evaluate the consumption of the auxiliary equipment during the operation. The most important auxiliary equipment in terms of operation and consumption are the air-gas circuit fans, pumps, electrostatic precipitators, milling system and ash evacuation system, which cover more than 95% of a conventional plant. The power consumed by these auxiliary equipment can be in the order of 4-10% of the generated gross power. Increasing the percentage of substitution, maintaining the same energy input and taking into account the low calorific value of the CMWR, supposes to increase notably the total mass flow of fuel fed to the furnace. This in turn leads to an increase in the required air flow if the same excess air is maintained. Likewise, the mass flow of gases and fly ash carried by this stream will also be higher as a greater amount of CMWR is introduced.

	0 %	5 %	10 %	15 %	20 %
% Increase total air	0,00%	2,93%	6,12%	9,61%	13,43%
% Increase total fuel	0,00%	18,40%	37,49%	57,40%	78,28%
% Increase total combustion gases	0,00%	3,59%	7,47%	11,67%	16,23%
% Increase flying ash	0,00%	64,98%	131,89%	201,20%	273,44%

Table 7: Increase of total air, total fuel, combustion gases and flying ash mass flows as a function of CMWR co-firing substitution percentage (full load conditions).

Table 7 shows the increase in the main mass flows streams of the plant as the percentage of substitution increases. While the increase in the air and gas flow rates is acceptable and would not require large modifications in the plant, the increase of mass fuel flows and the ashes drag with the combustion gases, is more problematic requiring deeper changes. Thus, by increasing the percentage of substitution above 10%, it would be necessary to replace and adapt the equipment responsible for transport and pretreatment of fuel (conveyors, hoppers, mills, pipelines), to install dedicated burners, and to modify or replace the equipment responsible for the removal of particles and their subsequent processing.

Alternativa 1

Consequently, the consumption of auxiliary equipment of the plant, related to the transportation, pretreatment, processing, combustion and cleaning of gases, will increase considerably with the percentage of substitution. Based on nominal data from the study plant and considering the increases in the main mass flows presented in Table 7, Table 8 presents an estimate of the overall power consumption of plant auxiliary equipment in the different scenarios.

Alternativa 2

Consequently, the consumption of auxiliary equipment of the plant, related to the transportation, pretreatment, processing, combustion and cleaning of gases, will increase considerably with the percentage of substitution. Based on available data from the study plant and considering the variation of the increases in the main mass flows presented in Table 7, a correlation has been fitted to estimate the power consumption of auxiliary equipment as a function of plant load and fuel, air, gas products and flying ash mass flow rates.

$$P_{Aux}(kW) = \left[\left(0{,}04 + 7E^{-4}(Load - 50)\right) \cdot I_{mf_u} + 0{,}015 \cdot I_{mf_d}\right] \cdot P_{gross}$$

Where P_{Aux} is the auxiliary equipment power consumption in kW, Load is the plant load in %, I_{mfu} is the average increment of the incoming fuel and air mass flows with respect to the base case (100 % coal), I_{mfd} is the average increment of the gas products and flying ash mass flows with respect to the base case and P_{gross} is the generated gross power in kW.

Load CMWR %	100%	80%	60%	50%
0%	13700	11621	8855	7419
5%	15710	13340	10187	8533
10%	17799	15137	11595	8961
15%	19984	17027	13095	10988
20%	22282	19030	14708	12364

Table 8: Auxiliary equipment power consumption estimation (kW)

The final impact on the overall efficiency of the plant is presented in Figure 5. The analysis shows how the efficiency of the plant is reduced to partial loads and as the percentage of substitution increases. This reduction is significant, above 2 points in percentage when the CMWR co-firing ratio is increased above 10%, and very significant in the case of operating at partial loads below 80%. It is concluded, therefore, that the use of CMWR in co-firing processes in a PCC unit is adequate when operating at full load or high partial loads (> 80%). Similarly, the percentage of substitution should be restricted to a maximum close to 10%. Operating above this percentage means a very sharp decrease in plant efficiency (more than 4% in the most favorable case under full load conditions), as well as the need for major modifications to the plant's auxiliary equipment.

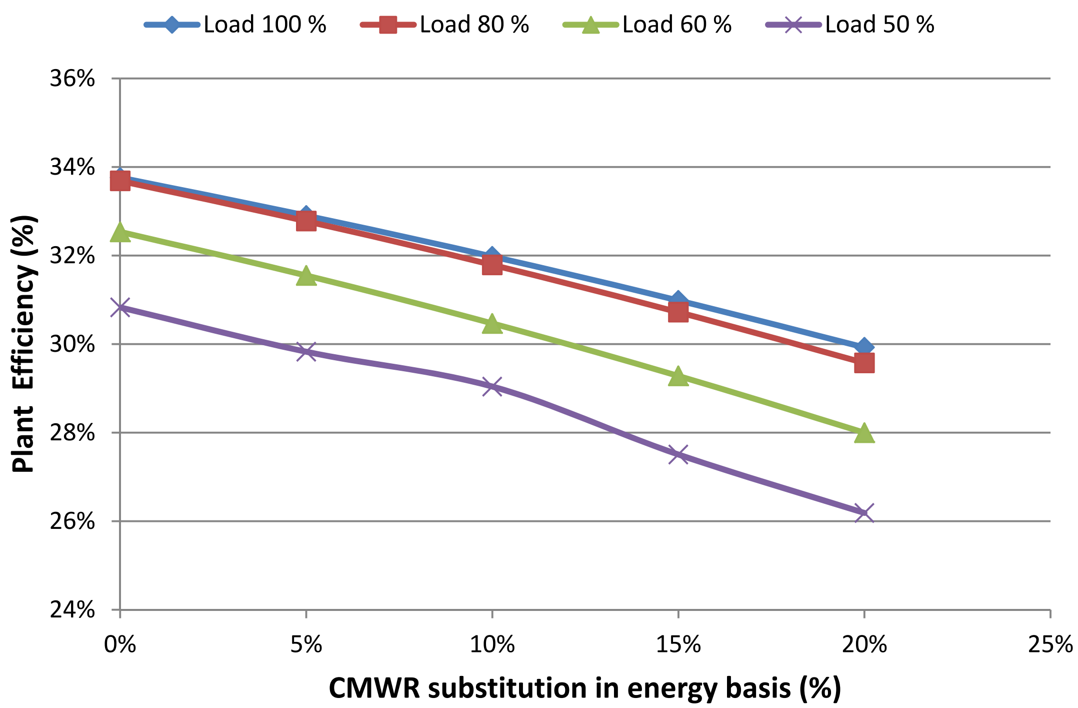

Figure 5: Influence of coal mine waste residue co-firing ratio (%) on the plant efficiency

The analysis is completed by analyzing the impact of CMWR co-firing on regulated pollutant emissions (NO_x, SO_2 and particulates).

Figure 6 present these pollutants emissions normalized (6% O_2) under full load conditions for different co-firing ratios. Results show how increasing the co-firing ratio, NO_x emissions remains practically constant. A little decrease is observed due to a minor nitrogen content of the CMWR and a lower reaction temperature in the furnace, reducing the fuel NO_x and thermal NO_x path formation, respectively. On the other hand, SO_2 emissions greatly increase since a much higher sulfur content by energy unit in the fuel is introduced. If the plant does not count with flue gas desulfurization systems, this fact represents a serious limitation for the CMWR co-firing process. Nevertheless, it should be noted that the sulfur content of this study CMWR is particularly high. From a general point of view, the sulfur content of the waste fuel depends on its origin and can be reduced selecting a low sulfur content CMWR if the SO_2 emissions represent a limitation. Finally, the particulate emissions increase in the same proportion as the co-firing ratio is increased due to the high ash content of the waste fuel. As it was stated in Table 7, this is specially relevant for high substitution rates (increasing up to 273 %), making necessary the installation of complementary and efficient ash removal systems.

It is also highlighted the agreement in the emissions predictions (Figure 6) with the experimental test measurements analyzed and presented in Table 6.

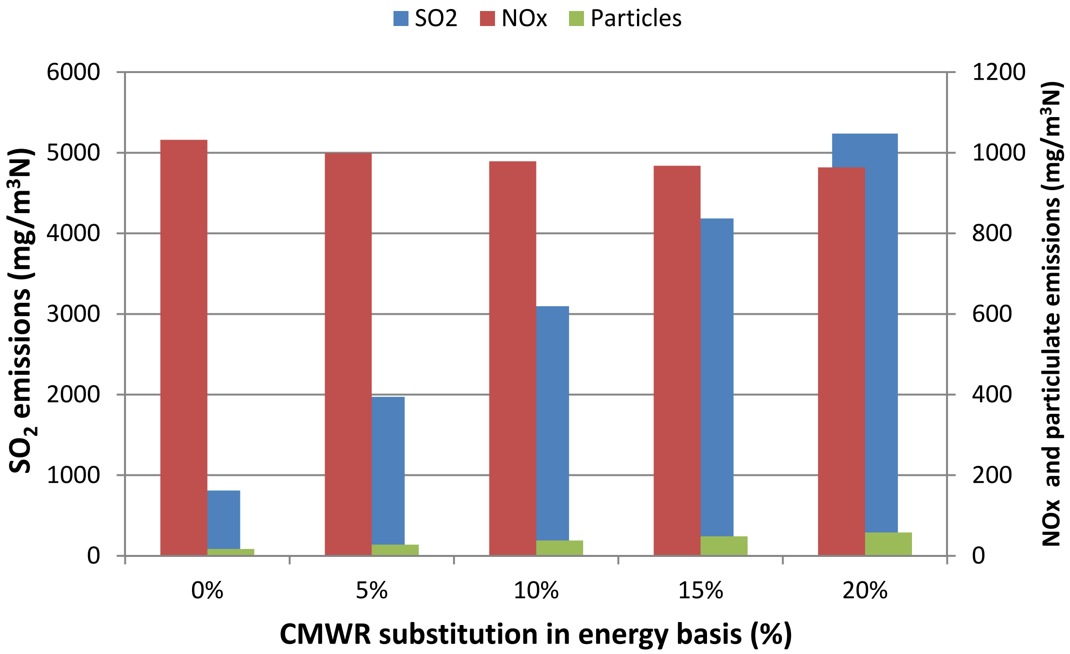

Figure 6: Normalized emissions (6% O_2) of SO_2, NO_x and particles as a function of the coal mine waste residue co-firng ratio (full load conditions)

Extending the analysis to partial load conditions, similar trends for the regulated emissions are obtained: SO_2 and particulate emissions increase and NO_x decreases as the co-firing ratio increases. It is worth noting that NO_x emissions presents a reduction under partial load conditions since the lower temperature in the furnace together with a lower excess air consign (see Table 5) contributes to a reduction in the thermal NO_x formation route (Figure 7).

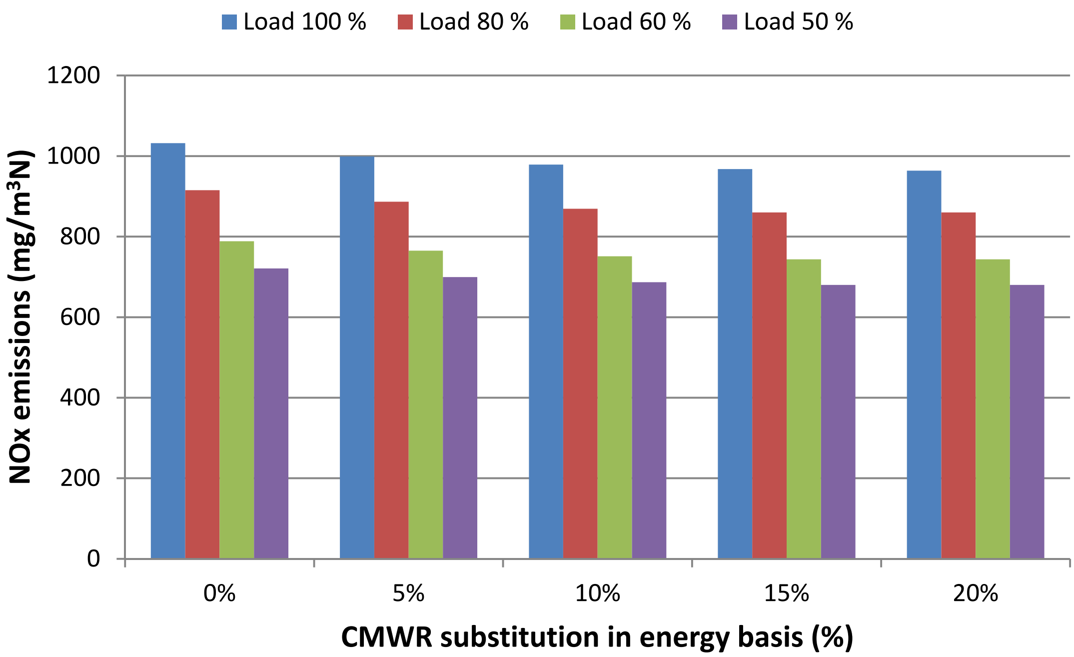

Figure 7: Normalized NO_x emissions (6% O_2) as a function of the co-firing ratio

Bringing together all previous results, and in the absence of a detailed study on the impact on the phenomena of slagging, fouling, corrosion and abrasion produced by the resulting ash particles, it can be concluded that co-firing of CMWR and coal in pulverized fuel unit is feasible and it is not a significant penalty on the plant efficiency (< 2%) for substitution percentages on energy basis under 10% and in an operation mode close to full load conditions. At the same time, special attention should be paid to particulate emissions levels and SO_2 emissions in the case of using CMWR with high sulfur content.

4. Conclusions

This work proves the technical feasibility of co-firing coal mine wastes residues and coal in pulverized fuel combustion systems up to a 20% of substitution percentage in energy basis and investigates the impacts of transferring this co-firing alternative into commercial pulverized fuel units, in terms of plant efficiency, increase on auxiliary equipment power consumptions and pollutants emissions.

Experimental co-firing tests of coal mine wastes residues and a subbituminous rank coal were conducted on a 500 kW_{th} semi-industrial pulverized fuel pilot plant, varying the CMWR co-firing ratio in energy basis from 0% (only coal) to 20%. During the tests stable combustion conditions were obtained for all the co-firing ratios analyzed. Combustion efficiency and stability were monitored during tests through the records of main operation variables, the pollutants emissions and the visible flame radiation with an image acquisition system, obtaining regular and stable flicker and flame brightness intensity levels in all the tests. Combustion efficiency decreases as the co-firing ratio of CMWR is increased due to the presence of a higher concentration of ash particles and lower temperatures in the region close to the burner. Such results were confirmed by obtaining acceptable emissions levels for CO (200 mg/m^3N) and NO_x (700 - 800 mg/m^3N) emissions. On the other hand, special attention should be paid to SO_2 emissions which increase notably with the substitution percentage due to the high sulfur level of the particular coal mine residues used in this work.

The impact analysis of co-firing CMWR in a full scale pulverized fuel plant was performed by simulating the power cycle and combustion process in a 160 MW_e PCC unit. Simulation case scenarios were chosen covering the full operation range of the plant (full load conditions and partial load conditions) and 0 – 20% CMWR co-firing ratios. Above the 80% of the load availability of the plant and CMWR co-firing ratios under 10%, the reduction in the boiler efficiency (2.5%), increase in the auxiliary equipment power consumption (9.4%) and reduction of the global plant efficiency (1.9%) may be acceptable considering the economics and environmental benefits of valorizating a waste fuel. On the other hand, as the CMWR co-firing ratio is increased up to a 20%, the reduction in the plant efficiency reaches 7.5%, compromising the profitability of the process. Moreover, the enormous increase in the fuel input mass compared to the reference case of burning only coal (up to 78 %) and ash production (up to 273%) would bring about the necessity of substituting all the equipment relate to the transport and pretreatment of fuel, burners and particulate removal systems, as well as the increase in the internal power consumption of the plant.

Simulated results on the regulated emissions levels, confirmed the measurements obtain during the experimental test campaign. While NO_x emission are little reduce with the CMWR co-firing ratio, since lower temperatures are attained, particulate and SO_2 emissions drastically increase, and special attention should be paid to these values in order to meet the maximum permitted emissions levels by introducing additional gas cleaning systems and/or using CMWR with low sulfur content.

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