COFIRING OF RICE STRAW AND COAL IN A COAL-FIRED UTILITY BOILER: THERMODYNAMIC ANALYSIS

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Abstract. *Cofiring combustion of biomass and coal is a near-term, low cost alternative for reduction fossil greenhouse gas emissions in coal fired power plants. Recent reviews identified over 288 applications in over 16 countries with promising results for different coal and biomass combinations. In Brazil, there is no previous experience of cofiring biomass and coal, resulting in new challenges to fuel handling and boiler operation. A first experience is now proposed into an existing coal power plant, using rice straw as biomass fuel. A thermodynamic model was developed in order to predict operating and emissions data, which should be used in cofiring system design. For 10% of biomass input, the total* CO_2 *emission is expected to slightly increase. However, considering only the coal* CO_2 *emission, it is expected to decrease in about 10%. Also, the corresponding* SO_2 *emission decreases in about 8%.*

Keywords*: Cofiring combustion, biomass, PF coal boiler, rice straw, greenhouse gas emissions.*

1. INTRODUCTION

The cofiring consists of simultaneous combustion of two or more fuels at the same time. The cofiring of biomass and coal is a near-term, low cost alternative for reduction fossil greenhouse gas emissions from coal-fired power plants. Biomass is a carbon neutral fuel and it is considered one of the main alternatives for clean electric energy generation in large scale utility boilers.

Recent reviews identify over 288 applications in about 16 countries, with promising results using different types of coal and biomass combinations (IEA, 2010). In Brazil, there is no previous experience in cofiring of biomass and coal, resulting in new challenges in fuel handling and boiler operation. Also, there is no similar application of rice straw in energetic generation.

A first Brazilian experience is now proposed to an existing coal power plant, located in the Southern Region of Santa Catarina. In this region, there is a large concentration of rice fields, contributing for the option of rice straw burning. In 2007/08 harvest, the total production of rice straw in that region was about 230,000 t. Currently, the rice straw is left on the field, where it decomposes and releases methane and greenhouse gases into the environment.

This paper consists in a thermodynamic analyzes, in order to predict important information about operating conditions and gas emissions that can be used for design the proposed cofiring system. The power plant currently operates with high ash and sulfur coal. Hence, this experience is quietly different from other cofiring experiences, leading to the necessity of preliminary studies for large scale application.

The combustion process of cofiring of coal and biomass is extremely difficult to simulate, even using CFD tools. Any solution has required large computational efforts for fluid dynamic and heat transfer problem inside the boiler. Also, it is required numerous constraints assumptions, usually not representative, leading to uncertainly results. The use of rice straw requires preliminary studies as innovation experience in cofiring of coal and biomass, as well as further measurements for data input in CFD simulation. Firstly, it is more important now to find out the right conceptual design and the potential of this experience.

2. REVIEW OF COFIRING EXPERIENCES

Biomass represents today about 10% of the total world energy production and it may even reach until 30% in development countries (IEA, 2007). Brazil has a great potential of biomass utilization for many energy carriers. Nowadays, there are about 337 biomass power plants in operation in Brazil, with an installed capacity of 5.8 GW (Brazil, 2009).

The actual biomass is restricted to small or medium scale power plants for electrical production. The cofiring of coal and biomass is a prospective option to power generating in conventional coal fired boilers due to the greater cycle efficiency, in relation of smaller dedicate biomass plants in electricity generation, the fuel flexibility and the potential for reducing emissions of greenhouse gases. (Waldron, 2007) (Pedersen, Nielsen, *et al.*, 1996)

The cofiring enables the use of the available infrastructural of the coal fired power plant, requiring low costs for implementation with minimal changes in plant infrastructure. The proximate conversion costs are about US$ 50-300 per kW of biomass capacity. This cost is attractive compared with other renewable technologies, mainly if there is no option for hydraulic power plants. (Baxter, 2005); (Koppejan e van Loo, 2008); (Hansson, 2009)

Cofiring coal with biomass involves risks in many different parts of the power plants, e.g. reduction of lifetime in fuel processing and handling system, increasing of plant outages, possible interference with the operation of burners, as well as problems related to the furnace, convective section and in the environmental control equipment. In the furnace, problems are related in ash deposition, reducing the heat transfer capacity in water-wall, which leads to an increasing of the operating cost. Also, the corrosion problems due high temperature and erosion in superheater could be increased. (Koppejan e van Loo, 2008)

The combustion of biomass and coal in cofiring can cause different heat flux and temperature profiles in the furnace, changing the boiler thermal behavior. Also, there is the possibility of occur high levels of unburned coal with formation of CO that increase the corrosion risks in water-wall. Furthermore, it is possible to find an increase of NO_x formation. (Savat, 2008)

The issues are different from those found in coal applications concerning the biomass delivery, storage and preparation. This issue presents a first obstacle for the continuous and long-term uses of biomass. The biomass average heating value and bulk density are in the range of 50-70% and 20% of the coal, which leads to a higher on-site delivery, storage and fuel handling demands.

The cofiring experiences contemplate over 288 initiatives in ranges from 50 MW_e to 700 MW_e. Demonstrations have been made with the most significant coal biomass types, e.g. herbaceous and woody fuel types generated as residues and energy crops (IEA, 2010).The cofiring of biomass has been developed on a commercial basis in about 40 of these tests facilities. These plants replaced about 3.5 Mt of coal, avoiding the release of about 10 Mt of CO_2. Also, the estimated technical potential and financially feasible of coal replacement is about 30 times higher. However, there are only 4 experiences in cofiring coal with any kind of straw, all in Europe. No previous cofiring experience had been described in the literature for rice straw utilization, including an innovative feature for the project.

3. BOILER DESCRIPTION

A coal-fired boiler is considered for retrofitting into a cofiring pilot plant. The boiler operates in a 50 MW_e power plant (UTLA1) located in Capivari de Baixo– SC and it is operated by Tractebel Energia at the Jorge Lacerda Thermoelectric Complex (Fig. 1).In operation since 1965, the pulverized coal-fired boiler was designed by MAN, with a dry bottom radiant furnace and balanced draft. The furnace radiant area is approximately 2000 m². It is equipped with 16 burners distributed in two rows on an inclined plan, down fired, from which it is fed by 4 coal ball mills. The boiler has a drum, two superheaters and one economizer, without reheater. A Ljungström air heater is placed in the end of the convection section, fed by two forced fans. An electrostatic precipitator is the only flue gas cleaning equipment available. The main coal supply is provided by the Southern Santa Catarina´s mines, with an approximate consumption of 0.77 t/MW_e. The main data are shown for the coal-fired boiler in Tab. 1. The coal and rice straw analyses are shown in Tab. 2.Figure 2 shows a rice straw sample.

Figure 1. Jorge Lacerda Thermoelectric Complex.

Table 1. Main data for the UTLA1 boiler.

Boiler operating data*	
Superheated steam temperature	510 ºC
Superheated steam pressure	90 bar
Superheated steam flow rate	180 t/h
Feed water pressure	98 bar
Feed water temperature	210 ºC
Secondary air temperature	350 ºC
Primary air temperature	110 ºC
Excess air	1.15

*Data collected in boiler operation.

(a) As received.

(b) Ready for burning.

Figure 2. Rice straw sample.

Table 2.Fuel analyses.

	Unit	Coal	Rice Straw
Proximate analysis			
Moisture	%	0.3	7.58
Ash content	%	41.9	12.88
Volatile matter	%	19.1	65.70
Ultimate analysis			
C	%	46.15	39.00
H	%	3.01	5.33
N	%	0.82	0.71
S	%	1.17	0.20
O	%	6.66	34.30
Cl	%	-	0.1
F	*PPM*	-	2
Higher heating value	*kcal/kg*	4250	3547
	kJ/kg	17765	14826
Lower heating value	*kcal/kg*	4105	3243
	kJ/kg	17158	13555

Source: (IFK, 2009).

The current project consists in a first conversion of the coal-fired boiler to direct cofiring of rice straw up to 10 % on thermal basis input at full load. The conceptual design defines that the rice straw arrives in the plant by bales, transported by trucks. The bales are stored in a warehouse and transported by a conveyor belt to the handling system. The handling system is composed by a de-baler and a hammer mill, that must process the rice straw up to a granulometry of 1 mm. A dosing silo with rotative valves stores and delivers the processed rice straw to the pneumatic transport system. This system is divided in four independent lines with dedicated blowers to the injection of the ground rice straw in four separated tubes of the boiler. The mixture of the rice straw with the coal must be as nearest as possible of the boiler inlet, avoiding possible operational problems. The schematic distributions of the rice straw processing system are showed in Figure 3.

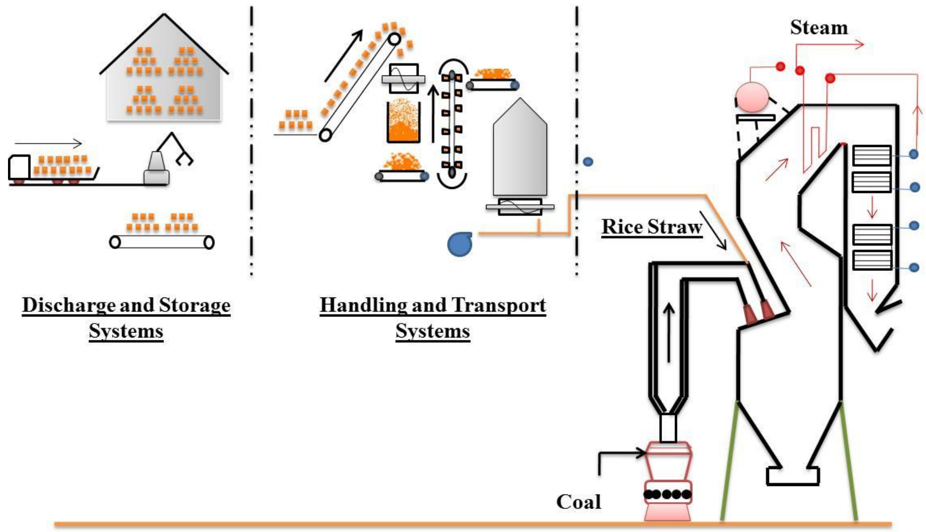

Figure 3. Rice straw processing system.

4. Thermodynamic analysis

A thermodynamic modeling is proposed in order to predict information about the cofiring combustion and gas emissions. Biomass mixtures fractions for up to 30% are analyzed. The principle of mass conservation and the first law of thermodynamics are applied in each component of the boiler for the analysis. Each component is defined as a control volume, evaluating the heat transfer, as well as the inlet and outlet streams. In the furnace, it is included the main fuel conversion reactions predicting the formation of only the major species in the flue gas. The governing equations for mass conservation are:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{1}$$

$$\sum \dot{m}_i y_i - \sum \dot{m}_o y_o = 0 \tag{2}$$

where y_i and y_o correspond to the inlet and outlet gas component mass fractions.

The first law of thermodynamics yields the energy balance of each boiler component into the form of:

$$\dot{Q} = \sum \dot{m}_o h_o - \sum \dot{m}_i h_i \tag{3}$$

and it is assumed the following assumptions:

- Steady state operation;
- Thermodynamic equilibrium at all components;
- No shaft work in any compound;
- Complete combustion in furnace;
- Total mixture of coal and rice straw in the inlet of the furnace;
- Excess air of 15 %;
- Primary air proportion of 15 %;
- Inlet boundary condition at fuel burner;
- Outlet boundary condition at the air heater outlet;
- Environmental conditions of 25 °C.

The boiler efficiency is calculated based in the standard method, which is described in Kakaç (1991), into the form of:

$$\eta_b = 100 - q_{eg} - q_{unbC} - q_{env} - q_{slag} \tag{4}$$

where q_{eg} is the heat loss by exhaust gases, q_{unbC} is the heat loss by incomplete combustion, q_{env} is the heat loss to environment and q_{slag} is the heat loss in ash removed as slag from the furnace. In this work, Eq. 4 results in 79% for nominal operation. For cofiring of coal and biomass, the corresponding efficiency should decrease. The field tests results described in EPRI (1999) indicates that the efficiency reduction in a coal-fired plant is about 0.5% for burning 10 % of biomass in thermal basis. As a consequence, the mass flow rate of rice straw can be determined using the Input-Output method (ASME, 2008) as the following

$$\eta_b = \frac{(1-\theta)\dot{Q}_{rO}}{\dot{m}_{coal} LHV_{coal}} + \frac{\theta \dot{Q}_{rO}}{\dot{m}_{straw} LHV_{straw}} \tag{5}$$

where θ is the rice straw fraction in thermal input basis and $\dot{Q}_{rO}$ is the output energy of the boiler.

The determination of gas temperature takes into account the variation of the specific heat capacity of flue gas with the temperature, using an average value determined for each flue gas component by an integral calculation.

The model provides important parameters using different rice straw fractions, e.g. fuel mass flow, flue gas flow rate, composition and temperature, air flow requirement, calorific value of the fuels and achievable combustion temperatures.

The calculations are carried out using the software EES (Engineering Equation Solver). The input parameters are defined over the boiler nominal condition, such as steam conditions, unburned coal, and primary and secondary air streams.

5. RESULTS

Results of the calculation of rice straw mass flow requirement are shown in Figure 4. This result is applied in the design specification of the rice straw processing equipment and for the bale logistic evaluation inside the UTLA1. The result shows a requirement of about 4.05 t/h of rice straw in a biomass fraction of 10%. The reduction of coal consumption is close to 9 %. This reduction is close to the percentage of rice straw substitution due to close values of lower heating value of the fuels.

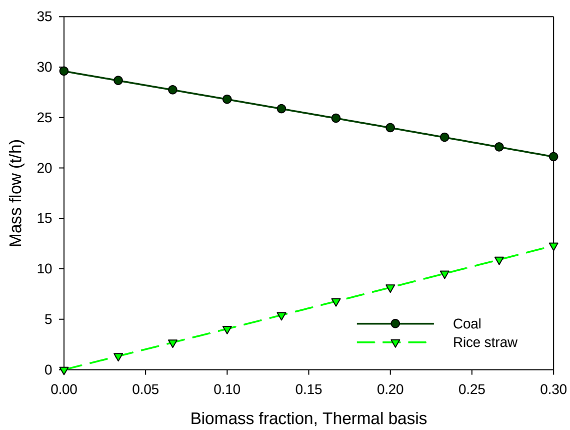

Figure 4. Fuel mass flow rate.

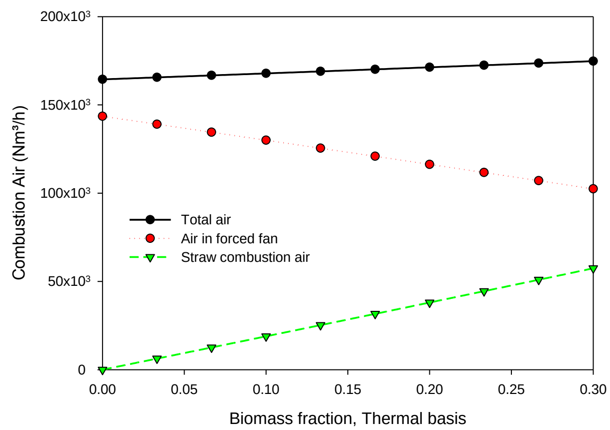

Figure 5. Combustion air requirements.

Figure 5 shows the results of the combustion air requirements for the both coal-only and cofiring combustion. Thus, it is shown that the air requirement of the forced fan of the boiler. The total air requirement is raised due the increase of total fuel consumption, even with the reduction of the coal consumption. The straw air requirement and the reduction of air in forced fan must be analyzed for the pneumatic system design. It must be defined the minimum flow air for the pneumatic blowers in order to not overload the boiler air fans. However, the reduction of the air requirement in forced fan can be helpfulness for the boiler due to problems in boiler operation related in the actual force fans.

Results concerning of CO_2 and SO_2 emissions are shown in Figure 6. For 10% of biomass input, there is in fact a slightly increase of the total CO2 emission. However, it is also clear a significant reduction of about 9.5 % in coal CO_2 emission. The corresponding SO_2total emission decreases about 9.5%. It is the expected result due to the low sulfur content found in rice straw composition. Thus, the alternative of cofiring coal and rice straw presents a great potential of reduction in greenhouse gas emissions, if the $CO_2$from rice straw is considered as neutral emission.

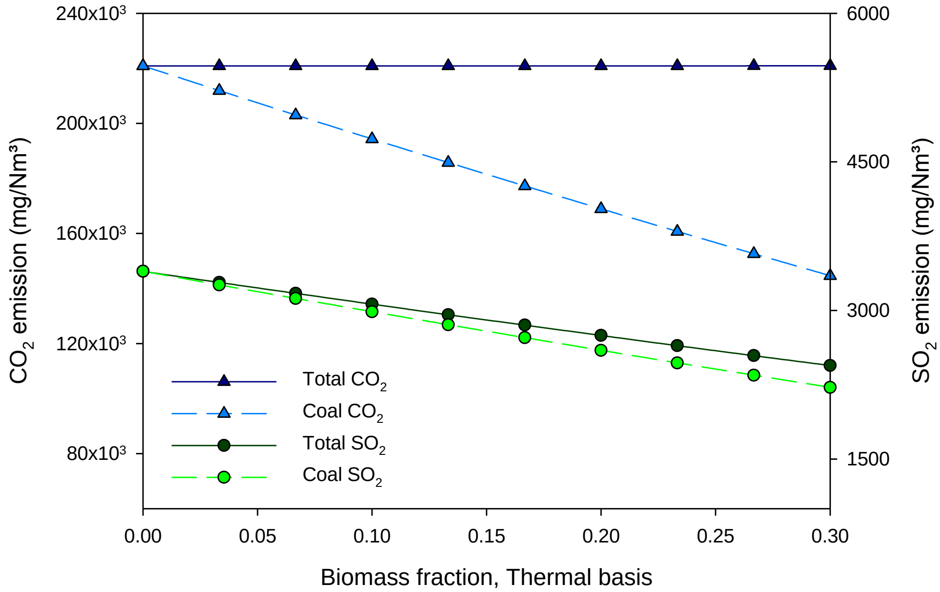

Figure 6. Gas emissions.

Figure 7 shows the flue gas temperature measurements at the two sides of the boiler convection section and the model temperature prediction for coal fired operation. The temperatures were measured in the steady-state condition of the boiler, with the system in thermal equilibrium. For the test procedures, the frequency of observations and the uncertainty determination used the indications of the PTC 4 code, described in ASME (2008). The temperature prediction of the model presents a similar behavior comparing with the temperature measurements, even using a first law analyses. With that result, it is possible predicts and compares in a qualitative mode the boiler temperature changing with different biomass fractions.

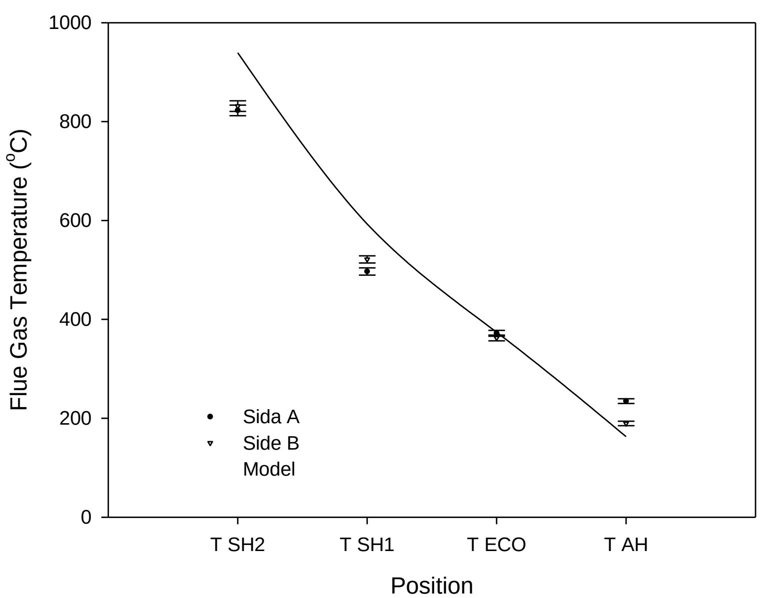

Figure 7. Flue gas temperature measurements and model prediction.

Figure 8 shows the boiler temperature changes with different biomass fractions. As can be seen in this figure, there is a slight flue gas temperature changes along the boiler convection region, what is a desirable behavior for the cofiring application in an existing boiler. The higher is the rice straw proportion in fuel mixture, the lower is the maximum temperature that can be reached inside the boiler and in consequent, the lower is all of flue gas temperature. Moreover, the adiabatic flame temperature is showed with the respective temperature profile for no excess air. These results are also promising for the ash fusibility problem, where the higher flue gas temperature, the higher is the probability of the ash fusion in the heat exchanger´s tubes.

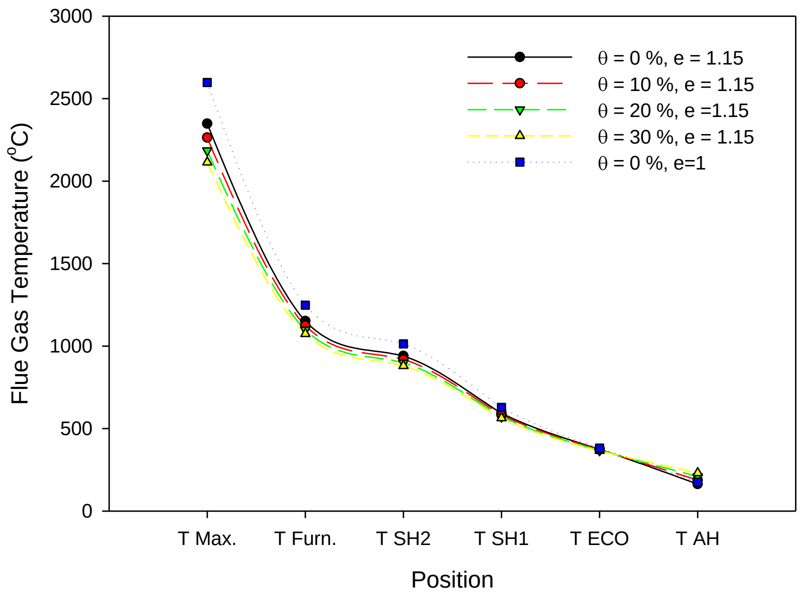

Figure 8. Flue gas temperature prediction.

6. CONCLUSIONS

The rice straw presents a great potential for cofiring in existing coal-fired boilers. The rice straw burning in boilers provides electricity and also, it has the advantage to avoid the methane emission in rice fields. A thermodynamic model was developed to an existing coal-fired boiler used in a 50 MW_e power plant, providing information to design of rice straw process systems and for boiler operation predictions. According to the found results, the following conclusions can be made:

- Minimal changes in boiler operations;
- Reduction up to 9 % in coal consumption for 10% of rice straw in thermal basis;
- Slightly reduction of temperature levels along the boiler;
- Great potential of reduction in greenhouse gas emissions, if the $CO_2$from rice straw is considered as carbon neutral emission;
- Significant reduction of SO_2 emission, about 9.5 % for 10% of rice straw in thermal basis.

The use of rice straw in a coal-fired power plant is a low cost, low risk and short-term option for electrical power generation, as well as it represents a potential alternative to mitigate the greenhouse gas emission. However, there are a lot of issues that must be still carefully evaluated in the processing equipment design and in the boiler operation.

7. ACKNOWLEDGEMENTS

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