EXERGETIC ANALYSIS OF A STEAM POWER PLANT USING COAL AND RICE STRAW IN A CO-FIRING PROCESS

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Abstract. *This paper presents an exergetic analysis concerning an existing 50 MWe steam power plant, which operates with pulverized coal from Santa Catarina- Brazil. In this power plant, a co-firing rice straw is proposed, replacing up to 10% of the pulverized coal in energy basis required for the boiler. Rice straw has been widely regarded as an important source for bio-ethanol, animal feedstock and organic chemicals. The use of rice straw as energy source for electricity generation in a co-firing process with low rank coal represents a new application as well as a new challenge to overcome. Considering both scenarios, the change in the second law efficiency, exergy destruction, influence of the auxiliary equipments and the greenhouse gases emissions such as* CO_2 *and* SO_2 *were considered for analysis.*

Keywords: *Power plants, Exergetic analysis, Co-firing process.*

1.INTRODUCTION

Coal is widely used worldwide as a main fuel in expressive number of industrial processes due to its relatively low cost in the international market. Coal might be co-gasified or co-fired with waste or biomass for environmental, technical or commercial reasons. It allows larger, more efficient plants than those sized for the biomass growth or waste arising within a reasonable transport distance. In this scenario, the co-firing biomass at existing coal-fired power plants can provide a significant contribution to the generation of electricity at a relatively low cost. Studies report a technical viability and highlight the environmental contribution of co-firing process in the reduction of greenhouse gases such as CO_2 and CH_4. Tillman (2000), Agostineto D. *et al*. (2002), Garcia *et al*. (2008), Julia Hansson *et al*. (2009).

Focusing on biomass from agricultural residues, Brazil has an estimated potential of 220 million tons per year (soy straw, corn stalk, rice straw, manioc stalk, wheat straw, cotton stalk, bean stalk and sugarcane bagasse) Pereira F. L. *et al* (2009) representing an important energy alternative regarding the contribution of coal in the national energy balance.

In this work, a thermodynamic model is presented for a power plant in co-firing process using pulverized coal and rice straw. The model considers the energy consumption required for the fuels to find the typical size characteristics for combustion in the burners. The thermodynamic simulation takes into account the change in the environmental temperature. An exergetic analysis was considered to quantify the exergy destruction of each power plant component.

2. POWER PLANT DESCRIPTION

The power plant is located in the thermoelectric complex Jorge Lacerda in the southern region of Santa Catarina State in Brazil. The thermodynamic cycle concerning the steam power plant is shown in Fig.1. It consists of a pulverized coal boiler, a steam turbine in two stages, without reheating, feeding water heaters and a deaerator with a feeding tank. The condenser uses water from a river for heat rejection. Both the nominal and operation characteristics are shown in Tab.1.

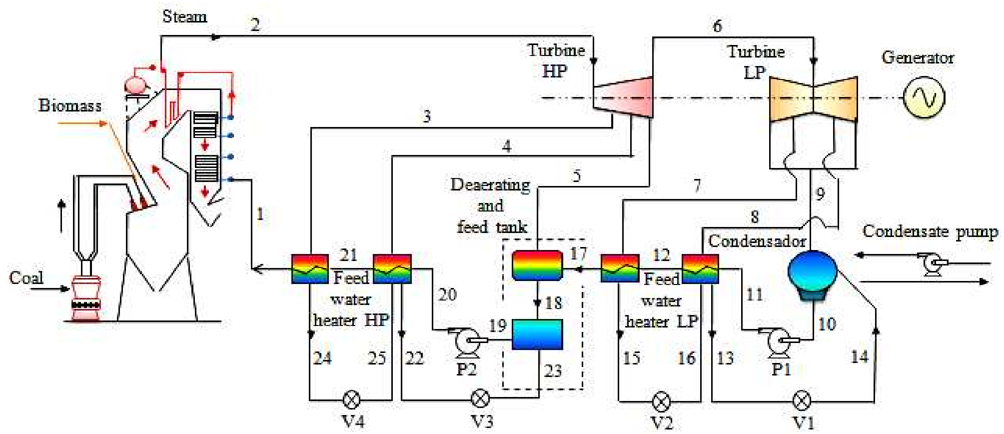

Figure 1. Steam Power Plant in Rankine Cycle

Table 1. Nominal and operation characteristics of the power plant.

Parameters	Nominal	Operation(1)
Temp. of water inlet to boiler	210 °C	210 °C
Pressure of water inlet to boiler	98.1 bar	96.8 bar
Temp. of steam out of the boiler	515 °C	510 °C
Pressure of steam out of the boiler	90.25 bar	89 bar
Power output	50 MWe	44.5 MWe
Steam flow	165 t/h	185 t/h

(1)From power plant (14/07/2010)

In this work the operation parameters were considered for analysis, with the corresponding boiler efficiency about 80%. The use of biomass should change the boiler efficiency and gas emissions. As there is no previous experience related to co-firing with rice straw, any change concerning the boiler efficiency is still unknown. Even for biomass in general there is no sufficient experimental data. According to a field test reported by Hughes (1999), the boiler efficiency decrease about 0.5% for 10% of biomass on mass basis.

The characteristics of both coal and rice straw are shown in Tab. 2. The ultimate analysis shown in Tab. 2 was obtained from samples specially collected from power plant and also from rice field of southern Santa Catarina.

Table 2. Chemical characteristic of both coal and straw rice

Fuel	HHV kJ/kg	LHV kJ/kg	Ultimate analysis(2)						
			C	H	O	N	S	Ash	H_2O
Coal	18840	18172	46.15	3.01	6.66	0.82	1.17	41.9	0.3
Rice straw	14718	13362	39	5.33	34.3	0.71	0.2	12.9	7.58

(2)IFK (2009)

In this work the thermodynamic model considered an extended boundary including both the coal and the rice straw handling process, as well as the global conversion from fuel chemical energy to electricity in the steam turbine generator. See Fig. 2. The coal handling facility is typical of steam power plants, consisting of belt conveyors, silos, coal feeders and its respective coal pulverizer (ball mill).

The rice straw handling facility is completely new and it was designed to provide a hammer-mill (or knife-mill) to reduce the fuel to a granulometry of about 1 mm or less before burning. The rice straw has fibrous characteristic and it will be received in cylindrical baler. The rice straw handling facility consists of belt conveyors, pre-milling (de-baler), milling and storage system. Considering the fuel properties and the proposed co-firing of rice straw in 10%, the facility must feed up to 5 t/h. Both pulverized coal and rice straw are transported to the burner with a pneumatic conveyor.

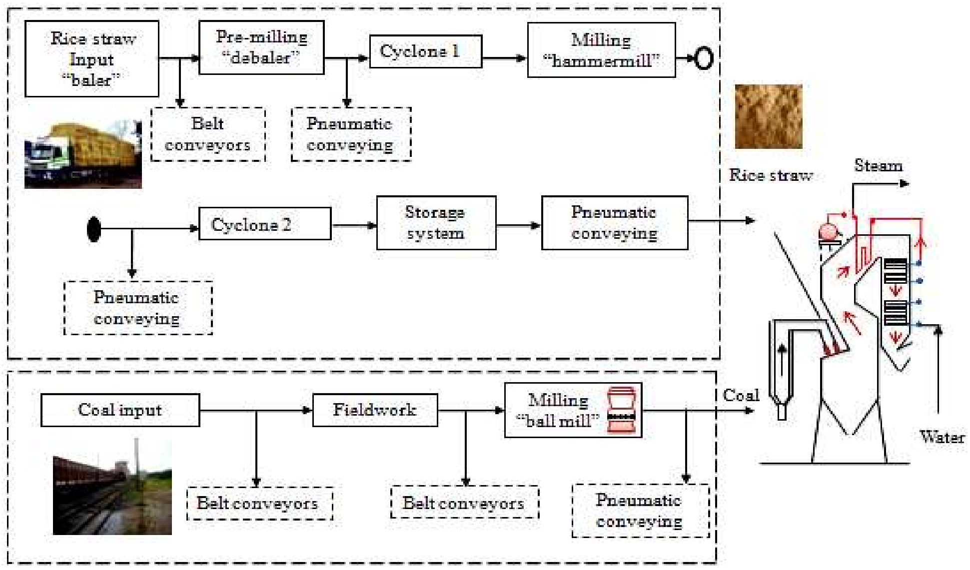

Figure 2. Coal and rice straw supply systems.

The Table 3 shows the energy consumption for handling operations of both coal and rice straw in equivalent units (kW). The energy consumption of some auxiliary equipment is also considered. The consumption associated with these operations was obtained in the power plant, usually for driving electric motors. The required fuels for field machinery (Tractors and bulldozer) were also considered.

Table 3. Energy consumption for handling coal, straw rice and auxiliary equipment

Coal field operations		Biomass operations		Auxiliary equipment	
Equipment	kW	Equipment	kW	Equipment	kW
Coal unloading	88.26	Input operations	50	Mill (Pulverizer coal)	855
Conveyor	288.4	Pre-milling	56	Forced draft fan	630
vibrating screens	57.54	Conveyor	74.8	Induced draft fan	578
Fuel (diesel)	311.4	Hammer-mill	75	Others	352
Others	12	Fuel (diesel)	156		
		Others	137.3		
		Pneumatic transport	85		
Total	757.6 kW	Total	634.1 kW	Total	2415 kW

3. MODELING AND GOVERNING EQUATIONS

A thermodynamic model considering the first and second law is proposed. The model was developed for evaluation of both scenarios: (i) direct coal burning and (ii) co-firing process with coal and rice straw.
The following hypotheses were considered:

- Steady state condition;
- Dead state (101325 Pa, 25ºC);
- Kinetics and potential energy changes negligible;
- Fixed electricity consumption for coal and rice straw handling facilities;
- Negligible makeup water (deaerator);

Mass, energy and exergy balances were done in all components of the steam power plant using the operating data showed in Tab. 1 as the boundary conditions. The governing equations are listed below

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (1)$$

$$\dot{Q} + \dot{W} = \sum h_o \dot{m}_o - \sum h_i \dot{m}_i \quad (2)$$

$$\sum \dot{m}_o e_o^{ph} - \sum \dot{m}_i e_i^{ph} = \left(1 - \frac{T_o}{T}\right)\dot{Q} + \dot{W} - \dot{E}_D \quad (3)$$

where $\dot{m}$ is the mass flow rate, $\dot{Q}$ and $\dot{W}$ are the net heat and net work, respectively, h is the enthalpy, the subscripts "i" and "o" indicate input and output of the system, $\dot{E}_D$ is the exergy destruction rate and $\left(1 - \frac{T_o}{T}\right)\dot{Q}$ is the time rate exergy transfer associated with heat transfer at the location on the boundary temperature T_o. In Eq. (2) the power input is assumed as positive.

The exergy efficiency and the exergy destruction are defined as shown in the Tab. 4.

Table 4. Exergy efficiency and the exergy destruction rate.

Equipment	Exergy Destruction $\dot{E}_{D,k}$	Exergy Efficiency ε_k
Boiler	$\dot{E}_{D;boiler} = \dot{E}_{fuel}^{ch} - \left(\dot{E}_2^{ph} - \dot{E}_1^{ph}\right)$	$\varepsilon_{boiler} = \frac{\eta_{boiler}}{\alpha}\left[1 - \left\{\frac{T_0+273,15}{T_m}\right\}\right]$ (3)
High Pressure Turbine	$\dot{E}_{D;HP,turbine} = \dot{E}_2^{ph} - \left(\dot{E}_3^{ph} + \dot{E}_4^{ph} + \dot{E}_5^{ph} + \dot{E}_6^{ph}\right) + \dot{W}_{HP,turbine}$	$\varepsilon_{HP,turbine} = \frac{\dot{W}_{HP,turbine}}{\dot{E}_3^{ph} + \dot{E}_4^{ph} + \dot{E}_5^{ph} + \dot{E}_6^{ph} - \dot{E}_2^{ph}}$
Low Pressure Turbine	$\dot{E}_{D;TLP} = \dot{E}_6^{ph} - \left(\dot{E}_7^{ph} + \dot{E}_8^{ph} + \dot{E}_9^{ph}\right) + \dot{W}_{LP,turbine}$	$\varepsilon_{LP,turbine} = \frac{\dot{W}_{LP,turbine}}{\dot{E}_7^{ph} + \dot{E}_8^{ph} + \dot{E}_9^{ph} - \dot{E}_6^{ph}}$
Condenser	$\dot{E}_{D;condenser} = \dot{E}_9^{ph} + \dot{E}_{14}^{ph} - \dot{E}_{10}^{ph} - \left(\dot{E}_o^{ph} - \dot{E}_i^{ph}\right)$	$\varepsilon_{condenser} = \frac{\dot{E}_o^{ph} + \dot{E}_i^{ph}}{\dot{E}_9^{ph} + \dot{E}_{14}^{ph} - \dot{E}_{10}^{ph}}$
Low Pressure Heaters 1	$\dot{E}_{D;LPheater,1} = \dot{E}_8^{ph} + \dot{E}_{16}^{ph} - \dot{E}_{13}^{ph} - \left(\dot{E}_{12}^{ph} - \dot{E}_{11}^{ph}\right)$	$\varepsilon_{LPheater,1} = \frac{\dot{E}_{12}^{ph} - \dot{E}_{11}^{ph}}{\dot{E}_8^{ph} + \dot{E}_{16}^{ph} - \dot{E}_{13}^{ph}}$
Low Pressure Heaters 2	$\dot{E}_{D;LPheater,2} = \dot{E}_7^{ph} - \dot{E}_{15}^{ph} - \left(\dot{E}_{17}^{ph} - \dot{E}_{12}^{ph}\right)$	$\varepsilon_{LPheater,2} = \frac{\dot{E}_{17}^{ph} - \dot{E}_{12}^{ph}}{\dot{E}_7^{ph} - \dot{E}_{15}^{ph}}$
High Pressure Heater 1	$\dot{E}_{D;HPheater,1} = \dot{E}_4^{ph} + \dot{E}_{25}^{ph} - \dot{E}_{22}^{ph} - \left(\dot{E}_{21}^{ph} - \dot{E}_{20}^{ph}\right)$	$\varepsilon_{HPheater,1} = \frac{\dot{E}_{21}^{ph} - \dot{E}_{20}^{ph}}{\dot{E}_4^{ph} + \dot{E}_{25}^{ph} - \dot{E}_{22}^{ph}}$
High Pressure Heater 2	$\dot{E}_{D;HPheater,2} = \dot{E}_3^{ph} - \dot{E}_{24}^{ph} - \left(\dot{E}_1^{ph} - \dot{E}_{21}^{ph}\right)$	$\varepsilon_{HPheater,2} = \frac{\dot{E}_1^{ph} - \dot{E}_{21}^{ph}}{\dot{E}_3^{ph} - \dot{E}_{24}^{ph}}$
Feeding Tank	$\dot{E}_{D;f.tank} = \left(e_{18}^{ph} - e_{19}^{ph}\right)\dot{m}_{18} - \left(e_{19}^{ph} - e_{23}^{ph}\right)\dot{m}_{23}$	$\varepsilon_{f.tank} = \frac{\left(e_{19}^{ph} - e_{23}^{ph}\right)\dot{m}_{23}}{\left(e_{18}^{ph} - e_{19}^{ph}\right)\dot{m}_{18}}$
Deaerator	$\dot{E}_{D;deaerator} = \left(e_5^{ph} - e_{18}^{ph}\right)\dot{m}_5 - \left(e_{18}^{ph} - e_{17}^{ph}\right)\dot{m}_{17}$	$\varepsilon_{dearator} = \frac{\left(e_{18}^{ph} - e_{17}^{ph}\right)\dot{m}_{17}}{\left(e_5^{ph} - e_{18}^{ph}\right)\dot{m}_5}$

(3) Expression of (Szargut J. M. D., 1988)

The energy efficiency (η_I), and the exergy efficiency (η_{II}), as well as, the exergy destruction rate ($y_{dest,k}$) are expressed as

$$\eta_I = \frac{\dot{W}_{electric}}{(LHV_c\ \dot{m}_c) + (LHV_{rs}\ \dot{m}_{rs})} \quad (4)$$

$$\eta_{II} = \frac{\dot{W}_{electric}}{\dot{E}_{fuel}^{ch}} \quad (5)$$

$$\dot{E}_{D;total} = \sum \dot{E}_{D,k} \quad (6)$$

$$y_{dest,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}} \quad (7)$$

where LHV_c is the coal lower heating value and LHV_{rs} is the rice straw lower heating value, $\dot{m}_c$ and $\dot{m}_{rs}$ are the mass flow rate of the coal and rice straw, respectively. $\dot{W}_{electric}$ is the net electrical power and $\dot{E}_{fuel}^{ch}$ is the chemical exergy of both fuels.

The specific chemical exergy $\left(e_{fuel}^{ch}\right)$ is calculated as proposed by Szargut (1988)

$$e_{fuel}^{ch} = \left(LHV_{fuel} + h_{fg;H2O} * m_{f;H2O}\right) * \beta_{fuel} + \left(e_S^{ch} - LHV_S\right) * m_{f;S} + \left(e_{H2O}^{ch} * m_{f;H2O}\right) \tag{8}$$

where $m_{f;C}$, $m_{f;H}$, $m_{f;O}$ and $m_{f;N}$ are the mass fraction of carbon, hydrogen, oxygen and nitrogen respectively. e_S^{ch} and e_{H2O}^{ch} are the chemical exergy of sulfur and water. LHV_S is the lower heating value for the sulfur. The Tab. 5 shows the β_{fuel} factor used in the equation above.

Table 5. The β factors used for calculate the chemistry exergy of the fuels.

Fuel	The β factor	Relation	Accuracy (+/-)
Coal	$\beta_{c=}1{,}0437 + 0{,}014 * \frac{m_{f;H}}{m_{f;C}} + 0{,}0968 * \frac{m_{f;O}}{m_{f;C}} + 0{,}0467 * \frac{m_{f;N}}{m_{f;C}}$	$\frac{O}{C} \leq 0{,}5$	0,38%
Rice Straw	$\beta_{rs} = \frac{1{,}044 + 0{,}016 * \frac{m_{f;H}}{m_{f;C}} - 0{,}3493 * \frac{m_{f;O}}{m_{f;C}} * \left[1 + 0{,}0531 * \frac{m_{f;H}}{m_{f;C}}\right] + 0{,}0493 * \frac{m_{f;N}}{m_{f;C}}}{1 - 0{,}4124 * \frac{m_{f;O}}{m_{f;C}}}$	$\frac{O}{C} \leq 2$	0,72%

The chemical exergy of the fuels ($\dot{E}_{fuel}^{ch}$) is calculated with

$$\dot{E}_c^{ch} = e_c^{ch}\,\dot{m}_c \tag{9}$$

$$\dot{E}_{rs}^{ch} = e_{rs}^{ch}\,\dot{m}_{rs} \tag{10}$$

$$\dot{E}_{fuel}^{ch} = \dot{E}_c^{ch} + \dot{E}_{rs}^{ch} \tag{11}$$

where, e_c^{ch} and e_{rs}^{ch} are the specific chemical exergy of coal and rice straw.

3. ANALYSIS

The change in the second law efficiency, exergy destruction, influence of the auxiliary equipments, ambient temperatures and also the CO_2 and SO_2 gases emissions is the main focus of this work. The EES software Klein, A. (2010) was used considering the power plant at steady state condition.

The corresponding fuel exergy, the first law efficiency, the second law efficiency and the exergy destruction of the power plant are presented in Tab. 6 for coal burning only as well as, for co-firing of 10% of rice straw in energy basis. The subscript "*eq*" in the second law efficiency represents the auxiliary equipment for coal and rice straw handling.

Table 6. Performance assessment parameters of both coal and co-firing process

Performance assessment parameters	Coal burning only	Co-firing 10%
$\dot{E}_{fuel}^{ch}$	169.19 MW	177.71 MW
η_I	28.05 %	27.52 %
η_{II}	26.31%	25.04%
$\eta_{II,eq}$	22.78%	21.68%
$\dot{E}_{D;total}$	124.05 MW	133.21 MW

As shown in Tab. 6 the fuel exergy increased about 4.8% for co-firing process of 10% of rice straw. Consequently the second law efficiency decreased 1.27%, from 26.31 to 25.04%. The similar LHV of both fuels is the main reason for this found small decrease. When considered the auxiliary equipment for coal and rice straw handling, the second law efficiency decreased 3.53%, from 26.31 to 22.78% for coal burning only or 4.63%, from 26.31 to 21.68% for co-firing

10%. For co-firing up to 30%, the corresponding results are shown in Fig. 3. Finally, it should be noted a significant increase of the exergy destruction after retrofitting the power plant from coal burning only to co-firing 10% on thermal basis, from 124.05 to 133.21 MW. The exergy destruction ratio ($y_{dest,k}$) for each component are shown in Fig. 4. As expected, the highest destruction exergy rate takes place in the boiler, in this work reaching 88.54% mainly due to the combustion process.

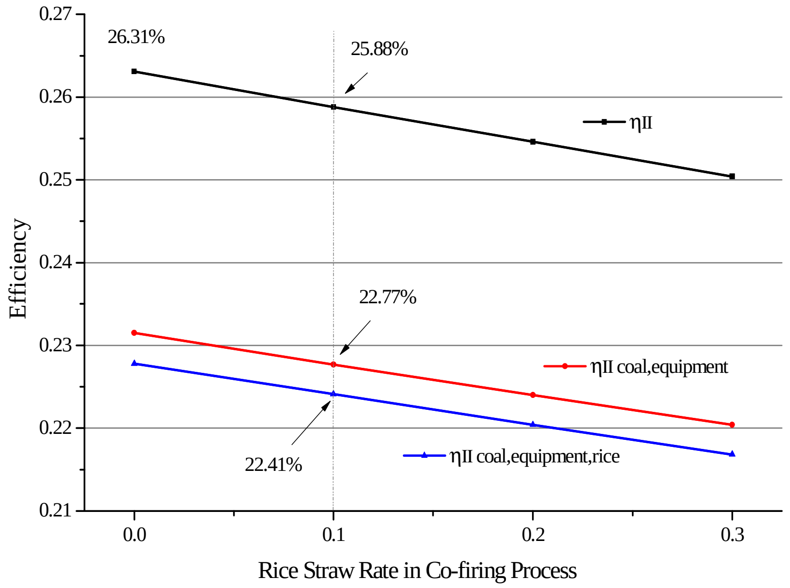

Figure 3. Behavior of the second law efficiency of the power plant considering the handling facility

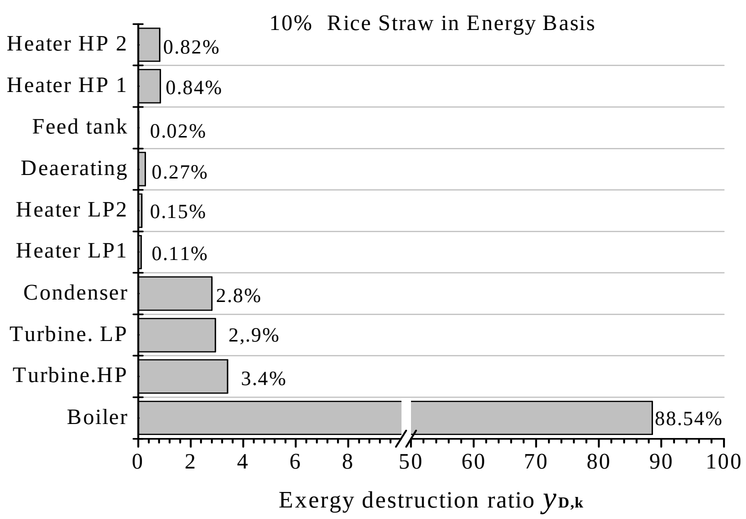

Figure 4**.** Exergy destruction ratio in the power plant for co-firing 10% rice straw on thermal basis.

Figure 5 shows the CO_2 and SO_2 emissions for co-firing up to 30% of rice straw on thermal basis. In coal burning only, it is generated about 1194 kg CO_2/MWe. For co-firing of 10%, the coal CO_2 emission decreases in about of 9.5%. The rice straw handling facility consumes 634 kWe, which is equivalent to 17 kg CO2/MWe. Thus, the effective CO_2 reduction is about 8%. For SO_2 emissions, it is generated about 16.51 kg SO_2/MWe in coal burning only. For co-firing of 10%, the SO_2 emission decreases in about of 7.1%. Taking into account the rice straw handling facility, the effective SO_2 reduction is about 5.7%.

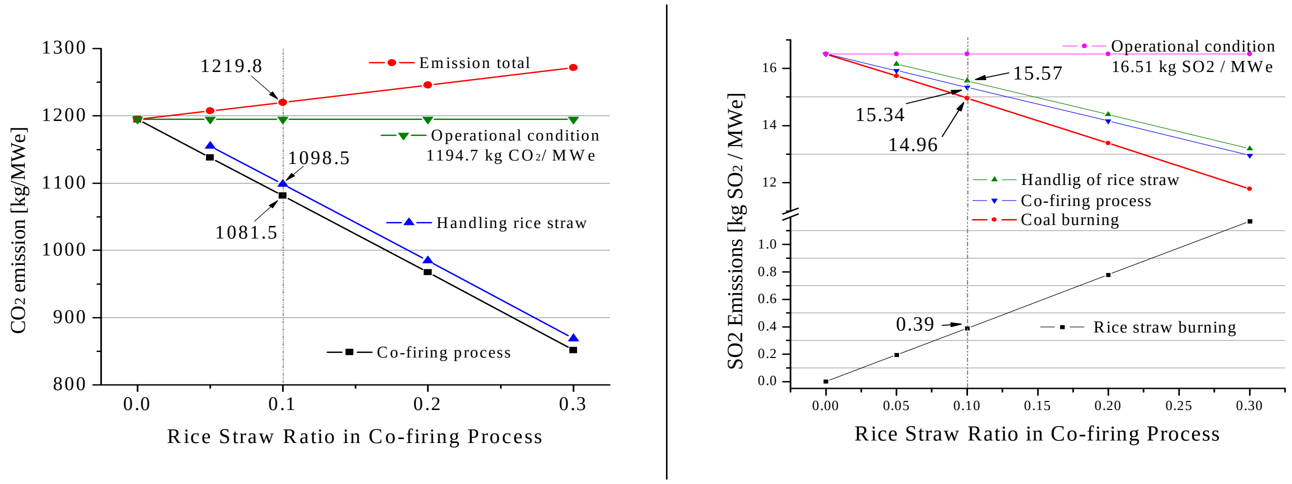

Figure 5. CO_2 and SO_2 emission for co-firing process

4. CONCLUSIONS

In the present work, an exergy analysis was presented, focusing a co-firing coal and rice straw up to 10% on thermal basis. Considering operation data of an existing coal fired power plant, it had been concluded:

- There is not significant change on the second law efficiency if compared the coal burning only to co-firing 10%;
- When considered the handling facility for both fuels, the second law efficiency decreased 4.63%, from 26.31 to 21.68%;
- The coal CO_2 emission reduced about 8% for co-firing 10%, growing up to 25% for co-firing 30%;
- The SO_2 emission reduced about 7% for co-firing 10%, growing up to 22% for co-firing 30%;

Further research is planed after the retrofitting of the power plant with the corresponding experimental data for co-firing coal and rice straw up to 10%. Also, more representative results should be expected extending the system boundary to the coal mines and rice fields.

5. ACKNOWLEDGEMENTS

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