

## EXPERIMENTAL ANALYSIS OF A COMBUSTION REACTOR UNDER CO-FIRING COAL WITH BIOMASS

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**Abstract.** *Mitigation of greenhouse gases emission is one of the most important issues in energy engineering. Biomass is a potential renewable source but with limited use in large scale energy production because of the relative smaller availability as compared to fossil fuels, mainly to coal. Besides, the costs concerning transportation must be well analysed to determine its economic viability. An alternative for the use of biomass as a primary source of energy is the co-firing, that is the possibility of using two or more types of fuels combined in the combustion process. Biomass can be co-fired with coal in a fraction between 10 to 25% in mass basis (or 4 to 10% in heat-input basis) without seriously impacting the heat release characteristics of most boilers. Another advantage of cofiring, besides the significant reductions in fossil CO<sub>2</sub> emissions, is the reduced emissions of NO<sub>x</sub> and SO<sub>x</sub>. As a result, co-firing is becoming attractive for power companies worldwide. This paper presents results of some experimental analysis on co-firing coal with rice straw in a combustion reactor. The influence of biomass thermal share in ash composition is also discussed, showing that alkali and earth alkaline compounds play the most important role on the fouling and slagging behavior when co-firing. Some fusibility correlations that can assist in the elucidation of these behavior are presented and discussed, and then applied to the present study. Results show that for a biomass thermal share up to 20%, significant changes are not expected in fouling and slagging behavior of ash.*

**Keywords:** *Co-firing, biomass, coal, fusibility, ash composition.*

### 1. INTRODUCTION

Mitigation of greenhouse gases emission is one of the most important issues in energy engineering. Essentially CO<sub>2</sub> neutral, biomass is an interesting potential renewable source of energy to attenuate this problem (mainly because it is becoming a low-cost CO<sub>2</sub> mitigation strategy for many pulverized coal boilers), but has a limited use in large scale energy production because of problems such as seasonality, relative smaller availability than fossil fuels, transportation costs, and technical issues not yet well understood.

Coal is by far away the most abundant fuel in nature. Proven reserves at the end of 2005 were around 900 billion tonnes, enough for 164 years at current production rates, according to IEA (2006). Biomass is the third largest primary energy resource in the world, and in developing countries it provides 35% of all energy requirements, according to Werther et al. (2000).

As an alternative for the use of biomass as a primary source of energy and to enhance the environmental image of coal, there is the co-firing or co-combustion, which is the use of two or more types of fuels combined in the combustion process. Broadly speaking, almost all kinds of biomasses can be co-fired with another fuel, but technically speaking, the application depends on several factors, as the technology of the combustion chamber and chemical constitution of fuels.

Literature still is sparse regarding co-firing, but some important information was already collected from pioneer researches. After conducting a research co-firing wood with coal in a pulverized coal power plant, Gold & Tillman (1996) found a decrease of 1.2% in boiler thermal efficiency, a decrease of 19,1% in SO<sub>2</sub>, 10% in NO<sub>x</sub> and 24.6% in HCl emissions. They concluded that co-firing biomass at 10-15% in thermal basis has a minimal impact upon boiler efficiency and flame temperature. Tillman (2000) says that biomass fuels such as wood wastes, short-rotation woody and herbaceous crops, and agricultural wastes can be co-fired at 4 to 10% in thermal basis without seriously impacting the heat release characteristics of most boilers. Lu et al. (2008) contend that flame stability has been found to be little affected by co-firing coal with an amount of biomass below 20% in weight basis in an industrial-scale combustion test facility. Molcan et al. (2009) say that co-firing biomass with coal on a combustion test facility improves combustion efficiency because of the lower CO concentrations and high char burnout level, and SO<sub>x</sub> emissions were reduced.

Ashes from straw usually present composition similar to that of ordinary glass, as stated by Jenkins et al. (1998). This finding helps to explain the rapid sintering, slagging, and fouling observed when burning straws in most power boilers designed for wood. Basically, this behaviour is caused by the high amount of silicon oxide, alkali and earth alkaline compounds found in biomass ashes.

Alkali and earth alkaline compounds concentration in biomass ash can be reduced through water leaching of biomass. Jenkins et al. (1998) showed that using this technique, alkali compounds concentration on rice straw ash were lowered from 4% to 2%, while earth alkaline compounds from 13% to 3%.

Co-firing is in its infancy today, and in Brazil one of the first approaches was introduced by Pereira et al. (2009), who presented a review on the co-firing worldwide, showed the energy potential from major Brazilian agricultural crops residues and made a comparison between characterization of Brazilian coal and biomasses.

The main objective of this paper is to present some experimental results regarding co-firing coal with rice straw, and through some fusibility correlations to show slagging and fouling trending.

This work is part of a project that is being held between Federal University of Santa Catarina and Tractebel Energia S/A, that aims to adapt a co-firing system in a commercial power plant for seasonal use.

## 2. EXPERIMENTAL FACILITY

It was used an atmospheric drop tube furnace, showed in the Figure 1, where the mixture air/fuel is fed from the top of a ceramic insulated cylindrical furnace with height of 2.5 m and diameter of 0.2 m. The insulated wall has 5 electrical resistances that maintain the temperature inside the furnace between 800 and 1,300°C, as desired. The furnace has a power input range of 8-20 kW, function of fuel mass flow. A lance, concentric to the furnace axis, can be inserted and positioned in any height of the furnace, through its bottom, and captures both gas samples (for instantaneous gas analysis) and bottom ash (for further laboratory analysis to determine concentration of unburnt carbon). Transverse to the bottom there is a depression duct that prevents combustion gases to be released through the bottom, and where fly ash can be captured by a filter.

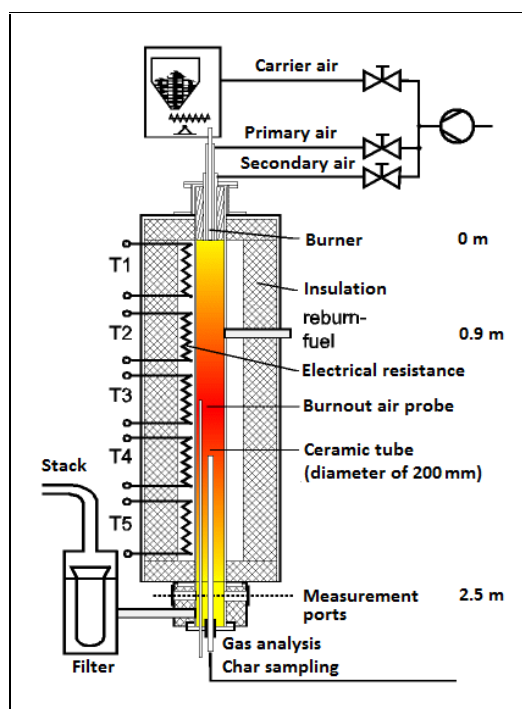
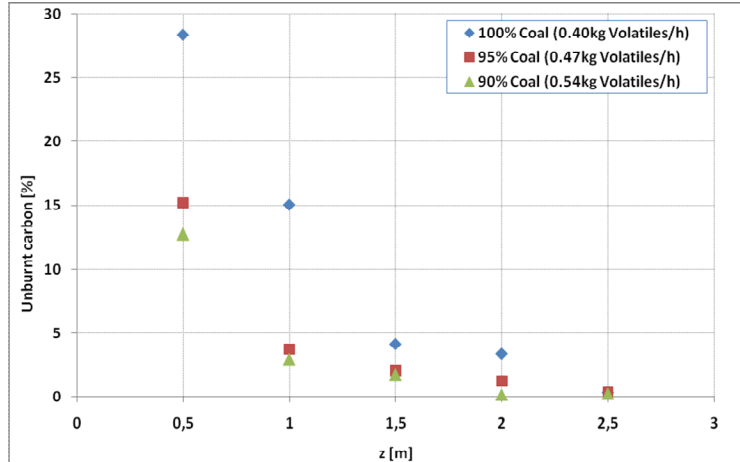


Figure 1 - Atmospheric drop tube furnace.

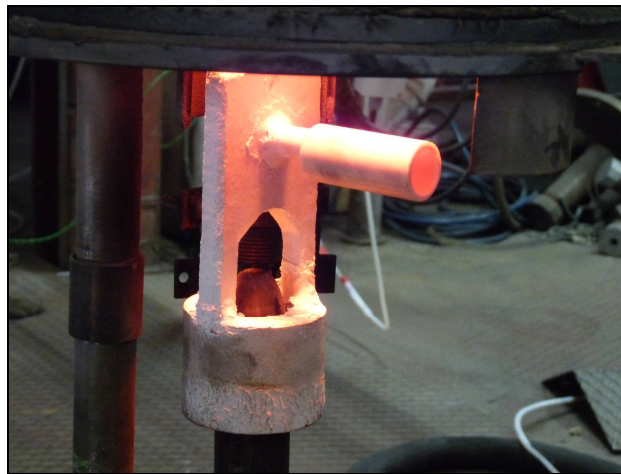
Tests were conducted using two Brazilian fuels: barro branco coal and rice straw. Three different mixtures of coal with biomass were tested: using biomass thermal shares of 0, 5 and 10%. The fuels were premixed and then fed into the furnace. Carrier, primary and secondary air flows were determined by calculations taking into account results from proximate, ultimate and heat content analysis.

Experiment was carried out aiming to study the burnout of coal over the axis, using the lance to collect ash samples in five different heights from burner: 0.5; 1.0; 1.5; 2.0 and 2.5 meters. Furthermore, these samples were analysed in laboratory to determine the amount of unburnt carbon. Figure 2 shows results from this analysis, according to DIN 51718 and 51720 standards. It can be seen that biomass plays an important role in char combustion because its high amount of volatiles compared to coal (see Table 2). After entering the drop tube, biomass quickly releases its volatiles (which causes a locally increase of temperature), and this way the coal particles will be located in a zone which favors char burnout.



**Figure 2 - Unburnt carbon, function of distance from burner.**

Another issue regarding pulverized fuel combustion chambers is related to the deposition of ash over surfaces like superheaters. Trying to quantify the influence of biomass thermal share on ash deposition, it was developed a cylindrical ceramic deposition probe, showed in Figure 3. The probe was placed 2.0 meters below burner, and then a 0.5 hours test was run for each of the three mixtures.



**Figure 3 - Ceramic deposition probe.**

After running the tests, probe's deposited ash was collected and weighed. It was also determined the normalized mass of ash regarding the area of probe's surface, the percentage of ash that sticks the probe and the collection efficiency, that can be thought as the product of an impaction efficiency and a capture efficiency. These data are showed in Table 1.

Percentage of ash that enters the furnace and sticks the probe can be determined by:

$$\rho = \frac{m_{dep}}{\dot{m}_{ash} \Delta t} \cdot 100 \quad (1)$$

Collection efficiency can be understood as a ratio between the mass of ash that is being deposited per area of the probe and the mass of ash that is being injected inside the furnace per area of cross section, and is given by:

$$\zeta = \eta \cdot G = \frac{\dot{m}_{dep} / A_{proj}}{\dot{m}_{ash} / A_{sec}} \quad (2)$$

According to Lokare (2008), an accurate description of  $\eta$  and G results in prediction of accurate collection efficiency of any fuel given the physical and chemical properties.

**Table 1- Mass of deposited ash, percentage of sticking ash and collection efficiency.**

Blend	$\dot{m}_{ash}$ [g/h] <sup>(1)</sup>	$m_{dep}$ [g] <sup>(2)</sup>	$m_{ash}/A$ [g/mm <sup>2</sup> ] <sup>(3)</sup>	$\rho$ [%]	$\zeta$ [ ]
100% Coal	879	1.87	0.58	0.43	0.0655
95% Coal	852	1.26	0.38	0.30	0.0436
90% Coal	825	0.99	0.31	0.24	0.0369

### 3. LABORATORIAL RESULTS

Proximate, ultimate and heat content analysis for coal and rice straw were experimentally determined in an as received basis (raw). Then, using equations (3) and (4) above, data were calculated, respectively, in a water free (wf) and dry, ash free (daf) basis (X variable can assume the value of any parameter from Table 2):

$$X_i^{wf} = \frac{X_i}{1 - \gamma_i^{water}} \quad (3)$$

$$X_i^{daf} = \frac{X_i}{1 - \gamma_i^{water} - \gamma_i^{ash}} \quad (4)$$

Table 2 shows data from proximate, ultimate and heat content analysis for coal and rice straw in all three bases, according to the following standards:

- Proximate analysis: Coal: DIN 51718; 51719 and 51720. Biomass: DIN CEN/TS 14774; 14775 and 15148.
- Ultimate analysis: Coal: DIN 51724; 51727 and 51732. Biomass: DIN CEN/TS 15104 and 15289.
- Heat content analysis: Coal: DIN 51900. Biomass: DIN CEN/TS 14918.

One can see that one characteristic of Brazilian coal is its high ash content, which reflects on its relatively low heat content. From this, it can be observed that in a water free basis, heat content of biomass has similar order of magnitude than coal. On the other hand, rice straw ash content is less than 1/3 of coal ash content. This way, the use of co-firing in Brazil presents an opposite behavior from that commonly observed in foreign countries: the use of biomass in co-firing reduces the ash content of the fuel mixture.

**Table 2 - Proximate, ultimate and heat content analysis for coal and biomass.**

	Coal			Rice Straw		
	raw [%] <sup>(4)</sup>	wf [%] <sup>(5)</sup>	daf [%] <sup>(6)</sup>	raw [%]	wf [%]	daf [%]
<b>Proximate analysis [%]</b>						
C <sub>fixed</sub>	38.71	38.83	66.96	13.84	14.98	17.40
Volatiles	19.10	19.16	33.04	65.70	71.09	82.60
Ash	41.89	42.02	-	12.88	13.94	-
Water	0.30	-	-	7.58	-	-
<b>Ultimate analysis [%]</b>						
Carbon	46.15	46.29	79.83	39.00	42.20	49.03
Hydrogen	3.01	3.02	5.20	5.33	5.76	6.70
Sulphur	1.17	1.17	2.02	0.20	0.22	0.25
Oxygen	6.64	6.66	11.49	34.21	37.02	43.01
Nitrogen	0.82	0.82	1.42	0.71	0.77	0.89
Chlorine	0.02	0.02	0.03	0.09	0.10	0.11
<b>Heat content [kJ/kg]</b>						
HHV	17,775	17,828	30,747	14,784	15,997	18,587
LHV	17,162	17,213	29,687	13,540	14,650	17,022

Table 3 shows results from laboratory analysis of ash from coal (according to DIN 22022 standard) and biomass (according to DIN CEN/TS 15290 standard). One can see that rice straw ash is mainly composed by silicon

<sup>1</sup> Ash mass flow (calculated from proximate and ultimate analysis data).

<sup>2</sup> Mass of ash deposited on probe's surface.

<sup>3</sup> Ratio between mass of ash and half the area of probe's surface.

<sup>4</sup> raw: as received basis.

<sup>5</sup> wf: water free basis.

<sup>6</sup> daf: dry, ash free basis.

dioxide and potassium oxide, and these compounds predict severe ash deposition problems at moderate or high combustion temperatures. According to Jenkins et al. (1998), primary source of these problems are:

- Formation of alkali silicates, that melt or soften at low temperatures (sometimes lower than 700°C), from reaction between alkali and silica compounds.
- Reaction of alkali with sulphur to form alkali sulfates on combustor heat transfer surfaces.

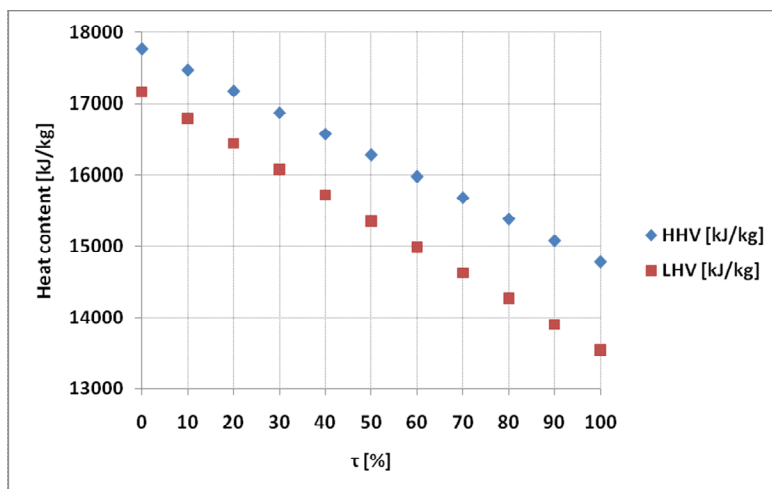
It can be seen that alkalis play the central role in both processes, with potassium being the dominant source of alkali in most biomass fuels.

**Table 3 - Ash compound weight concentration.**

Compound	Coal [%]	Rice Straw [%]
K <sub>2</sub> O	6.0	10.7
Na <sub>2</sub> O	0.8	0.2
CaO	2.9	5.1
MgO	1.5	1.1
Al <sub>2</sub> O <sub>3</sub>	12.5	0.1
Fe <sub>2</sub> O <sub>3</sub>	16.8	0.4
P <sub>2</sub> O <sub>5</sub>	0.2	1.5
SO <sub>3</sub>	1.3	1.1
SiO <sub>2</sub>	55.2	79.2
TiO <sub>2</sub>	2.9	0.0

Figure 4 shows both higher and lower heat content in function of the biomass thermal share. Values were calculated by (HV variable can assume the value of HHV or LHV from Table 2):

$$HV = (1 - \tau).HV_{coal}^{raw} + \tau.HV_{biomass}^{raw} \quad (5)$$



**Figure 4 - Heat content, function of biomass thermal share.**

Ash fusion behavior was also studied, through determination of deformation, spherical, hemispherical and fluid temperatures according to DIN 51730 standard (for coal) and DIN CEN/TS 15370 standard (for biomass), and results are showed in Table 4. These temperatures are important because give an indication of the softening and melting behavior of fuel ash.

**Table 4 - Ash fusion behavior.**

Temperature	Coal	Rice straw
Deformation [°C]	>1,550	750
Spherical [°C]	>1,550	1,460
Hemispherical [°C]	>1,550	1,550
Fluid [°C]	>1,550	1,550

#### 4. INFLUENCE OF BIOMASS THERMAL SHARE ON ASH COMPOSITION

From the values showed in Table 3, was possible to calculate the weight concentration of any  $\chi$  ash forming compound, for whatever biomass thermal fraction, by using the equation ( $\chi$  variable can assume the value of any parameter from Table 3):

$$\chi = \frac{\sum_{i=biomass}^{coal} \chi_i \cdot \dot{m}_i \cdot \gamma_i^{ash,raw}}{\sum_{i=biomass}^{coal} \dot{m}_i \cdot \gamma_i^{ash,raw}} \quad (6)$$

where fuels mass flow are function of biomass thermal share:

$$\dot{m}_i = \begin{cases} \tau \cdot \frac{P}{LHV_i^{raw}}, & \text{if } i = biomass \\ (1 - \tau) \cdot \frac{P}{LHV_i^{raw}}, & \text{if } i = coal \end{cases} \quad (7)$$

Figure 5 shows results for the calculations of ash forming compounds concentration using equation (6). Data were calculated based on laboratory analysis results from Table 3. Observing the graphics, one can predict the influence of adding a biomass thermal share in co-firing with coal. It can be seen that alkali and earth alkaline compounds will increase with the biomass thermal share, but this increase is not significant for biomass thermal share less than 20%. In the same direction, silicon dioxide also is increased, but since coal already has a high concentration of it, it is not clear if this increase will contribute to amplify deposition problems. On the other hand, metals compounds decrease with an increase on biomass thermal share.

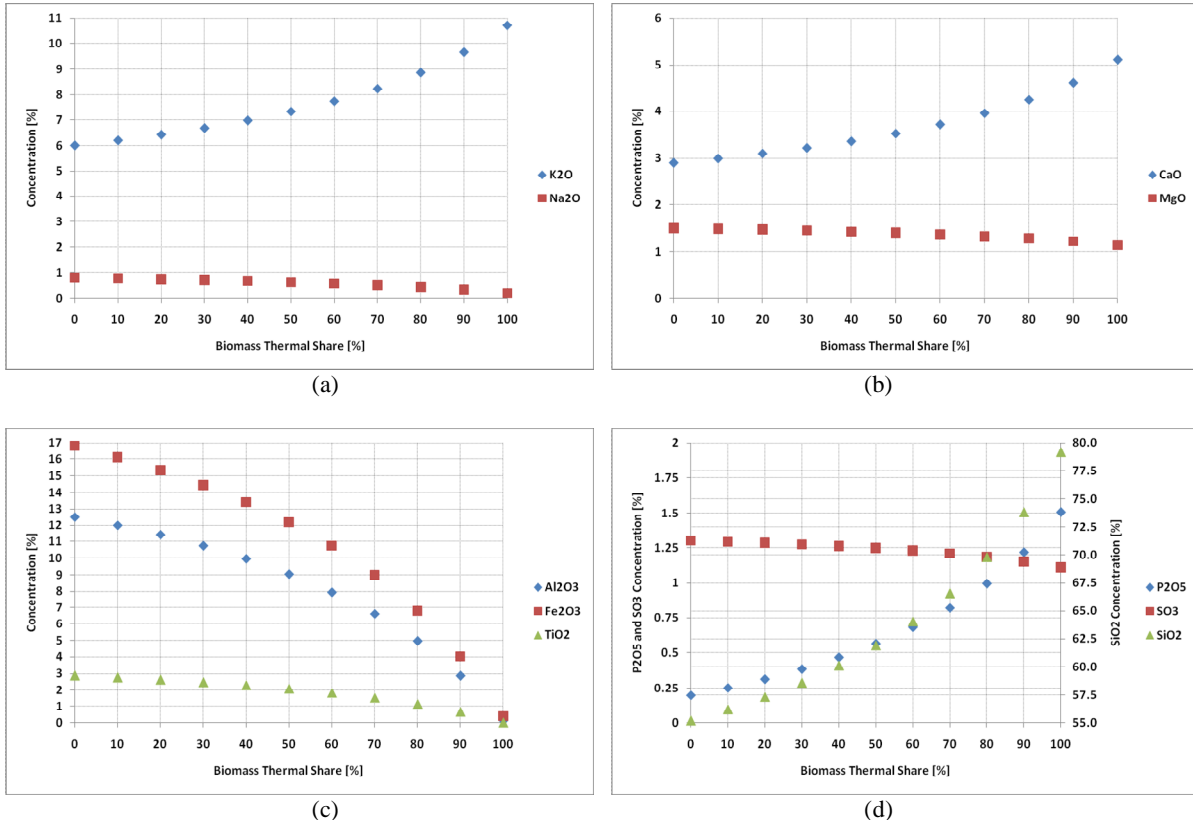


Figure 5 - Ash compounds concentration, function of biomass thermal share: (a) Alkali, (b) Earth alkaline, (c) Metals, and (d) Nonmetals.

#### 4. FUSIBILITY CORRELATIONS

In order to understand fouling and slagging behavior mainly for solid fuels, some indexes and correlations have been developed, but no single index is capable to describe with reliably the ash behavior under all combustion conditions. This way, usually a few ones are taken into account for determining the behavior of the ash. One of the most popular index as a threshold indicator for fouling and slagging is the alkali index, given by:

$$AI = \frac{\gamma^{ash,raw} \cdot (\gamma^{K_2O} + \gamma^{Na_2O})}{HHV^{wf}} \quad (8)$$

Miles et al. apud Pronobis (2005) have suggested that when AI is above 0.17 kg/GJ, fouling is probable, and above 0.34 kg/GJ is virtually certain to occur.

A long time ago it was found that basic compounds lower melting temperature of ash, while acidic ones increase it. The percentage of basic constituents in ash, given by:

$$R_b = \gamma^{Fe_2O_3} + \gamma^{CaO} + \gamma^{MgO} + \gamma^{K_2O} + \gamma^{Na_2O} \quad (9)$$

is often used to verify if ash will tend to melt at low temperatures. It has been found that the minimum ash softening temperature occurs with  $R_b=35-55\%$ . A relationship between basic and acidic compounds can be useful to indicate the fouling tendency of a fuel ash. The base-to-acid ratio relative to a fuel ash is given by:

$$R_{b/a} = \frac{R_b}{\gamma^{SiO_2} + \gamma^{TiO_2} + \gamma^{Al_2O_3}} \quad (10)$$

The melting temperature of ash tends to be parabolic with respect to  $R_{b/a}$ . For coal the minimum is around  $R_{b/a}=0.75$ , but for biomass this value tends to appear at lower values.

Aluminum to silicon ratio is a slagging indicator: the increase of this ratio enhances slag formation. It was shown that if this ratio increases from 1.0 to 4.0, slag viscosity is doubled. Al-Si ratio is given by:

$$K_{Al} = \frac{\gamma^{SiO_2}}{\gamma^{Al_2O_3}} \quad (11)$$

Slagging, fouling and slag viscosity indexes, respectively, are given by:

$$R_S = R_{b/a} \cdot \gamma^{S, wf} \quad (12)$$

$$F_u = R_{b/a} \cdot (\gamma^{Na_2O} + \gamma^{K_2O}) \quad (13)$$

$$S_R = \frac{\gamma^{SiO_2}}{\gamma^{SiO_2} + \gamma^{Fe_2O_3} + \gamma^{CaO} + \gamma^{MgO}} \cdot 100 \quad (14)$$

Recommended range for low slagging inclination is  $R_S < 0.6$ , and if this index is above 2.6 risk of slagging is extremely high. It is recommended that  $F_u \leq 0.6$  for low fouling inclination, and above 40 risk of fouling is extremely high and there exists tendency to sintering deposits. High  $S_R$  value corresponds to high viscosity and therefore to low slagging inclination. If  $S_R > 72$  there exists low slagging inclination, and below 65 the risk of slagging is high.

Another two indexes are the  $Fe_2O_3/CaO$  ratio, that in the range from 0.3 to 3.0 contain eutectics enhancing slag formation, and the chlorine content of the fuel in a water free basis, that should be less than 0.2% for low slagging inclination (above 0.5% slag inclination is extremely high).

Table 5 lists all cited indexes for the fuels studied. Unfortunately, most of indexes have proved to be of limited value as predictors for biomass, but Pronobis (2005) stated: "in case of co-firing biomass with coal, when thermal fraction of the biomass does not exceed 20%, the chemical constitution of ash does not differ significantly from that for coal. Therefore, it can be assumed that the correlations can still be used as predictors for slagging tendency of ashes from fuel mixtures of this kind". This way, the following table list results for a biomass thermal share in the range from 0 to 20%, and also for the combustion of 100% biomass, regardless of its lack of meaning.

**Table 5 - Fusibility correlations, function of biomass thermal share.**

$\tau$ [%]	0.0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	100.0
AI [kg/GJ]	1.598	1.598	1.597	1.594	1.590	1.585	1.579	1.572	1.564	0.878
Cl <sup>wf</sup> [%]	0.020	0.022	0.025	0.027	0.030	0.032	0.034	0.036	0.039	0.097
S <sup>wf</sup> [%]	1.174	1.143	1.114	1.084	1.055	1.027	0.999	0.971	0.943	0.216
R <sub>b</sub>	28.000	27.897	27.790	27.680	27.566	27.449	27.328	27.202	27.072	17.550
R <sub>b/a</sub>	0.397	0.395	0.393	0.391	0.388	0.386	0.384	0.382	0.379	0.221
K <sub>al</sub>	4.416	4.479	4.545	4.615	4.688	4.766	4.849	4.936	5.029	719.545
R <sub>s</sub>	0.465	0.451	0.437	0.424	0.410	0.397	0.383	0.371	0.358	0.048
F <sub>u</sub>	2.697	2.700	2.703	2.705	2.708	2.711	2.713	2.716	2.718	2.416
S <sub>r</sub>	72.251	72.473	72.702	72.937	73.179	73.429	73.686	73.951	74.225	92.260
Fe <sub>2</sub> O <sub>3</sub> /CaO	5.793	5.694	5.594	5.492	5.388	5.282	5.175	5.066	4.955	0.076

One can observe that AI values suggest that fouling is certain to occur, but looking at the equation, it is clear that mass fraction of ash is the governing variable. For Brazilian coal, we must be careful on the use of this index, because it presents ash content several times greater than most of American and European coals. Despite of being an important parameter on fouling behavior, ash content is not the only one.

Percentage of basic compounds decreases with the increase of biomass thermal share, indicating that ash melting temperature will increase. The same behavior is observed relative to the base-to-acid ratio, where this index tends to values significantly below 0.75, suggesting that ash melting temperature is distant from unwanted range.

K<sub>Al</sub> index indicates that slag viscosity is high, enhancing slag formation. With the increase of biomass thermal share, situation is worst. Slagging and slag viscosity indexes suggests that there is low and decreasing inclination, but fouling index indicates high and increasing inclination. Fe<sub>2</sub>O<sub>3</sub>/CaO ratio shows that there exists no eutectics enhancing slag formation.

#### 4. DISCUSSION

This paper presented a study on experimental analysis on co-firing coal with rice straw in a combustion reactor. Experimental studies for determining unburnt carbon, mass of deposited ash, percentage of sticking ash and collection efficiency were carried out by using an atmospheric drop tube furnace. The use of biomass in co-firing showed substantial decrease in all of these indicators. Two main causes are believed to be linked with this behavior:

- An increase of biomass thermal share in the mixture causes a decrease in the amount of ash that is injected into the reactor, as one can observe from ultimate and proximate analysis data.
- With an increase of biomass thermal share, there is a substantial increase in percentage of volatiles, which benefits the combustion of coal.

Influence of biomass thermal share in ash composition was also discussed, showing that alkali and earth alkali compounds play the most important role on fouling and slagging behavior. A more deep study on fouling and slagging behavior was made through the use of some fusibility correlations. Results show that for a biomass thermal share up to 20%, significant changes are not expected in fouling and slagging behavior of ash.

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### List of symbols:

$AI$  : Alkali index [kg/GJ].

$G$  : Capture efficiency [ ].

$LHV$  : Lower heating value [kJ/kg].

$m$  : Mass [kg] or [g].

$\dot{m}$  : Mass flow [kg/h] or [g/h].

$P$  : Power input on the furnace [kW].

$R_{b/a}$  : Base-to-acid ratio [ ].

$X$  : Proximate, ultimate or heat content parameters [%] or [kJ/kg].

$\Delta t$  : Running test period [s].

$\zeta$  : Collection efficiency [ ].

$\eta$  : Impaction efficiency [ ].

$\chi$  : Ash compound weight concentration on a co-firing mixture of coal and biomass [%].

$\gamma$  : Mass fraction [kg/kg Fuel] or weight concentration in ash [kg/kg Ash]

$\tau$  : Biomass thermal fraction [%]

### Subscripts:

$ash$  : Ash.

$dep$  : Deposition.

$i$  : Refers to a fuel (it can be biomass or coal).

$proj$  : Projected.

$sec$  : Cross section.

### Superscripts:

$ash$  : Ash.

$raw$  : As received basis.

$wf$  : Water free basis.

$daf$  : Dry, ash free basis.