

# Mitigation of CO<sub>2</sub> emission from power industry through co-gasification of coal and energy crops

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**Abstract** — The efforts of the world research activities involved in clean coal technologies development focus to a considerable extent on the development of integrated hydrogen and power generation technologies based on the process of gasification with CO<sub>2</sub> capture. Further improvement in terms of process sustainability may be sought in partial replacement of coal with “green” energy source - biomass. In the paper a study of steam co-gasification of biomass and hard coal, in a laboratory scale fixed bed reactor at the temperature of 900°C are presented. The effectiveness of steam co-gasification of biomass and hard coal blends, in terms of flows and composition of product gas and carbon conversion were studied. Based on the experimental results a conclusion was drawn that the co-gasification of coal and biomass might be considered to be one of the promising ways for hydrogen-rich gas production. Co-gasification of coal and biomass may be considered as contributing to CO<sub>2</sub> emission reduction, when compared to fossil fuel gasification, since biomass is claimed to be carbon neutral (CO<sub>2</sub> emitted from gasification process is balanced by the amount captured from the atmosphere in the process of photosynthesis).

**Keywords** — biomass, gasification, hard coal, hydrogen

## 1 INTRODUCTION

Coal is considered to be the most carbon-intensive fuel. Global dependence on all fossil fuels since the mid-19th century led to the release of over 1100 GtCO<sub>2</sub> into the atmosphere [1]. World CO<sub>2</sub> emissions from fuel combustion account for about 70% of total greenhouse gas (GHG) emissions and 80% of total CO<sub>2</sub> emission [2]. The emission of CO<sub>2</sub> from energy sector is expected to grow from 29.0 billion metric tons in 2006 to 40.4 billion metric tons in 2030. Coal share in the world CO<sub>2</sub> emission is also expected to grow from 42% in 2006 to 45% in 2030 [3]. In the light of the above, the technologies aiming at more sustainable coal processing, so called clean coal technologies (CCT) are of special importance, especially in case of economies with energy sectors heavily dependent on coal. At present, the technologies of coal gasification combined with separation of hydrogen and sequestration-ready carbon dioxide constitutes the subject of extensive research works worldwide. There are also studies devoted to co-gasification of biomass and coal, as it offers some advantages over the gasification of biomass or coal separately [4-6].

In the paper the results of experimental steam co-gasification of hard coal and biomass blends, with biomass content of 20, 40, 60 and 80 wt.%,

respectively are presented. In the study *Salix Viminalis* was used as a biomass source. It is characterized by high calorific value in comparison with other energy crops. However, its high moisture content, up to 50% when harvested, imposes the need of applying some drying methods, i.e. the Superheated Steam Drying (SSD) [7], considered to be the optimal solution for a large scale biomass production. The yield of the *Salix Viminalis* is ranged from 8 to 20 tons per hectare on dry basis. The effectiveness of steam co-gasification at the temperature of 900°C in terms of gas flow, composition and carbon conversion was analyzed. The reactivities of hard coal, *Salix Viminalis* and their blends in the process of steam co-gasification were tested.

## 2 EXPERIMENTAL PROCEDURE AND MATERIALS

Fig. 1 presents the laboratory scale installation for hard coal and biomass steam co-gasification in a fixed bed reactor. The reactor was designed in a shape of a cylinder with the external dimensions of 300 x 60 mm. A sample of 10 g of hard coal, *Salix Viminalis* or their blends with biomass content of 20, 40, 60 and 80 wt.%, respectively, prepared in accordance with standard PN-G-04506:1996, was placed at the bottom of the reactor on quartz wool, used for better temperature distribution and for protection against entrainment of fuel grains by the inert gas and gasification agents passing through the reactor. The sample was then heated to the temperature of 900°C in an inert gas (nitrogen) atmosphere. After the temperature had stabilized, steam from a steam generator was injected upward

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to the gasifier with a flow rate of  $5.33 \cdot 10^{-2} \text{ cm}^3/\text{s}$ . The amount of cooled, dried and filtered produced gas was measured with a flow meter and its composition was determined on-line with GC. The coal chars reactivity for 50% of carbon conversion and the maximum reactivity were calculated as follows:

$$R_X = dm / (m_o \cdot dt_X) \quad (1/s) \quad (1)$$

where  $R_X$  denotes the reactivity for  $X\%$  carbon conversion,  $m_o$  denotes the initial molar carbon content in a sample,  $m$  denotes the time-dependent molar carbon content in product gas, and  $t_X$  denotes time of reaching carbon conversion of  $X\%$  [8-10].

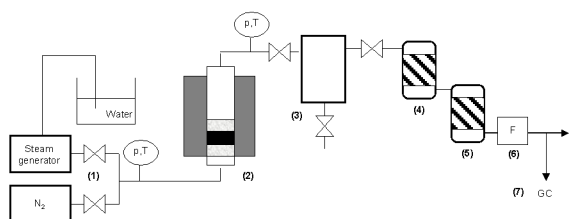


Fig. 1. Scheme of the laboratory scale installation: gasification agents inlets with valves and flow regulators (1), reactor with resistance furnace (2), gas cooling system (3), gas dehumidifier (4), solid particles filter (5), mass flow meter (6) and gas chromatograph (7)

Hard coal and *Salix Viminalis* samples used in the experiments were provided by Piast coal mine and *Salix Viminalis* plantation in Swierczow (Poland). The basic analyses of the selected physical and chemical parameters of tested samples are presented in Table 1. The samples were analyzed in the accredited Laboratory of Solid Fuels Quality Assessment of the Central Mining Institute in accordance with the relevant standards.

Table 1. Basic physical and chemical parameters of *Salix Viminalis* and hard coal samples

Parameter	Sample	
	<i>Salix Viminalis</i>	Hard coal
Total moisture W (%)	4.74	6.02
Ash A (%)	1.51	5.69
Volatiles V (%)	73.16	31.12
Heat of combustion $Q_s$ (kJ/kg)	18171	28805
Calorific value $Q_i$ (kJ/kg)	16697	27616
Total sulfur $S_t$ (%)	0.05	0.5
Carbon $C_t$ (%)	52.19	70.64
Hydrogen $H_t$ (%)	6.22	4.08
Nitrogen N (%)	<0.01	0.98
Oxygen O (%)	35.29	18.11
Fixed carbon (%)	20.59	57.17

### 3 RESULTS AND DISCUSSION

The results of the comparative study of reactivities of hard coal, biomass and their blends in the process of steam gasification at 900°C is presented below (see Fig. 2).

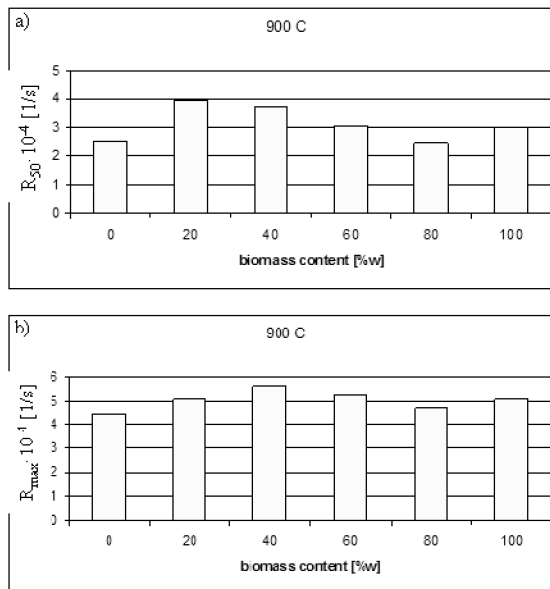


Fig. 2. Reactivity at 50% of carbon conversion,  $R_{50}$ , and the maximum reactivity,  $R_{max}$ , in the process of steam co-gasification of hard coal and *Salix Viminalis* at 900°C.

Values of  $R_{50}$  and  $R_{max}$  varied significantly with changing ratios of biomass in a fuel blend.  $R_{50}$  and  $R_{max}$  increased with increasing biomass content up to 40wt%. Blends with 20 and 40wt% of biomass were characterized by higher reactivities, and shorter times needed to reach  $R_{50}$  (see Fig. 3) when compared to the remaining weight ratios and pure hard coal and biomass samples. In general,  $t_{max}$  were shorter than  $t_{50}$ .

The synergy effect resulting from co-gasification of coal and biomass was observed in tests on blends of 20 and 40 wt.% of biomass content at tested temperature, which was reflected in higher amount of hydrogen produced when compared to gasification of hard coal and biomass separately (see Table 2). In tests on co-gasification of blends with biomass content of 60 and 80 wt.% a decrease in the volume of product gas was observed in comparison with gasification tests in which biomass and hard coal samples were gasified separately.

The synergy effect observed in the co-gasification tests on blends with biomass content of 20 and 40 wt.%, could be attributed to strong positive influence of biomass on carbon conversion of coal, which led to increase in total product gas yield. Further increase in biomass content led, however, to decrease in total amount of product gas, when compared to gasification of respective amounts of coal and biomass separately, mainly due to lower

total carbon conversion.

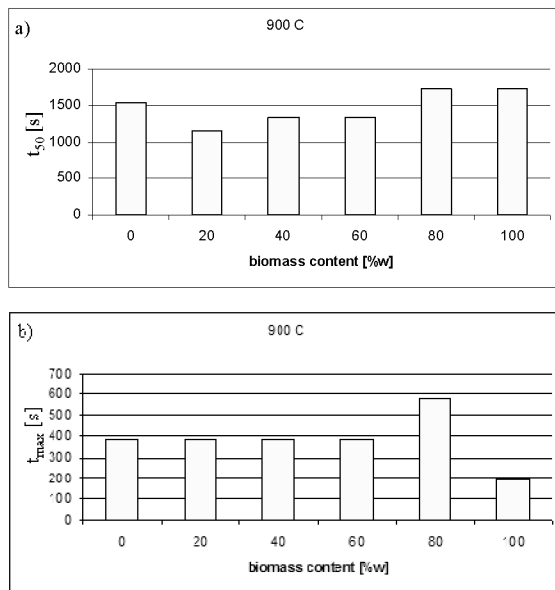


Fig. 3. Time of reaching a) the reactivity for 50% of carbon conversion,  $t_{50}$ , and b) maximum reactivity  $t_{max}$  in the process of steam co-gasification of coal and Salix Viminalis at 900°C.

The role of biomass in the co-gasification process reported in the literature is not unequivocally determined [6, 11-14]. Some authors reported a positive effect of using of up to 10 wt.% of biomass in coal/biomass blends resulting in higher hydrogen and carbon monoxide content in product gas in the co-gasification experiments [15]. Pan et al. [16] based on the results of co-gasification tests of residual biomass/poor coal blends in a fluidized-bed reactor at atmospheric pressure concluded that the ratios of no less than 20% of residual biomass for the low-grade coal and 40% of biomass for the refuse coal were the optimal in the co-gasification process in terms of improvement in thermal efficiency of the co-gasification process as well as increase in product gas heating value and carbon conversion. Other authors reported lack of synergy effects in coal/ biomass co-gasification. They acknowledged however the co-gasification process as a more sustainable alternative to biomass gasification process [17], beneficial in terms of GHG emission reduction when compared to coal gasification process since biomass is considered to be neutral in terms of CO<sub>2</sub> emission; of higher fuel supply security resulting from abundant and widely distributed coal resources as well as of higher efficiency stemming from the process scale, when compared to biomass thermal processing.

The total amount of hydrogen generated in the co-gasification tests on blends with 20 and 40 wt.% biomass content were respectively 4% and 10% higher than the amount of hydrogen produced in the process of coal or biomass gasification. This

observation proves the interaction between hard coal and Salix Viminalis. It can be attributed to the increase in carbon conversion of coal in the presence of biomass.

Table 2. The experimental results of gasification and co-gasification of hard coal (HC) and Salix Viminalis (SV) at 900°C

Sample	Amount (g)	Total volume (cm <sup>3</sup> )	Hydrogen amount (cm <sup>3</sup> )	Total volume (cm <sup>3</sup> )	Hydrogen amount (cm <sup>3</sup> )
SV	2	1232	734	16974	10205
HC	8	15742	9471		
SV+HC	2+8			22229	14280
SV	4	2465	1471	14271	8574
HC	6	11806	7103		
SV+HC	4+6			19771	12738
SV	6	3698	2207	11568	6942
HC	4	7870	4735		
SV+HC	6+4			14284	9309
SV	8	4931	2944	8866	5310
HC	2	3935	2366		
SV+HC	8+2			10341	7015

Based on the composition and the total amount of product gas generated in one-hour steam gasification tests, the calorific value of product gas was computed from the equation:

$$Q_g = \sum_i c_i \cdot W_i \text{ (MJ/m}^3\text{)} \quad (2)$$

where  $c_i$  denotes a concentration of a particular component in product gas (vol.%) and  $W_i$  denotes its heat of combustion (MJ/m<sup>3</sup>). The calorific values of product gas are presented in Table 3.

The synergy effects observed could be explained by high reactivity of Salix Viminalis as well as the catalytic effects of alkali metals present in the mineral matter of the biomass. Carbon conversion values reported in tests of fuel blends co-gasification were higher than those reported in coal gasification tests. The maximum carbon conversion was observed in tests of co-gasification of blends with 20 and 40 wt.% biomass content.

The statistical methods may be useful in investigation of potential synergy effects in co-gasification of fuel blends at various temperatures and with various weight ratios. Principal component analysis (PCA) [18] was applied in an attempt of tracing the relations between tested samples and measured parameters (see Table 4). The PCA is one of the most commonly used chemometric techniques of exploratory analysis of multivariate data sets. It

allows reduction of data dimensionality, its visualization and interpretation of the relationships between objects (which in our case represent blends of coal and biomass of various mass ratios) and parameters.

Table 3. Calorific values of product gas

SV content in a sample (wt.%)	Q <sub>g</sub> (MJ/m <sup>3</sup> )
0	11.14
20	8.41
40	10.23
60	10.25
80	9.18
100	9.30

In the PCA the data matrix, **X** (m x n), is decomposed into the matrices, **S** (m x fn), **D** (n x fn) and **E** (m x n), where m and n denote, respectively, the number of objects and parameters, fn denotes number of significant factors. **S** represents the scores matrix, whereas **D** represents the loading matrix and **E** is the residuals matrix. The columns of the matrix **S** are called the principal components (PC's) or eigenvectors. Scores and loading matrices are orthogonal. If the reduction of data dimensionality is effective, it is possible to use scores vectors and loadings vectors (i.e. the columns of the matrix **S** and **D**, respectively) to visualize and interpret the relationships between the objects and the parameters in the matrix **X**. The analyzed data set was organized in the matrix **X** (6 x 10). The rows represented blends with different biomass content (0, 20, 40, 60, 80 and 100 wt.%) , whereas columns represented 10 measured parameters.

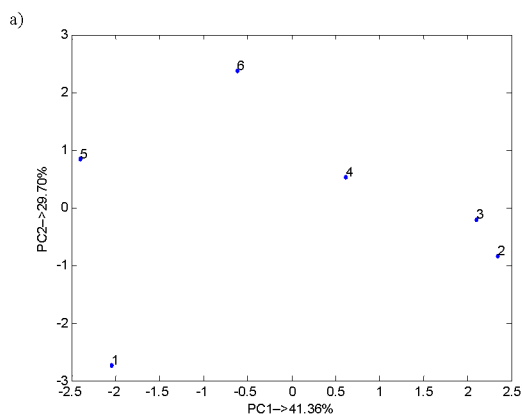
Table 4 Parameters measured in hard coal/biomass co-gasification tests

No.	Measured parameters	Unit
1	H <sub>2</sub> content in synthesis gas	(%vol.)
2	CO content in synthesis gas	(%vol.)
3	CH <sub>4</sub> content in synthesis gas	(%vol.)
4	CO <sub>2</sub> content in synthesis gas	(%vol.)
5	Calorific values of synthesis gas	MJ/m <sup>3</sup>
6	Reactivity for 50% of carbon conversion $R_{50}$	(1/s)
7	Maximum reactivity $R_{max}$	(1/s)
8	Time to reach $R_{50}$ ( $t_{50}$ )	(s)
9	Time to reach $R_{max}$ ( $t_{max}$ )	(s)
10	Carbon conversion $X$	(%)

The PCA model was constructed for the centered and standardized data since the studied data set contained measurements performed within different magnitude ranges. The percent of the modelled variance [19] was used for the determination of the

number of significant components (PCs) of the data set. The PCA model with three significant Principal Components described 86.64% of the data variance. Score plots and loading plots obtained as a result of the analysis are presented in Fig. 4.

The PC1 (describing 41.36% of the total variance) reflected the difference between the blends with biomass content of 20 and 40 wt.%, respectively (parameters nos 2 and 3) and all the remaining samples due to the highest CO<sub>2</sub> amount in the product gas and  $R_{50}$  (parameters nos 3 and 6) and relatively higher amount of H<sub>2</sub>, CH<sub>4</sub> in the product gas, high  $R_{max}$  and carbon conversion (parameters nos 1, 4, 7 and 10). Moreover for blends with 20 wt% of biomass the shortest time needed to reach  $R_{50}$  was observed (parameter no. 8). The PC2, which described 29.70% of the total variance, was constructed mainly due to the difference between the hard coal sample (sample no. 1) and the biomass sample (sample no. 6). Based on the loading plots these differences were attributed to the highest content of H<sub>2</sub> and CO in product gas and the highest calorific value of product gas (parameters nos 1, 2 and 5), high CO<sub>2</sub> content in product gas (parameter no. 3) and the lowest  $R_{max}$  and carbon conversion (parameters nos 7 and 10) observed for hard coal (sample no. 1). The sample no 6 was characterized by relatively long time needed to reach  $R_{50}$ ,  $t_{50}$ , (parameter no. 8) and the lowest H<sub>2</sub> content in product gas (parameter no. 1). The PC3 described 15.58% of the total variance and reflected the differences between the blend with biomass content of 80 wt.%, (sample no. 5) and all the remaining samples. The highest differences were observed between samples nos. 5 and 6. The sample 5 was unique mainly due to the longest time needed to reach  $R_{max}$ ,  $t_{max}$  (parameter no. 9) and the lowest carbon conversion (parameter no. 10). Loading plots revealed a positive correlation between  $R_{max}$  and the amount of CO<sub>2</sub> in product gas and carbon conversion (parameters nos 7, 3 and 10), and negative correlation between time needed to reach  $R_{50}$ ,  $t_{50}$ , and amount of CO<sub>2</sub> in product gas (parameters nos 8 and 3).



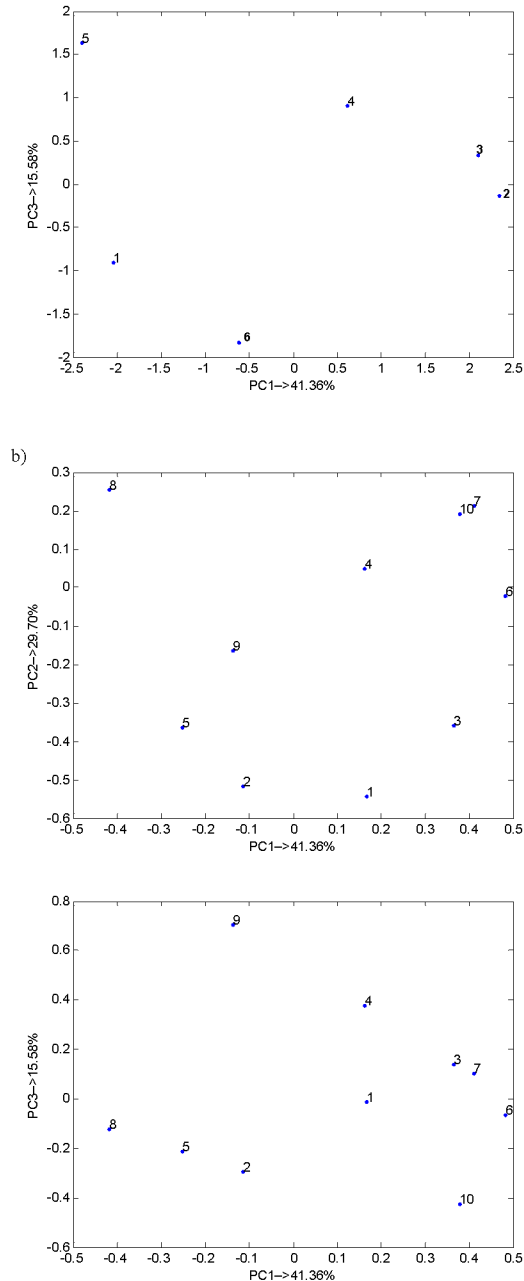


Fig. 4. a) Score plots and b) loading plots as a result of PCA for the centered and standardized data  $X$  ( $6 \times 10$ ).

## 5 CONCLUSIONS

Based on the experimental results a conclusion was drawn that the co-gasification of coal and biomass might be considered as one of the promising ways of hydrogen-rich gas production. A synergy effect was observed in co-gasification tests on blends with 20 and 40 wt% content of biomass, consisting in an increase in the volume of hydrogen produced, when compared to the tests of coal and biomass gasification. In tests of co-gasification of blends with biomass content of 60 and 80 wt% a decrease in the volume of product gas was observed, when compared to the tests of coal and biomass

gasification. Moreover, co-gasification of coal and biomass may be considered as contributing to  $CO_2$  emission reduction, when compared to fossil fuel gasification, since biomass is claimed to be carbon neutral ( $CO_2$  emitted in gasification process is balanced by the amount captured from the atmosphere in the process of photosynthesis).

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