

*Short Communication*

# Formation of Pollutants in the Process of Co-Combustion of Different Biomass Grades

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## Abstract

Our paper investigates the problems of co-combustion of select grades of biomass, i.e. hay, straw, and wood waste, with natural gas. Research comprised both a laboratory experiment and numerical simulations with the use of a professional software application, Chemkin-Pro. The chemical mechanism of co-combustion of biomass with natural gas was described using 224 reactions and 56 chemical compounds. Based on the flow data determined on an experimental stand, the initial conditions were formulated and numerical simulations were performed. As a result of numerical simulations, the detailed chemical composition of combustion gas at the heating chamber outlet was obtained. The investigation has shown that the use of biomass for energy purposes significantly contributes to the reduction of pollutant emissions in flue gas.

**Keywords:** combustion, biomass, reburning, numerical modelling, Chemkin-Pro

## Introduction

According to literature data, biomass constitutes the world's third most abundant energy source in terms of amount and availability. It is also one of the oldest energy sources (wood combustion) adopted by humans for heating purposes. At present, one of the main uses of biomass is as a heat source. Heat of biomass is recovered by many thermochemical transformations, in particular by the combustion process. One of many advantages of biomass energy use is the reduction of greenhouse gas emissions, namely carbon dioxide, as well as toxic components of flue gas-sulphur dioxide, nitrogen oxides, and carbon monoxide. Bioenergy is assumed to be carbon neutral because of the fact that during biomass growth the plant absorbs as much CO<sub>2</sub> as is emitted during its combustion. Thus, the balance of carbon dioxide emissions from biomass combustion equals zero. However, considering the energy needed for

biomass transport and preparation (fragmentation), it is estimated that the amount of greenhouse gases formed in the biomass combustion process is smaller by over 90% in comparison with the combustion of coal. Due to the diverse composition of biomass, differing from that of conventional fuels, as well as high volatile matter content, the combustion of biomass requires the appropriate technology to be selected. The most economically effective solution is the co-combustion of biomass in already existing utility boilers [1-3]. A special form of biomass co-combustion is the gradual supplying of biomass to the heating chamber in the reburning process.

## Formation of Pollutants in the Biomass Combustion Process

The quantity and type of pollutants formed in the biomass combustion process are determined not only by the process operation conditions, but the type of combusted biomass as well [2, 4, 5]. Wood, due to its physicochemical

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properties, is considered to be an ecologically competitive fuel. It includes only trace contents of sulphur, which effects a zero SO<sub>2</sub> emission. The most important pollutants emitted to the atmospheric air during wood combustion are airborne particulates (including PAH) and gaseous pollutants (NO<sub>x</sub>, CO, hydrocarbons). During combustion of industrial wood waste, some specific pollutants such as Cl<sub>2</sub>, HCl, salts, dioxins, and furans may also occur. Cinder left after the combustion of wood is suitable to be used as a fertilizer. During wood combustion, carbon monoxide is also emitted, whose content in flue gas depends primarily on the method of leading the combustion process. A large CO emission is caused by incomplete combustion and results from the poor organization of the process. The nitrogen oxides emitted during wood combustion are in particular in the form of NO (90%) and NO<sub>2</sub> (10%). Wood contains a relatively insignificant amount of bounded nitrogen (0.07-0.2%); nevertheless, literature data shows that considerable NO<sub>x</sub> fractions are present in flue gas (170-920 mg/m<sup>3</sup>). This content is determined by the furnace type, thus the combustion temperature and type of combusted wood. An effective technique of NO<sub>x</sub> emission reduction during wood combustion is gradual burning, which allows for a reduction in NO<sub>x</sub> emissions by up to 50 g/GJ. In the case of pollutants emitted during the combustion of other biomass grades (e.g. straw), increased emissions of PAHs, CO, and HCl are a serious problem [3].

### Testing

The scope of the work included the following:

- selection of material: wood waste, straw, hay
- preparing of the biomass: drying, fragmentation
- determining of thermophysical properties (Table 1)
- laboratory experiment, consisting of
  - determination of flow parameters (Table 1),
  - measurements of NO<sub>x</sub> concentrations in flue gas (Table 1)
- computer simulations

In experimental research, a cylindrical cross-section heating chamber built of 12 concrete rings was used. The chamber's internal diameter was 0.34 m and its total length, 3.18 m. The chamber was insulated with a 0.05 m mineral wool layer and covered with an aluminium sheet casing. The main burner was installed at the chamber inlet, where natural gas of the composition CH<sub>4</sub> = 96.7%, C<sub>2</sub>H<sub>6</sub> = 0.6%, N<sub>2</sub> = 2.5%, CO<sub>2</sub> = 0.2% was combusted. At the chamber length the measuring holes were placed, which enabled the measurement of temperature and flue gas composition. Biomass was supplied to the chamber at a distance of 1/3 of the chamber length from the main burner with the use of a conveying screw, which was contingent on combustion conditions. Flue gas composition was measured with the use of a TESTO analyzer connected to a computer, and the temperature was measured by NiCr-Ni thermocouple.

The obtained results have proved that the NO<sub>x</sub> concentration depends on the reburning fuel type. The lowest concentration was from a combustion of wood waste (89 ppm),

and the highest for straw (99 ppm). The observed concentration discrepancies are significantly influenced by the volatile matter content of fuel. The higher volatile matter content, the greater reduction of nitrogen oxides (Table 1).

Among nitrogen oxides, in flue gas other pollutants occurred as well. Due to the limitation of control-metering equipment, their participation was not possible to determine during the experiment. Concentrations of other compounds forming in the co-combustion process was determined by numerical calculations (Table 1).

### Numerical Modelling

The Chemkin-Pro program used in calculations enables detailed analysis of combustion process chemistry.

Considering the complexity of the biomass combustion process, in the numerical analysis, the problem was reduced to two burning phases, namely:

- thermal decomposition, which is accompanied by the liberation of volatile matter
- combustion of gaseous products of thermal decomposition

The combustion of so-called char was left out of consideration. Selection of a chemical reactor and combustion mechanism was based on the experience of other authors, who have modelled the processes of biomass combustion and co-combustion with the use of older versions of the Chemkin application [5-13]. The various types of applied chemical reactors (PSR, PFR, OPDIF), as well as combustion mechanisms (including several dozen or even 276 species and 3,798 reactions), suggest that the issue of numerical modeling of chemistry of the biomass combustion process is of great interest to many scientists and is still being researched.

Based on the above-mentioned facts and the researchers' own experiences in the numerical modelling of the biomass co-combustion with conventional fuels [14], the authors of this paper have proposed a simplified combustion mechanism including 224 reactions, 56 chemical compounds, and elements. The plug flow reactor (PFR) was chosen to research. The initial stage of the calculation procedure was the formulation of boundary conditions and the preparation of "input file," based on data obtained from experimental research (Table 1). A simplified diagram of the simulation course is shown in Fig. 1.

The chemical composition of biomass was taken from literature [2]. Input data for modeling procedure were determined as follows:

- temperature of input media: 293 K
- combustion temperature: 2,073 K
- pressure: 1 atm.

### Analysis and Discussion of the Results

Conducted research suggests that the amount, as well as the composition of pollutants formed during the co-combustion process of biomass with natural gas, depend significantly on the applied biomass type (Table 1).

Table 1. Presentation of selected results of research and analyses.

The selected physicochemical properties of the biomass used								
	Wood waste		Straw		Hay			
Caloryfic value, MJ/kg	17.172		14.660		16.391			
Ash contents, %	0.36		3.311		4.569			
Contents of volatile matter, %	76.015		64.971		70.853			
Moisture, %	12.2		11.2		5.8			
Elemental compositions of biomass [2]								
Carbon, %	49.9		44.92		46.68			
Hydrogen, %	5.9		5.46		5.82			
Oxygen, %	41.8		41.77		37.38			
Nitrogen, %	0.61		0.44		0.77			
Sulfur, %	0.07		0.16		0.19			
Chlorine, %	0.01		0.23		0.19			
Ash, %	1.71		7.02		8.97			
Quantity share of grains, thousand								
Grain size, 0-11 $\mu\text{m}$	92031		73930		65085			
Grain size, 11-23 $\mu\text{m}$	38112		28345		35759			
Grain size, 23-34 $\mu\text{m}$	13588		10170		13789			
Grain size, 34-46 $\mu\text{m}$	5850		4330		7075			
Grain size, 46-267 $\mu\text{m}$	21405		10680		27908			
Parameters of ceramic chamber operation								
	Primary zone	Reburning zone						
		Wood waste		Straw		Hay		
Fuel stream, $\text{m}^3/\text{h}$ ; kg/h	2.9	0.65		0.76		0.68		
Air stream, $\text{m}^3/\text{h}$ ,	29							
Excess air ratio, $\lambda$	1.07	0.85		0.85		0.85		
Heat fraction, %		10		10		10		
Selected results of experiment (ex) and calculation (cal)								
Concentration, ppm	ex	cal	ex	cal	ex	cal	ex	cal
$\text{NO}_x$	122	114	89	81	99	90	91	87
HCl	-	-	-	2,1	-	52	-	44
$\text{SO}_2$	-	-	19	15	39	37	40	38

Concentration of  $\text{NO}_x$  due to the specificity of the applied method of co-combustion, leads to minimize the nitrogen oxide concentrations in flue gas.

The highest nitrogen oxide reduction effectiveness was achieved for wood waste (26%). The degree of reduction was influenced by the volatile matter contents of the examined biomass due to the presence of hydrocarbons. The reduction of nitrogen oxides in the reburning method

occurs with the participation of hydrocarbon free radicals forming from decomposition of the reburning fuel, through the agency of which the transformation of nitrogen oxides into molecular nitrogen takes place. During research a constant biomass heat share was assumed, which was equal to 10%. According to the relevant literature data, the amount of heat contributed by reburning fuel should not exceed 20% of the total heat amount. This results from the fact that

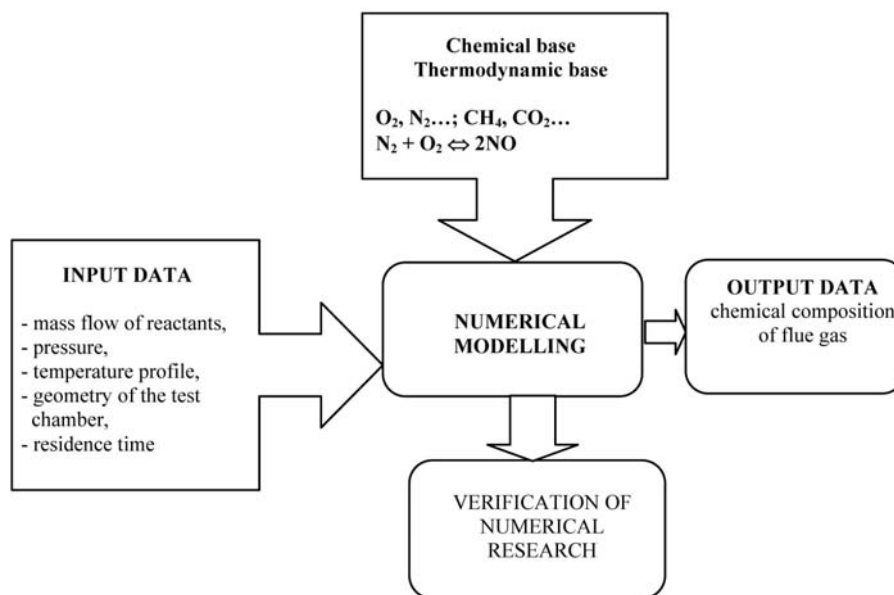


Fig. 1. Background modeling.

there is a limit, beyond which further increasing the amount of fuel does not affect the reduction of  $\text{NO}_x$  concentration, and even leads to a decrease in efficiency due to changing combustion conditions.

The comparison of experimental results with numerical calculations, shows that the values obtained from calculations were slightly lower than from the experiment.

The output  $\text{NO}_x$  concentration of natural gas combustion was equal to 109 ppm, whereas during co-combustion with biomass it was equal to 81 ppm. The above-mentioned discrepancies are a result of assumptions, such as combustion temperature, as well as the chemical mechanism implemented in calculations.

Performed calculations show that apart from the positive environmental effects resulting from the co-combustion of natural gas with fuels of vegetable origin such as reduction of nitrogen oxides, a content of undesirable compounds in flue gas, i.e. HCl and  $\text{SO}_2$  also is observed. According to the data compiled in Table 1, the content of both  $\text{SO}_2$  and HCl is the greatest for straw, i.e. for these fuels that contain large amounts of sulfur and chlorine.

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