

# Analysis of operation of cogeneration installation equipped with a fix bed downdraft gasifier

Marian Wysocki\*, Witold Elsner

*Institute of Thermal Machinery*

*Czestochowa University of Technology, Poland*

## Abstract

The study presented in this paper examines the operation and performance of a low-power cogeneration plant equipped with a downdraft gasifier for biomass, municipal waste and sewage sludge treatment. Use of this technology opens up promising prospects for significant saving of fossil fuel resources, and environmentally friendly utilization of gasified wastes. The cogeneration installation is well-suited for a distributed energy system, in locations where biomass resource density is high and there is demand for both heat and power.

The analysis was performed using SimTech's IPSEPro program. The most important objectives were to analyze the efficiency of the cogeneration plant and the gas composition as a function of key fuel and operating parameters. The results indicate that complementing the gasifier design by adding an internal heat exchanger boosts the efficiency of the gasification process and causes an increase in the lower heating value (LHV) of syngas. It was proved that one of the most important process parameters is the air flow rate, which controls the degree of combustion. It was shown that by changing the air flow rate it is possible to control the gasification process and to change the gas composition. The analysis presented in the paper demonstrates the possibility of using the gas composition for diagnostics of the gasifier operation point. Supplementary tests of the real installation as well as discussion of the results of measurements, i.e., gas composition, lower heating value (LHV) are presented.

**Keywords:** gasification, biomass, cogeneration, downdraft gasifier, numerical simulation

## 1. Introduction

Currently, the main energy sources in the world are fossil fuels, mainly coal, oil and natural gas. Considering the economic development of the world, relying only on those sources of energy is not justified. Firstly, it is assumed that fossil fuels are non-renewable and their resources are being depleted. On

the other hand, their use results in the release of carbon dioxide CO<sub>2</sub> which has led to concerns about climate change. One alternative is to use biomass, which could be treated as a neutral process since the carbon dioxide released during combustion was captured during photosynthesis. The term biomass covers many different types of fuel: agricultural and forestry residues and organic parts of municipal and sewage sludge produced as byproducts during municipal wastewater treatment. Following rapid urbanization, the problem of municipal waste and sewage sludge management is now a major environmental

\*Corresponding author

Email address: mawy@imc.pcz.czest.pl (Marian Wysocki\*)

problem the world over.

Two main ways of converting biomass energy into biopower are biochemical conversion and thermochemical conversion processes [1]. Biochemical conversions convert biomass into liquid or gaseous fuels by fermentation or anaerobic digestion. Fermentation produces gaseous fuels containing primarily ethanol, and anaerobic digestion produces gaseous fuels containing primarily methane. According to Werther and Ogada [2] there are several thermal processes available for use with biomass, including combustion, co-firing, gasification, and pyrolytic gasification. Particularly interesting, in terms of both the economy and environment, is gasification technology, which has been developed in recent years. The main product of gasification and pyrolysis is often referred to as syngas, which is composed mainly of carbon monoxide and hydrogen (up to 85%), with smaller quantities of carbon dioxide, nitrogen, methane and various other hydrocarbon gases. There are many different kinds of technologies for gasification, from a small fix/moving bed gasifier up to a large CFB installation. The main advantages of gasification processes are that the feedstock can be of any type of biomass including agricultural residues, forestry residues, non-fermentable byproducts from biorefineries and organic municipal wastes. The product gases have a much higher energy density and can also be converted to a variety of fuels (e.g.  $H_2$ , synthetic gasoline). The major disadvantage of this technology is the high cost associated with cleaning the product gas of tar and of unwanted contaminants such as alkali compounds.

The purpose of this study is to present one of the basic solutions, which could be used locally as an element of a distributed power generation system. Attention is focused on a small cogeneration installation with capacity of about 75 kW<sub>e</sub> equipped with a technologically simple, Imbert-type downdraft gasifier. This technology opens up promising prospects for significant saving of fossil fuel resources, and environmentally friendly utilization of gasified wastes accompanied with conversion of its energy, which would otherwise remain unused. A cogeneration installation is better-suited to a distributed energy system than a centralized system, because it is easier to utilize the heat locally, in public

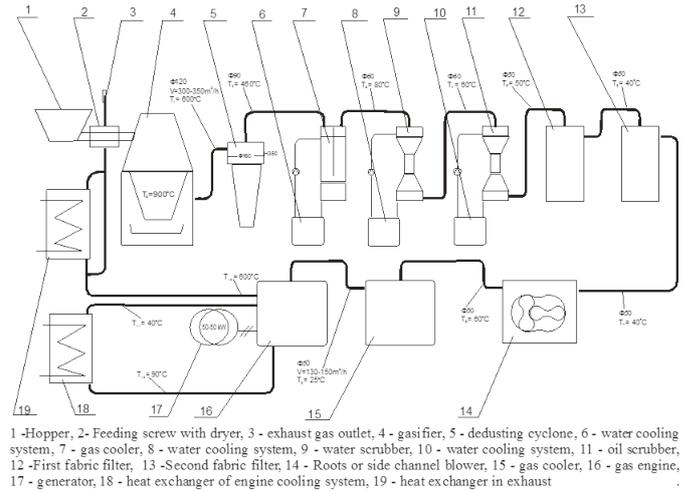


Figure 1: The scheme of cogeneration installation designed for biomass gasification

buildings, farms, gardening and others. In the first section of the paper the simulation and then optimization of the thermal cycle of cogeneration installation equipped with gasifier is presented. For this purpose it was decided to use SimTech's IPSEpro software [3]. In the next section, a comparison of the numerical results and the tests of the real installation are presented and parameters such as gas composition, lower heating value (LHV) are discussed. Attention is focused on operating parameters like gasification temperature, equivalence ratio, and on details of the gasifier design.

## 2. Design assumptions of the installation

Due to the relatively small output power of the installation and the planned use of syngas to feed the piston engine, it was decided to use an Imbert-type downdraft gasification reactor. This type of gasifier produces gas of lower calorific value than the countercurrent gasifier, but it contains less dust and tar. Additionally, purification of gas with this type of generator is much easier. The gasification process is conducted usually in a temperature range of 900...1,100°C. It was assumed that the gasifier can be fed various substrates. A schematic diagram of the cogeneration installation is shown in Fig. 1. It consists of a fuel supply system, downdraft gasifier, water cooler, gas purification system, blower—used to reduce the pressure in the system—and a reciprocated piston engine. A number of heat exchangers

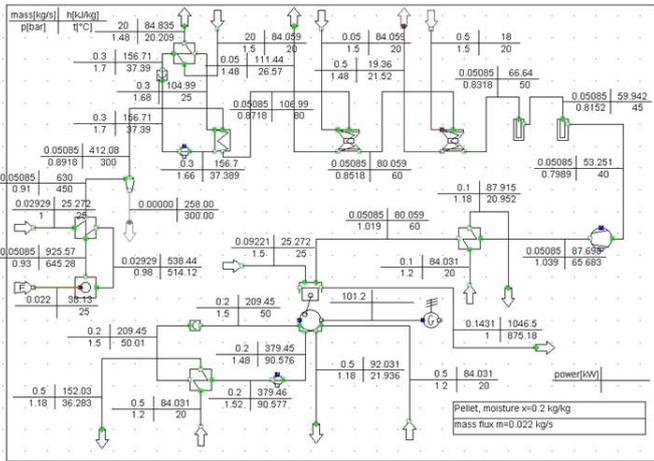


Figure 2: The diagram of modeled cogeneration installation

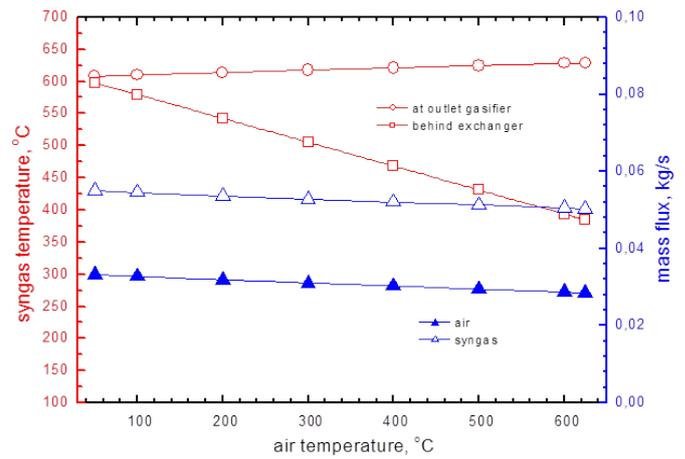


Figure 3: The influence of air temperature on syngas temperature and syngas air flux

to recover waste heat were also designed. The key element of the installation is the purification system.

The product gas contains particulates, tar, alkali compounds, nitrogen and sulfur containing compounds which need to be removed prior to feeding the engine. For this purpose, the installation is designed to include cyclone separators, a set of wet scrubbers and fabric filters. The cogeneration installation employs a number of innovative solutions. The most interesting is the internal heat exchanger, a built-in gasifier in the form of a coil. The idea was to use the heat from produced hot gases to heat up the supplied air. At the outlet of the gasifier, gas usually reached a temperature of 500...900°C, but it had to be significantly reduced before entering the scrubbing system. To be effective, the scrubbers must work in a temperature lower than 150°C. In higher temperatures tar aerosol particles are less than 1 μm in size and are sticky in nature and have a tendency to deposit on walls. An analysis of the effect of air inlet temperature is presented in the next section.

### 3. Initial calculations of gasification process

The calculations were conducted using SimTech's IPSEpro software [3]. The structure of the thermal cycle of the cogeneration system is presented in Fig. 2. As was said previously, the most important component of the system is the gasifier. For calculations, the heterogeneous gasifier model (gasifier\_het) was chosen, while modeling the gasification process we had to choose between the equilib-

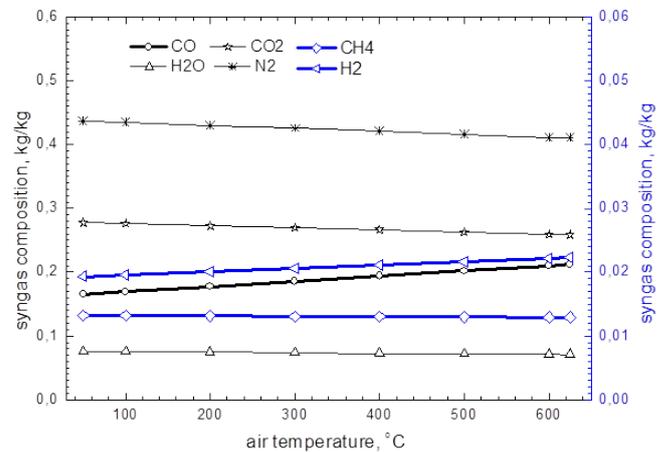


Figure 4: The influence of air temperature on syngas composition

rium model or the nonequilibrium model (the kinetic rate model). By choosing the equilibrium model it was assumed that the substrate had to be in the gasifier long enough to reach chemical equilibrium. During the simulation, the advantage of the equilibrium model was the independence of the generator dimension and its structure, which allowed for higher flexibility and better optimization of the gas parameter.

In the gasifier most of the coal was reacted into syngas and the level of conversion was described by the conversion rate, which for current calculations is 0.97. The initial calculations were carried out for two cases, with and without the internal heat exchanger, assuming the mass flow rate of a fuel (wood pellets)

is up to  $\dot{m}=2.22$  g/s with a moisture level of 20%. In the second case the temperature of supplied air was varied in the range 50...625°C. The results are presented in Fig. 3 and 4.

As can be seen in Fig. 3, the increase in temperature of the air supplied to the gasifier causes a slight increase in temperature of the syngas (from 608 to 628°C), which is associated with an increase in temperature of the gasification process. The heat flux received from the gas generator and transmitted to the inlet air in the heat exchanger significantly lowers the temperature of the gas, from 597 to 384°C, which causes a drop in temperature of subsequent elements of the installation and reduces heat loss. The rise in temperature of the gasification process causes a slight decrease in the demand for air, from 3.32 to 2.85 g/s, resulting in a decreasing gas flux, assuming there is a constant flow of biomass supplying the gasifier.

As might be expected, the change in temperature and amount of air supplying the gasifier, ensuring equilibrium of the biomass gasification process, causes a change in the composition of the gas generator, as shown in Fig. 4. The increase in air temperature practically does not affect the intensification of the methane reaction, as the mass share of methane ( $\text{CH}_4$ ) in the syngas does not change. However, rises in the shares of carbon monoxide (CO) from 0.165 to 0.212 kg/kg, and of hydrogen ( $\text{H}_2$ ) from 0.019 to 0.022 kg/kg are observed, although the latter is smaller by almost an order of magnitude. The increase in the weight fraction of the two combustible gas components leads to a consequent increase in the energy content of the produced gas. The lower heating value (LHV) rises by 14.8 % from 4,827 to 5,663 kJ/kg. This means that the proposed modification of the gasifier design improves the efficiency of the gasification process and, therefore, was included in the final design of the gasifier [4, 5].

Comparisons of basic fuel parameters and produced gas compositions (volume fraction), with and without heat exchanger, where the second one is for a maximum inlet air preheating, are presented in Table 1. Compared to the literature data [6] the volume fractions of syngas referenced to normal conditions are in the given range (for  $\text{CH}_4$ ,  $\text{CO}_2$ ) or are very close to them (for CO,  $\text{H}_2$ ). Small discrepancies ob-

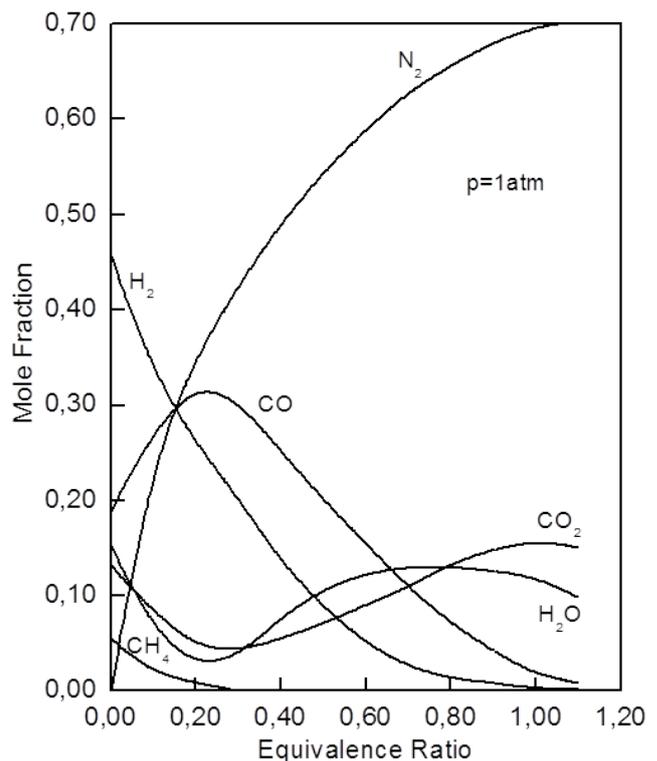


Figure 5: Equilibrium gas composition for reaction with air

served in the calorific value of gas are due to the fact that the literature [6] gives a value of dry gas, while the researchers' own data presents the calorific value of moist gas. The calorific value refers to the unit volume of syngas.

#### 4. The role of operational variables

Gasification takes place at high temperature, in the presence of an oxidizing agent (air in our case), but at a lower level than would be required for stoichiometric combustion of biomass. The energy value of the useful gas is typically 75% of the chemical heating value of the original solid fuel. In the presence of an oxidizing agent the large polymeric molecules of biomass decompose at high temperatures of 600...1,000°C, into lighter molecules and eventually to permanent gases (CO,  $\text{H}_2$ ,  $\text{CH}_4$  and lighter hydrocarbons), ash, char and tar. Char and tar are the result of incomplete conversion of biomass. To obtain syngas of the required quality, and so, of proper composition, a number of parameters need to be optimized. Apart from gasifier design, biomass

Table 1: Basic fuel parameters and produced gas compositions

	Calculation IPSEPro		Knoef
	without heat exch	with heat exch	
Biomass moisture, %	20	20	20
Biomass temperature, °C	25	25	
Biomass flux, g/s	2.22	2.22	
Biomass LHV, MJ/kg	15.0	15.0	
Syngas outlet temperature, °C	609	385	
Syngas temp. behind clean. syst., °C	40	40	
Syngas mass flux, g/s	5.56	5.06	
Syngas volumetric flux, nm <sup>3</sup> /h	191	181	
Syngas LHV, MJ/m <sup>3</sup>	4.19	4.53	5...5.9
Syngas composition—volum., %			
CH <sub>4</sub>	1.9	1.0	0...2
CO	13.8	17.3	17...22
CO <sub>2</sub>	14.6	13.0	9...15
H <sub>2</sub>	22.1	24.9	12...20
H <sub>2</sub> O	9.7	8.7	
H <sub>2</sub> S	1.0	1.1	
N <sub>2</sub>	36.8	33.3	50...54

quality and moisture, the most important are the operating conditions, i.e., temperature and the equivalence ratio ER. That is the ratio of actual air flow to the air flow required for stoichiometric combustion of the biomass, which indicates the extent of partial combustion and is related to the air flow rate. It is a very important parameter because by varying the air flow rate we control the degree of combustion, which in turn affects the gasification temperature [4]. A higher air flow rate results in higher temperature, which leads to a higher biomass conversion and higher quality of syngas. On the other hand, an excess degree of combustion results in decreased energy content of the gas, as part of the biomass energy is consumed during combustion. Additionally, a higher air flow rate shortens the residence time, which may decrease the extent of biomass conversion. To show the important role of ER, the equilibrium gas composition as a function of equivalence ratio, quoted after Red and Das [7] is presented in Fig. 5 and Fig. 6. As can be seen, the optimal ER is theoretically 0.25, where the mole fraction of CO peaks and syngas energy content is the highest. In the following part the impact of ER on the real gasi-

fier operation is discussed. During the preliminary tests of the installation the process temperature, syngas composition and LHV were recorded [8].

Fig. 7 presents the temperature of syngas measured at the gasifier outlet. The temperature is very stable and is maintained at about 385°C. Assuming that the average temperature of the gas passing through the grate is about 650°C, the strong impact of the internal gas-to-air heat exchanger is visible. It makes it possible to cool the gas by more than 220°C. The measured bed temperature is not so stable, and its variation results from periodic refueling and moving of the oxidation zone in relation to the thermocouple. In Fig. 8 the most important syngas components are presented. As can be seen, the shares of combustible gas components are very high and, most importantly, remain stable. The average values over the analyzed period are as follows: CO—22.2%, H<sub>2</sub>—15.05%, CH<sub>4</sub>—2.21%. The share of CO<sub>2</sub> stabilizes at 9.3%. The gas composition is reflected in the calorific value LHV, which is approximately 5.2 MJ/m<sup>3</sup>.

The recorded data was compared against the simulation, which is given in Table 2 (columns 3 and 4).

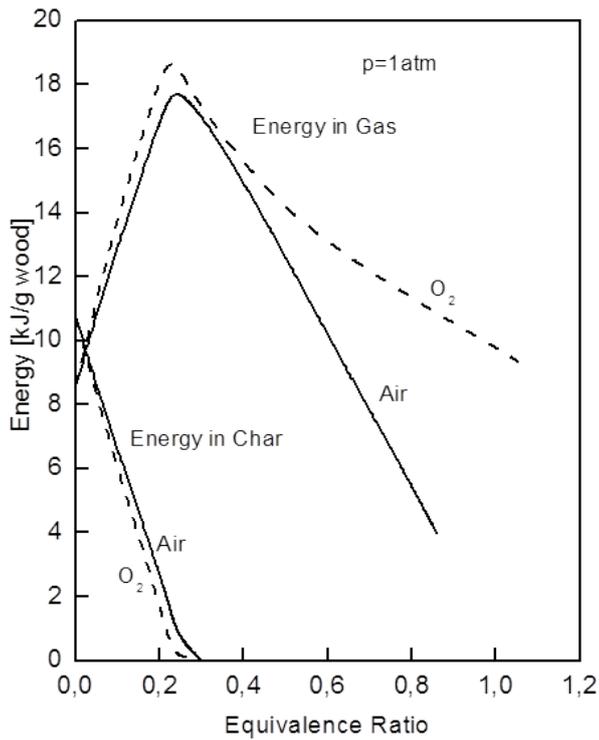


Figure 6: Energy in solid and in gas

The results display great similarity. Syngas temperature measured behind the internal heat exchanger and at the inlet of the blower differs only slightly. However, when the syngas composition is compared, some differences can be observed. The content of combustible  $\text{CH}_4$  and  $\text{CO}$  in the syngas from the experiment is slightly higher ( $\text{CH}_4$ —2.2%,  $\text{CO}$ —22.2%) than the results from the numerical simulation ( $\text{CH}_4$ —1.8%,  $\text{CO}$ —17.3%), although the share of the two gases are in the range of values given

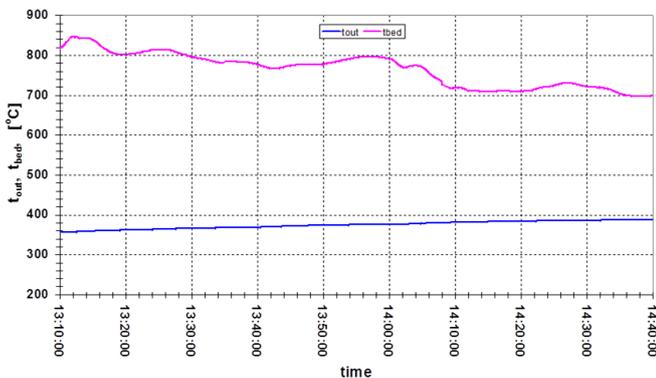


Figure 7: Time traces of bed and syngas temperature

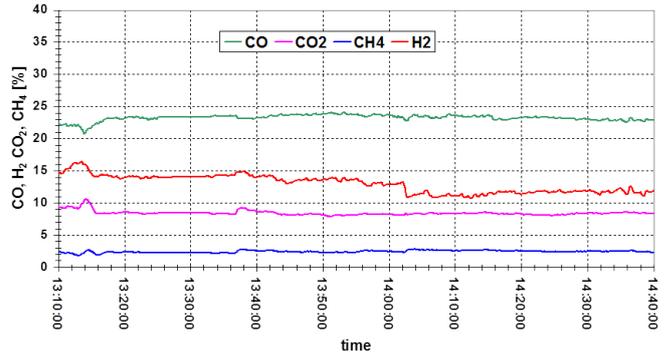


Figure 8: Syngas components time traces from the experiment

in [6]. On the other hand, in the case of hydrogen, its share is lower (15.05%) than was predicted in the simulation (24.09%). Of the non-combustible syngas components, only  $\text{CO}_2$  was measured. Its level is also lower (9.3%) than the value obtained from the numerical simulation (13.0%). Many factors could account for these differences. However, in light of the discussions above, it was decided to observe the effect of the equivalence ratio on the gas composition. The simulation was performed for the same biomass flow rate and the installation structure, with the internal heat exchanger. The variable parameter in the calculation was the inlet air flow rate in the range from 2.3 to 5 g/s. The results presenting the gas composition (volumetric rates) vs. air flow rate are shown in Fig. 9. As can be seen, the shape of the curves is quite similar to that presented in Fig. 5. For  $V_a = 3.8$  g/s the share of  $\text{CO}$  peaks (27.7%) and  $\text{H}_2$  is 10.0%. The results for equilibrium modelling corresponding to those in column 3 (Table 2) are shown on the graph by a vertical thin line. The air flow rate is  $V_a = 2.85$  g/s in this case. Shifting the operation point of the generator by supplying more air leads to a rise in  $\text{CO}$  and a drop in  $\text{H}_2$ . For  $V_a = 3.3$  g/s (dashed line in Fig. 8), we obtain a gas composition similar to the experimental data.

A precise comparison can be performed on the basis of the data in columns 4 and 5 (Table 2). Bearing in mind that the actual operation of the gas generator depends on many factors, it can be assumed that one of the reasons for discrepancies with the initial calculation results may be the amount of air supplying the gasifier and hence the equivalence ratio. The correctness of the conclusions will be reviewed dur-

Table 2: Simulation results

	IPSEPro I	Experiment	IPSEPro II
1	3	4	5
Biomass moisture, %	20	20	20
Bed temperature, °C		≈800	
Syngas outlet temperature, °C	385	380	
Syngas temp. before blower, °C	40	36	
Syngas flux, g/s	5.06		
Syngas LHV, MJ/m <sup>3</sup>	4.503	5.2	
Air mass flux, g/s	2.85		3.3
Syngas composition—volum., %			
CH <sub>4</sub>	1.8	2.2	0.5
CO	17.3	22.2	23
CO <sub>2</sub>	13.0	9.3	5.9
H <sub>2</sub>	24.9	15.05	17.8
H <sub>2</sub> O	8.7		
H <sub>2</sub> S	1.1		1.0
N <sub>2</sub>	33.3		35.1

ing field tests of the installation, to be done at a later date.

## 5. Conclusion

The paper discusses the operation of a cogeneration plant equipped with a downdraft gasifier. Based on the literature data as well as the researchers' own experience, it was shown that syngas composition depends on many factors, including gasifier design, chemical composition of the fuel, moisture and operation parameters. The most important is the air flow rate, which controls the degree of combustion by influencing the equivalence ratio and superficial velocity of air penetrating biomass. It was shown that by changing the air flow rate it is possible to control the gasification process and to change the gas composition. Another finding of the analysis performed in the paper is a demonstration of the possibility of using gas composition for the diagnostics of the gasifier operation.

It was also demonstrated that complementing the gasifier design with an internal air/gas exchanger makes it possible to increase the efficiency of the gasification process and thus increase the gas lower heating value. The correctness of the conclusions

will be reviewed during field tests of the installation, to be done at a later date.

## Acknowledgement

The work was prepared under the strategic program of scientific research and experimental development of the National (Polish) Centre for Research and Development: "Advanced Technologies for Energy Generation"; Task 4."Elaboration of Integrated Technologies for the Production of Fuels and Energy from Biomass as well as from Agricultural and other Waste Materials".

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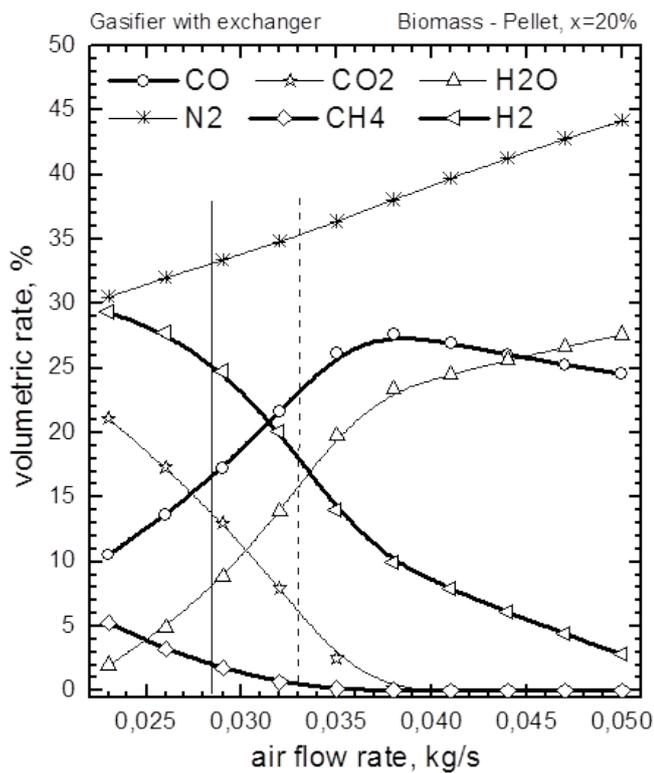


Figure 9: Syngas composition versus air flow rate

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