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A CO-GENERATION POWER SET WITH A COMBUSTION ENGINE FUELLED BY WOOD WASTE GAS

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Abstract

This paper presents a concept and a technical analysis of a co-generation power set with a combustion engine powered by syngas produced in the process of wood waste gasification. The set is composed of a wood waste gas generator fitted with a filter system, a combustion engine, a current generator and heat exchangers. The foundations of the gasification process are described together with the most common solutions used worldwide. Moreover, the methods of adapting spark-ignition and compression-ignition engines to be powered by syngas produced in the wood waste gasification process are presented. The advantages of the presented solution and its possible applications in industry are shown. The assumed technical parameters of the set are as follows: mechanical-electrical energy – 200 kWh, heat recovered from the gasifier – 250 kWh, heat recovered from the engine – 200 kWh. The concept and design of the module cogeneration set is the effect of actions taken by the Institute of Automobiles and Internal Combustion Engines and by the Institute of Thermal Power Engineering of the Cracow University of Technology.

Keywords: *biomass, combined heat and power (CHP) plant, wood gasification, renewable energy sources, internal combustion engine*

1. Introduction

Actions are now being carried out in connection with the European Union energy policy to increase the share of energy obtained from renewable sources and clean power-engineering technologies. Moreover, diversification of energy sources has become an issue of great importance [1]. Renewable energy sources are more and more widely used within new technological solutions currently applied for the purposes of electricity generation. One of such directions is the use of fuels of vegetal or animal origin. However, using such fuels to generate energy meets with strong opposition voiced by global organizations fighting famine [2]. Due to that, the European Union has issued a directive that recommends that renewable fuels of the second generation, i.e. fuels made from products of vegetal origin, should be used for power generation only if they cannot be used as food. One of such products is wood waste. The effect of the implementation of the act on renewable energy sources (RES) is that the use of wood waste for multi-fuel combustion, including co-firing with coal, will become unprofitable on a big scale [3]. Consequently, a large amount of wood processing waste will appear on the market to be utilized.

One of the methods of utilization of the waste from mechanical processing of wood is to use it to produce wood waste gas. The gas may then be used to power a combustion engine [4-6]. Wood gasification can be classed as a clean fuel technology based on the closed circulation of CO_2 in nature.

An engine powered in this way will be the driving force for a current generator. At the same time, heat will be recovered from the exhaust gas, syngas and coolants. This will make it possible to create a combined heat and power (CHP) generation system. Moreover, the ash arising from the gasification process may be used in the chemical industry, or as a fertilizer.

2. Wood waste biomass gasification

Gasification is a process of a solid fuel thermal conversion into a combustible gas, which is accompanied by a reducing atmosphere being the effect of feeding an oxidizer in amounts not smaller than required for complete combustion of the substance. The most common oxidizers are oxygen (contained in air or as a homogeneous gas), carbon dioxide or steam. The product of the gasification process is syngas with a relatively low calorific value. The gas is mainly composed of carbon oxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), other gases classed as hydrocarbons and nitrogen (N_2). The content of individual gases depends on the applied gasification technology. The fuel produced in the process can be used directly for combustion, or to make other fuels, e.g. liquid ones [7-12].

Depending on the type of the oxidizer fed into the process, it is possible to obtain syngas with a different calorific value. The ranges of the calorific value are listed in Tab. 1.

Tab. 1. Syngas calorific value [10]

Process type	Oxidizer	Obtained gas calorific value $[MJ/m_N^3]$
Direct gasification	Air	4-7
Gasification in pure oxygen	Oxygen	10-12
Indirect gasification	Steam	15-20

The biomass (including wood biomass) gasification process gives very good results. The content of oxygen in the obtained syngas is not too high. In biomass, the oxygen content is usually included in the range of 30-60% by mass. If the calorific value is determined using empirical formulae, the oxidizer content in fuel contributes to a decrease in the obtained result. Due to that, one of the reasons why the idea of biomass gasification is worthwhile is the opportunity to increase the fuel calorific value.

The gasification process may be divided into several essential stages [7, 8, 10]:

- the material preheating and drying in a bed,
- pyrolysis,
- combustion,
- reduction.

The first stage consists of reducing the content of moisture of the gasification process feed. In the case of biomass, the moisture content drops by 20-50%, which takes place in the temperature of up to 300°C. The arising steam may participate in the reaction during the next stages of biomass convers C ion into syngas.

When drying is completed, the pyrolysis process begins – the thermal decomposition of biomass proceeds in a substantial shortage of oxygen. The minimum temperature for pyrolysis to start is about 225°C. However, the process efficiency rises abruptly only after the temperature of 400-500°C is reached. Volatile fractions, gases that are not subject to condensation in the syngas cooling process, tar substances and porous structures with a large content of carbon are released at this stage. The produced gaseous substances are composed mainly of CO, CO_2, H_2 and short hydrocarbon chains – methane in the first place.

The following reactions occur between gases and solid substances during pyrolysis:

- reaction between carbon and oxygen:

$$C+\frac{1}{2}O_2 \leftrightarrow CO, \tag{1}$$

- Boudouard reaction:

$$C+CO_2 \leftrightarrow 2CO, \tag{2}$$

– reaction between carbon and water:

$$C + H_2O \leftrightarrow H_2 + CO, \tag{3}$$

– reaction of hydrocarbon formation:

$$C + 2H_2 \leftrightarrow CH_4. \tag{4}$$

The reaction between carbon and oxygen (1) is exothermic and produces 110 MJ·kmol^{-1} of heat. Reaction (4) also gives energy that can be used for drying and in Reactions (2) an (3), which are endothermic and which require a supply of heat: 172.4 MJ·kmol^{-1} in the case of the Boudouard reaction and 131.3 MJ·kmol^{-1} or Reaction (3) between carbon and water [8].

The volatile fractions released during pyrolysis take part in the reactions between the gaseous substances. The process occurs during the entire period of the residence of gases in the high-temperature zone. Of many reactions, the following have the biggest impact on the final composition of the produced gas:

– the exchange-taking place between water and carbon oxide:

$$CO + H_2O \leftrightarrow CO_2 + H_2, \tag{5}$$

– methanation:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O. \tag{6}$$

Reactions (5) and (6) have a substantial effect on the input fuel calorific value due to the produced hydrogen and methane. Moreover, the processes are exothermic and in the case of Reaction (5) and Reaction (6) give up to 41.1 MJ·kmol^{-1} and up to 206.1 MJ·kmol^{-1} of heat, respectively.

The gasification process efficiency relates to two states of the gas: the cold and the hot state. The factor of efficiency related to a cold gas is expressed by the ratio of chemical energy contained in the syngas to the chemical energy of the fuel used in the gasification process. The quantity mentioned above is included in the range of 60-80%. The process efficiency for hot gases is described in a similar way, but the enthalpy related to the produced gas initial temperature is added to its chemical energy. In this case, the process efficiency factor is included in the range of 80-95%.

Another index of the process efficiency is the degree of conversion of carbon contained in the gasified substance. For typical gasification processes, the carbon conversion degree is included between 60 and 99%.

Gasification methods are usually categorized due to the technique of heat supply and the technology of gasification. Heat can be supplied [8, 10]:

– directly – the heat supplied to the reactor comes from combustion of 20-30% of fuel,
– indirectly – the supplied heat comes from an external source.

Another division can be made due to the technical solutions adopted in generators and the applied technology of the process:

– fixed-bed gasification,
– fluidized-bed gasification,
– jet reactors.

Fixed-bed gas generators are characterized by a high temperature of the process (even higher than 1200°C), a large temperature gradient in the bed and the occurrence of characteristic zones (of preheating, drying, carbonization, gasification and combustion). The downside of this solution is that the produced gas contains tar substances, which necessitates the use of purification installations.

In fluidized-bed reactors, the oxidizer is the fluidizing medium. This solution creates the possibility of maintaining a constant temperature in the entire volume in the range of 700-900°C. Gas generators of this type make it possible to construct high-power devices characterized by a large contact area between the oxidizer and the feed particles. This results in stabilization of the gas parameters, such as its composition and temperature. Moreover, the bed may be fed with additives bonding tar substances. As a result, the obtained gas does not require complex purification systems. The disadvantage is the high concentration of dusts, which involves the need to use often multi-stage systems of cyclones. Keeping appropriate control of the velocities of flowing gases to ensure the fluidization process efficiency poses another difficulty.

3. Technical assumptions of the module cogeneration set

It is assumed that the module cogeneration set will use systems and assemblies for wood gasification, current generators with a combustion engine and heat exchangers currently available on the market. In order to achieve the target – the CHP plant optimum energy efficiency – it is necessary to adapt the gasification system to cooperate with a combustion engine as well as possible. The device most favourable operating parameters have to be established, i.e. the optimum fuel feed and the appropriate nature of the process need to be selected to achieve the gas parameters that will ensure the combustion engine best performance. Moreover, the produced gas purification system and the hot wood waste gas heat recovery systems have to be optimized. A buffer system storing the gas fuel for the engine is necessary in the installation to ensure a steady supply of the driving unit. The buffer system will make it possible to use the optimum parameters of the gasification system operation.

A combustion engine driving a 200 kW current generator is anticipated in the local module cogeneration set fired with wood waste from a wood processing plant (e.g. a sawmill). The temperature of the gas leaving the gasifier will be 300-500°C, and the temperature of the engine exhaust gases – 300-700°C. Therefore, two heat exchangers are anticipated to allow the recovery of about 450 kW of heat.

Such a solution will make it possible to use generated electricity locally by the plant where the cogeneration set is installed. A part of the recovered heat will be used to dry wood waste intended for gasification; the rest will satisfy the plant own needs.

Such sets can potentially be applied in wood processing plants, e.g. in sawmills. The solution makes industrial plants independent of external supplies of heat and electricity. It also means diversification of energy sources and an improvement in the reliability of local power networks. Moreover, the problem of industrial waste recycling is solved.

Additionally, owing to its relatively small fuel requirements and the module structure, the gasification system can easily be installed in a place where there is a sudden short-term rise in demand for heat and electricity.

4. Design of the module cogeneration set

The module cogeneration set (Fig. 1) is made of the following elements:

– Gasifier – to produce wood waste gas. The fuel is fed in the form of pieces of wood with the size of at least 2×2 mm, which may be wood briquettes or chips resulting from technological wood processing.
– Centrifugal cyclone – intended for mechanical purification of the wood waste gas leaving the gasifier.
– Heat exchanger – to recover a part of the wood waste gas heat. The gas leaving the gasifier will have the temperature of 300-500°C. This will make it possible to recover about 250 kWh.
– Scrubber – to thoroughly purify the obtained wood waste gas.
– Buffer fuel tank – to ensure the required amount of fuel – gas. The combustion engine fuel consumption per hour is not constant as it changes almost linearly with variations in the load. The current generator loads can vary too. Therefore, the buffer tank is absolutely necessary in the system.

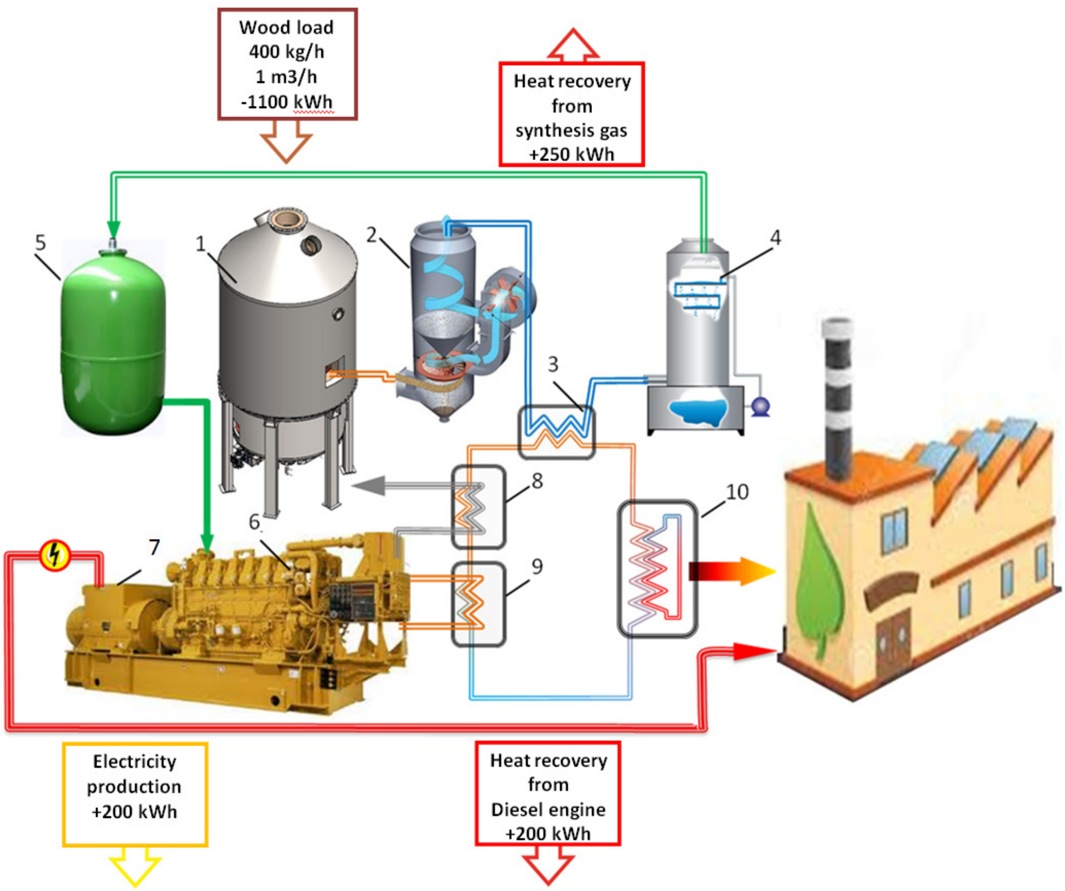

Fig. 1. Diagram of the module cogeneration set with an engine powered by wood waste gas: 1 – wood gasification installation, 2 – gas purification system (cyclone), 3 – wood waste gas heat exchanger, 4 – scrubber, 5 – wood waste gas buffer tank, 6 – combustion engine with the supply system, 7 – current generator with a control system, 8 – heat exchanger cooling the engine exhaust gases, 9 – engine cooling system heat recovery exchanger, 10 – plant main heat exchanger

Tab. 2. Basic assumed technical parameters of a CHP plant fired with wood waste gas

Parameter		Amount
Feed (wood) mass flow Feed volume flow		400 kg/h 1 m^3/h
Feed energy		–1100 kWh
Wood waste gas heat recovery		+250 kWh
Mechanical ~ electrical energy		+200 kWh
Combustion engine heat recovery		+200 kWh
Efficiency of heat recovery		> 75%
Efficiency of the entire cycle		75%
Feed wood size		min. 2×2 mm
Wood required moisture		15-20%
Wood waste gas composition	CO	20%
	H_2	10%
	CH_4	4%
	N_2	52%
	CO_2	14%
Wood waste gas temperature before cyclone and scrubber		300-500°C
Wood waste gas calorific value		6 MJ/Nm^3

- Combustion engine – to drive the current generator. A 200 kW natural gas combustion engine requires both structural changes and determination of new optimum regulation parameters – the ignition advance and the excess air factor mainly – to ensure the same power output using wood waste gas. The wood waste gas calorific value is almost 6 times smaller compared to natural gas.
- Heat exchanger for the engine exhaust gases – for partial recovery of the heat carried with exhaust gases. Naturally, the bigger the engine load, the higher the exhaust gas temperature; for the maximum torque it is slightly higher than 700°C. In this case, the heat exchanger should ensure the collection of about 200 kW of heat.
- Current generator with the nominal power of 200 kW.

5. Adapting a combustion engine to be powered by gas

An internal combustion reciprocating engine manufactured to be powered by gas has a slightly different structure compared to a conventional combustion engine powered by a liquid fuel. Essential differences result from the type of the engine – whether it is going to be a spark-ignition device with a quantitative power control or a compression-ignition one with a qualitative power control. Only four-stroke engines are used for energy-related reasons and because their emissions of the exhaust gas toxic components are smaller compared to two-stroke devices.

Gas-powered compression-ignition engines are dual-fuel structures. The gas ignition source is droplets of injected diesel oil. In consequence, the structure of the supply system in such engines is much more complex compared to spark-ignition engines. Compression-ignition engines are less commonly used even though they ensure better energy parameters than spark-ignition engines.

A natural-gas spark-ignition engine is usually powered alternatively by gas or petrol. Therefore, two parallel supply systems exist in it. In the simplest solution, the part of the carburettor in a gas-fuelled engine is played by a mixer being a functional counterpart of the elementary carburettor. The structure of a spark-ignition engine mixer is usually based on that of a factory-made carburettor modified by mounting a special fixture supplying the gas down ducts placed in the choke zone. A technically more advanced solution is interference with the structure of the carburettor itself – the gas is fed directly into the carburettor choke. The main advantage of this solution is the possibility of using the gas fuel under a low pressure (slight partial vacuum occurs after the mixer). This is an essential feature of this supply system (the mixer) in the case of producing a gas fuel, which (due to the applied gas generation technology) is naturally not compressed. The use of a mixer-based supply system is a typical example of a quantitative control of the engine power. In turbo-supercharged engines, the mixer must of course be placed before the compressor. However, this solution, like the carburettor in earlier SI engines, is not flawless. Regardless of the shape and length of the inlet passages (or wave phenomena), the same mixer prepares the gas-air mixture for all cylinders. This obviously has a negative effect on the ignition and combustion phenomena occurring later on, as they proceed in a slightly different manner in each cylinder of the engine. A different value of indicated pressure in each cylinder has an unfavourable impact on the mean indicated pressure value of the entire driving unit.

To a large extent, a gas-powered engine equipped with a multi-point injection (MPI) system has no such faults. In modern driving units, fuel injectors open synchronously, at the right moment of the crankshaft turn, in a manner oriented with respect to the piston top dead centre (TDC). Owing to that, the process of the fuel supply, mixing with air, ignition and combustion is more repeatable in each cylinder of the engine and proceeds under greater control than in the case of a mixer-based system [13-18]. In addition, the engine power control is different. Fuel proportioning (the time when injectors are open) and changes in the position of the air throttle correspond to changes in the engine load. Therefore, the engine power is controlled both qualitatively and quantitatively. However, in order to ensure correct operation of electromagnetically controlled nozzles, this system requires a gas fuel that is fed under a much higher pressure (about 5 bar) compared to the mixer-based system. At a constant rotational speed of the combustion engine, which is the case for a current generator, a rise in the load and the increasing dose of the fuel-gas related thereto require a longer time of the injector opening. So that the process of supplying fuel to the cylinder should not end too late, leading to delayed combustion and a drop in thermal efficiency, an appropriately higher pressure of the gas injection has to be applied compared to the supply system using a mixer.

In gas-fuelled spark-ignition engines, combustion anomalies may occur in the form of misfiring, knock combustion or backfiring into the suction manifold. This can be prevented mainly by appropriate adjustment of the mixture composition and the ignition timing. The bigger the ignition advance, the higher the danger of an excessive rise in the propagation velocity of the working medium pressure wave front. On the other hand, due to the drop in the engine thermal efficiency and the rise in the exhaust gas temperature, the ignition lag cannot be extended at will and with impunity. Most manufacturers of mass-produced turbines (in turbo-supercharged engines) do not anticipate their operation in temperatures higher than 700°C. Therefore, even at a constant rotational speed, as the engine load rises, a precise control is necessary of the ignition advance α_{wz} and of the excess air factor λ. The task may be facilitated a bit by using knock combustion sensors to send information to the engine controller that ignition has to be delayed. Nevertheless, in practical operation of the combustion engine, even if it is equipped with a synchronous MPI fuel supply system, the effect of the fluctuations in combustion in the engine individual cylinders is that not all cylinders are exposed to knock combustion in the same way. By a systematic measurement of individual parameters of the operation of cylinders of a multi-cylinder unit (including the exhaust gas temperature), the ignition advance α_{wz} and – within certain limits – the excess air factor λ can be optimized individually. The supply system with individual control of these parameters (λ, α_{wz}) has so far been the most perfect solution to the problem of a gas-powered engine fuel supply. In a way, it constitutes an equivalent to the common-rail system used in state-of-the-art compression-ignition engines. The common tank of the fuel-gas under raised pressure makes it possible, on the one hand, to avoid harmful variations in pressure before injectors as they open synchronously; on the other – it allows full control of the injection process, including the ignition advance α_{wz} and the excess air factor λ. The only "downside" of this supply system is the need to maintain an appropriately high pressure of the gas fed into the engine (~5 bar).

6. Adapting a combustion engine to be powered by wood waste gas

Based on the performed analyses and on the survey of gas engines available on the market, a MAN turbo-supercharged, 6-cylinder in-line spark-ignition engine with the cubic capacity V_{ss} = 12 dm^3 was selected.

The engine was manufactured to be powered by natural gas being a mixture of 74% of CH_4 and about 25% of CO, with a slight ~1% completion of other gases. Wood waste gas used to power a combustion engine is on average composed of 20% of carbon oxide (CO), 10% of hydrogen (H_2) and about 4% of methane (CH_4). The other 70% is a mixture of non-flammable gases (nitrogen (N_2) and carbon dioxide (CO_2)), which are a thermodynamic ballast.

Due to that, the wood waste gas calorific value is about 6 times smaller in compared to natural gas. For this reason, the combustion engine supply system needs a substantial reconstruction. Moreover, due to the different chemical composition and combustion properties of the two gases, regulation characteristics of the mixture composition (the excess air factor λ) and of the ignition advance α_{wz} need to be made and analysed. In order to perform the engine regulation characteristics and establish new, optimum values of λ and α_{wz}, a different, new programmable engine controller is needed. This will allow optimization of the real working cycle of the used combustion engine with respect to wood waste gas. The new values of the regulation parameters (λ, α_{wz}) for wood waste gas, different for different loads of the engine, need to be stored in the created engine controller in the form of a map of the engine operation. The controller will thus make it impossible to interfere with the engine regulation parameters. Using in a CHP plant an engine manufactured originally to be powered by natural gas, it is also necessary to adapt its suction manifold to the wood waste gas-air mixture and to make special fuel nozzles suitable for wood waste gas.

7. Advantages of using the module cogeneration set

The module cogeneration set with an engine powered by gas produced in the process of wood waste gasification makes an industrial plant independent of external supplies of heat and electricity. A device like this will generate electrical energy (in this case – about 200 kW) and thermal energy (about 450 kW). The heat and electricity may be used to satisfy the industrial plant own needs. Biofuel of the second generation will be used for this purpose. In this case, it is a waste product from technological wood processing. Another advantage is the increase in the share of energy obtained from renewable sources and cleans power-engineering technologies. Diversification of energy sources and ensuring energy supplies where it is actually used are also important issues in the light of the European Union energy policy.

The concept and design of the module cogeneration set is the effect of actions taken by the Institute of Automobiles and Internal Combustion Engines and by the Institute of Thermal Power Engineering of the Cracow University of Technology.

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