Simulation of a process for the two-stage thermal conversion of biomass into the synthesis gas

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Abstract. The paper presents results of simulation of a process for the two-stage thermal conversion of wood biomass into the synthesis gas. The first stage of process is pyrolysis of raw materials, the second stage is cracking of volatile pyrolysis products which blown through the char at a temperature of about 1000°C. Char is a porous biomass residue with carbon content about 90%. The simulation based on the results of experimental investigations of a pilot plant with capacity up to 50 kg of raw material per hour. The main result of simulation is estimation of an energy conversion efficiency of wood biomass into synthesis gas for three different operation modes. The first mode is conversion of biomass into fuel gas and char, and the char is not further used. The second mode is the same, but char used as fuel for producing heat for own demand of the process. The third mode includes gasification of char by means of water steam, aimed to obtaining an additional yield of synthesis gas. The simulation shown, that total efficiency of power plant was 17.1% in the first mode, 22.4% in the second mode and 22.6% in the third mode.

1. Introduction

Even in the face of low prices for the traditional fuels, the problem of developing the technologies for co-production of heat and electricity based on renewable energy sources remains urgent because of the fact that world reserves of oil, gas and coal are not infinite. One of such renewable sources is biomass. The article will discuss wood biomass. About 70% of the territory of the Russia is covered with forests, which makes up about 23% of world reserves. Conversion of wood biomass into gas fuel allows efficient cogeneration by means of gas engines. The development of efficient technologies of wood waste processing is an actual problem from the point of view of environmental protection. Storing of wood waste is accompanied with emission of carbon dioxide, phenol compounds and many other harmful substances.

Pyrolysis and gasification are the most popular processes for obtaining of gas fuel from biomass. They have characteristic advantages and disadvantages. Pyrolysis is thermal decomposition of raw material, heated in the absence of an oxidant. Pyrolysis products of wood biomass are char, non-condensable gas and liquid fraction that is mixture of tar and pyrolygenous liquor. Calorific value of the non-condensable gas is relatively high (about 12–13 MJ/m³), but gas yield is very small, that determines low conversion efficiency of wood biomass into fuel gas (about 18%). The composition of gas depends on a number of process parameters, such as heating rate, temperature, reaction duration and so on.
One of the easiest and most developed methods to convert biomass into gas is air gasification. Syngas calorific value is about 2–5 MJ/m$^3$, because of high carbon dioxide and nitrogen content (up to 60%). It is too low for many types of engines with combustion chambers of high energy density. Overall efficiency of gasification gas power plant is limited to 20%. Syngas contains many undesirable sub-products, such as tars and dust which are need to be removed [1]. Oxygen and water steam are used as a gasification agent instead of air to increase a calorific value of the syngas. Such syngas contains no nitrogen and less amount of carbon dioxide. Syngas yield up to 1.3 cubic meter per kg of raw material, its calorific value is about 11 MJ/m$^3$ [2]. The simplicity of steam gasification process made it very popular. The necessity of steam generation is the main disadvantage, because of reduction of overall effectiveness. The necessity of an air separation unit for oxygen gasification causes the significantly rise in price of syngas.

Two-stage process eliminates the main disadvantages of pyrolysis and air gasification. Its idea is that gas yield increases due to the cracking of volatile pyrolysis products on the char at the temperature about 1000$^\circ$C [3]. The final products of the process are carbon monoxide and hydrogen as well as porous char with carbon content about 90%, which is residue of wood biomass after heating. Produced gas contains no tar due to their complete decomposition during blowing through a porous char at high temperature. The absence of the liquid fraction in the final products is also an advantage of the process.

2. Experimental Studies
An experimental power plant capacity up to 50 kg per hour of raw material based on the technology of two-stage thermal conversion of biomass into synthesis gas, which is using as fuel for gas-diesel power generator, was designed and tested. The scheme of biomass processing unit is shown in figure 1.

Biomass is fed to the pyrolysis reactor via a hydraulic jack. The pyrolysis reactor is a steel pipe with perforation for outlet of volatile. Biomass is gradually heated through the pipe wall to a temperature of about 600$^\circ$C. There take place pyrolysis of biomass. Char and volatile pyrolysis products are moved into the cracking reactor. The volatile pyrolysis products interact with a char heated to a temperature of about 1000$^\circ$C. Cracking of tars on the carbon surface
and formation of carbon monoxide, hydrogen and other gases are occurred. Syngas is removed from bottom of the cracking reactor through a pipeline. It is moved to the cooling-purification system (not shown). Then syngas is stored in the elastic gasholders, whence it is supplied to gas-diesel engine as needed.

The heat required for the processes of pyrolysis and cracking of volatile, is transferred through the steel wall of reactor from the combustion products of additional amount of biomass. A furnace for solid fuel combustion is shown in the scheme.

A part of char is gasified in cracking reactor. Gasification process depends on moisture content of biomass. However, this amount of moisture is not enough to gasify the char completely. An excess of char is outputted to the char storage. The combustion of an excess of char for own heat demand is considered as a way to increase the overall efficiency of the power plant. The power plant photo is shown in figure 2.

A number of thermocouples installed in the reactor at various points. Temperature control of combustion products from furnace and flow distribution of the hot combustion products by
Table 1. Experimental data.

| Parameter                                           | Dimension | Value |
|-----------------------------------------------------|-----------|-------|
| Biomass consumption for conversion into syngas      | kg/h      | 42    |
| Moisture content of biomass                         | %         | 5.6   |
| Ash content of biomass                              | %         | 0.5   |
| Low calorific value of biomass                      | MJ/kg     | 17.7  |
| Measured chemical composition of syngas:            | vol.%     |       |
| H₂                                                  |           | 50.4  |
| CO                                                  |           | 40.8  |
| CH₄                                                 |           | 0.8   |
| CO₂                                                 |           | 1.9   |
| N₂                                                  |           | 0.6   |
| Other (not identified)                              |           | 5.5   |
| Low calorific value of syngas                       | MJ/kg     | 10.7  |
| Syngas volume                                       | m³/kg     | 1.32  |
|                                                     | m³/h      | 55.6  |
| Char residue                                        | kg/kg     | 0.21  |
|                                                     | kg/h      | 8.75  |
| Biomass energy conversion efficiency                | %         | 80.3  |

means of bypass provide the certain temperature settings inside the each part of reactor. Volume of obtained syngas was measured by a flow meter. The syngas composition was measured by gas chromatograph. Gas sampling was carried out from the gas pipeline at the outlet of the biomass-processing unit.

The experimental data obtained in the pilot plant test are shown in table 1.

3. Results and Discussion
Mass balance was made based on composition of wood biomass and composition of syngas taking into account the capacity of processing unit. Estimated weight of char residue resulting from the conversion of wood biomass amounted to 0.21 kg per kg of initial biomass, which agrees well with the data obtained during the experiments.

The energy balance of the reactor is based on the sum of the combustion heats of all entering and exiting materials, heat transfer and heat loss, received from a system of hot combustion products. The specific energy consumption in the two-stage conversion process is about 4.3 MJ/kg of processed biomass. In addition there was determined the amount of biomass needed to the own heat demand.

There is a reduction of overall conversion efficiency due to incomplete conversion of the carbon contained in the biomass, which is unloaded in the form of char. There are two main ways to increase the energy efficiency of the power plant:

(i) burning of an excess of char in the furnace for the own heat demand;
(ii) complete gasification of an excess of char by means of water steam.

The developed model describes energy and mass balance and allows estimating the parameters of biomass processing unit for both cases.

The simulation data are shown in table 2.
Table 2. The simulation data for three cases: the experimental data ("0"), burning of the char for the own heat demand ("1"), complete gasification of char by means of water steam ("2").

| Parameter                                      | Dimension | "0" | "1"   | "2"  |
|------------------------------------------------|-----------|-----|-------|------|
| Biomass consumption for conversion into syngas | kg/h      | 42  | 42    | 28   |
| Biomass consumption for the own heat demand    | kg/h      | 16.0| 1.8   | 17.1 |
| Power consumption for the own demand           | kW        | 1.0 | 1.15  | 1.0  |
| Low calorific value of syngas                  | MJ/kg     | 10.7| 10.7  | 11.2 |
| Syngas volume                                  | m³/kg     | 1.32| 1.32  | 1.93 |
| char residue                                   | kg/kg     | 0.21| 0.21  | 0.005|
| Char consumption for own heat demand           | kg/h      | 8.75| 8.75  | 0.14 |
| Specific water steam consumption†              | kg/kg     | —   | —     | 0.223|
| Conversion unit efficiency                      | %         | 58.2| 77.0  | 76.3 |
| Electrical efficiency of gas engine power unit | %         | 30  | 30    | 30   |
| Electrical power output                        | kW        | 48.7| 48.6  | 49.6 |
| Total electrical efficiency                    | %         | 17.1| 22.6  | 22.4 |
| Total efficiency in cogeneration mode‡         | %         | 52.2| 68.9  | 68.3 |

† for gasification of the char residue
‡ electricity and heat

In the first case, the biomass consumption for combustion in the furnace becomes less and so the efficiency of the entire plant is raised. In the second case, there is a significant increase in gas yield per kilogram of processed biomass, which can reduce by about one-third the amount of biomass, which need to be loaded into the reactor to produce the same amount of gas.

The implementation of any of the suggested ways will significantly raise the overall energy conversion efficiency of power plant. Furthermore, optimization of the gas-diesel engine for operation on the syngas will further increase the overall efficiency.

The research showed that the syngas produced by a two-stage thermal conversion of biomass could be also used as a feedstock for the synthesis of liquid fuels because of the high content of carbon monoxide and hydrogen in approximately equal proportions (synthesis gas). Due to the low content of sulfur and nitrogen in the raw material (biomass), synthesis gas almost not contains compounds of nitrogen and sulfur in its composition. The final purification of synthesis gas up to the desired parameters (about several ppm) of sulfur and nitrogen compounds will allow to synthesize liquid fuel, which will conform to the required standards [4].

4. Conclusions
Experimental investigations of two-stage process of thermal conversion have shown that wood biomass can be used for obtaining tarless mid-calorific syngas. The experimental power plant capacity up to 50 kg of raw material per hour, combined with a gas-diesel engine with an electric generator of 50 kW was designed and tested. The simulations based on experimental data shown, that total efficiency of power plant can be raised from 17.1% up to 22.4% by means of water steam gasification of char residue and up to 22.6% by means of combustion of the char residue for the own heat demand. The syngas obtained by means of developed technology also can be used for the synthesis of liquid fuels.
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