Modelling of the developed system for wood waste gasification

A A Aizyzan¹, A V Fedyukhin¹, K V Strogonov¹, E L Shaburov²*, S A Kravchenko², N B Kirillov², N V Nikitkov², Yu M Pankratov² and T R Akhmetov³

¹National Research University "Moscow Power Engineering Institute", Krasnokazarmennaya 14, Moscow, 111250 Russia.
²Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation
³Kazan State Power Engineering University, Kazan, Russian Federation

* Corresponding author: shel7439245@mail.ru

Abstract. The aim of this work is mathematical modelling of the developed technological scheme of the combined-cycle gas generator unit. An efficient technological scheme for gasification of wood waste with electricity generation is proposed in the paper. Mathematical modelling of the developed biomass gasification scheme was carried out. The payback period of the proposed combined-cycle plant with gas generator is calculated.

Keywords: combined-cycle gas generator, mathematical modelling.

1. Introduction
During gasification, biomass usually includes wood materials, waste from logging and woodworking industries, agricultural organic waste from plant growing and animal husbandry, and agricultural processing industries [1-6]. Plant biomass is considered one of the most "noble" types of fuel and in many countries is considered as a promising source of energy for the near future. The annual reproducible potential of biomass is estimated to be 10 times higher than world mineral production. However, the availability and economic feasibility of using different types of biomass is different [7-11].

One of the main problems in regions with sufficient forest resource base is the inefficient use of wood waste. A huge amount of waste, representing valuable raw materials, remains unused. For their disposal large financial costs are consumed.

Recycling of wood waste shows a high energy potential for supply of industry and utilities, as well as economic potential.

2. The developed system for biomass gasification
Figure 1 shows the basic scheme of a combined-cycle plant based on biomass gasification [12]. Dried biomass and vapor-air mixture under pressure of 20 atm are fed into the fluidized bed gas generator. Gasification produces generating gas. Before being supplied to the gas turbine unit, the generator gas is subjected to cleaning from dust and ash in the filter. Exhaust gases after the gas turbine are sent to the waste-heat boiler, in which superheated steam is produced.
The paper proposes a technological scheme for biomass gasification with a combined-cycle plant (Figure 2). The principle of operation of the scheme is similar to the basic scheme. Advantages of the developed scheme are the following:

- An increase in the energy efficiency of the circuit due to a decrease in energy consumption for own needs (absence of drying unit and additional air compressor for gas generator);
- Heating of compressed air in a new gas generator 4;
- Obtaining a certain pressure in the developed gas generator using an ejector 6.

Figure 1. Gas-steam plant based on biomass gasification (basic scheme):
1 - gasifier, 2 - cyclone, 3 - booster compressor, 4 - air compressor, 5 - combustion chamber of gas turbine, 6 - gas turbine, 7 - generator, 8 - waste heat boiler, 9 - steam turbine, 10 - heat extraction, 11 - condenser, 12 - feed pump, 13 - condensation heat exchanger, 14 - separator, 15 - drying drum

Figure 2. The developed technological scheme of the combined-cycle plant with a gas generator:
1 - biomass; 2 - crusher; 3 - crushed biomass; 4 - circulating fluidized bed gas generator with a heat exchanger; 5 - ash; 6 - ejector; 7 - generating gas; 8 - cold air; 9 - compressed air; 10 - compressor; 11 - combustion chamber; 12 - gas turbine; 13 - waste gases; 14 - waste heat boiler; 15 - feedwater; 16 - flue gases; 17 - superheated steam; 18 - steam turbine; 19 - generator.
An efficient circulating fluidized bed gas generator with a heat exchanger (Figure 3) has been developed.

**Figure 3.** The developed scheme of the circulating fluidized bed gas generator with a heat exchanger:
1 - biomass;
2 - feeder;
3 - gasification zone;
4 - a layer of fuel;
5 - ash;
6 - ejector;
7 - superheated steam;
8 - heat exchanger;
9 - compressed air;
10 - cyclone dust collector;
11 - generator gas.

The features of the proposed gas generator are the following:
- The use of physical heat of the generator gas 11 in the heat exchanger 8;
- Increase of pressure of compressed air 9 in the ejector 6 using superheated steam 7;
- Cleaning of the generator gas from dust and ash in a vertical cyclone dust collector 10;
- Reduction of carbon loss in the fluidized bed due to recycling of captured particles of dust and ash.

3. Mathematical modeling of the developed system for biomass gasification

To assess the energy potential of the products of thermal conversion of wood waste, one can apply a mathematical model, which with sufficient accuracy allows one to perform the calculation without additional experimental research. The main results of such a simulation will be the composition, volume, and calorific value of the combustible gas at the outlet of the reactor.

To calculate the developed gas generator we took:
- Pressure in the gas generator \( p = 27 \text{ atm} \);
- Air flow coefficient \( \alpha = 0.3 \);
- The amount of superheated steam \( \mu = 0.2 \text{ kg/kg of biomass} \).

Assumption: all carbon enters the gasification process due to recirculation in the gas generator, ash leaves the gas generator with the temperature of the generating gas. The calculation was carried out in the Mathcad 15 software environment according to the method [13].

Table 1 presents the composition of wood waste per dry mass.

| Sample     | C, %   | H, %   | O, %   | N, %   | S, %   | A, %   | W, % | \( Q^0_p \), MJ/kg |
|------------|--------|--------|--------|--------|--------|--------|------|---------------------|
| Wood waste | 49.75  | 6      | 43     | 0.5    | 0.05   | 0.7    | 10   | 16.3                |

Knowing the composition of biomass and the main thermal parameters of gasification, a calculation was made on the basis of the equation of the material and heat balance of the gas generator, as a result of which we obtained:
- Heat of combustion of generator gas \( Q_{bc} = 5016.4 \text{ kJ/m}^3 \);
- Temperature of generator gas \( t = 843^\circ\text{C} \);
- Volume output of generator gas \( V_{gg} = 2.7 \text{ m}^3/\text{kg} \);
- Composition of generator gas (Table 2):
Table 2. Composition of gasification products of wood waste.

| Components | CH4 | CO | H2 | CO2 | H2O | N2 | SO2 |
|------------|-----|----|----|-----|-----|----|-----|
| %          | 1.79| 17.74| 19.78| 11.21| 13.35| 36.12| 0.01|

- Gasification efficiency: chemical is 83.81%, thermal is 97.65%.

As a result of thermal calculation of the gas turbine plant, we obtain: the electric power is 16 MW; efficiency is 36%.

The electric power of steam turbine is 8 MW, and the total electric power of the entire installation is 24 MW, while the efficiency of the combined-cycle plant is 53%.

In order to compare and verify the obtained results, mathematical modeling of the developed technological scheme for biomass gasification with a combined-cycle gas installation was carried in the Aspen Plus 8 software environment out according to the procedure [14-15] (Figure 4).

At the beginning simulation of the developed gas generator takes place, which includes:
- 5 blocks: DECOMP, MIXER, GASIF, SPLIT and TO;
- 10 material flows: BIO, STEAM, COMPAIR, IN-GASIF, AIRSTEAM, COMPAIR1, PRODUCTS, GENGAS, ASH, GEANGAS1.

At the initial stage, biomass BIO is subjected to pyrolysis in the DECOMP unit. Then, the IN-GASIF pyrolysis products are sent to the GASIF reactor, which produces the generator gas using the AIRSTEAM vapor-air mixture. Oxidizer obtained from the mixer (in Figure 2 ejector) MIXER. After thermal conversion in the GASIF reactor, the resulting generating gas is cleared of dust and ash in the SPLIT unit. At the end, purified gas GENGAS heats the compressed air COMPAIR. The heated air COMPAIR1 enters the mixer MIXER together with the superheated steam STEAM.
Figure 4. Mathematical modeling of the technological scheme for biomass gasification with gas-steam installation.

After the gas generator there is a combined-cycle plant, having the following parts in the gas turbine plant:

1) Units:
   - Compressor COMPR;
   - Combustion chamber KC;
   - Gas turbine GT;

2) Material flows:
   - Atmospheric air AIR;
- Compressed air SAIR;
- Some part of the pressed air to the combustion chamber SAIR1;
- Waste gases from the combustion chamber OG;

And in the steam turbine plant:

1) Units:
   - Pump NASOS;
   - Waste-heat boiler BOILER;
   - Steam turbine PT;

2) Material flows:
   - Feed water PV;
   - Overheated stream STEAM;
   - Spent steam STEAM1;
   - Steam for gasification STEAM2;
   - Exhaust gases UG.

Units CSPLIT and SPLIT1 allow one to separate streams. The power of compressor, gas and steam turbines is provided by the flows WORKC, WORKGT and WORKPT.

In the simulated scheme, the parameters in each flow are shown above the names: above – temperature, and below – pressure. This allows one to monitor the changes in the parameters in each stream as the source data changes.

This program allowed us to simulate the developed technological scheme.

As a result of modeling the developed scheme, we obtained the following characteristics:

- Molar consumption of generator gas components (Table 3):

\[
\begin{array}{cccccccc}
\text{Components} & \text{kmol} / \text{h} \\
\hline
\text{CH}_4 & 31.74 \\
\text{CO} & 233.84 \\
\text{H}_2 & 213.74 \\
\text{CO}_2 & 106.41 \\
\text{H}_2\text{O} & 101.55 \\
\text{N}_2 & 421.23 \\
\text{SO}_2 & 0 \\
\end{array}
\]

- Molar gas flow rate of 1108.64 kmol/h or 25807.4 kg/h;
- The electrical power of the gas turbine plant was 16.72 MW, the electrical power of the steam turbine unit was 7.08 MW and the total electrical power of the entire plant was 23.75 MW.

To assess the economic feasibility of the developed scheme of combined-cycle plant with a gas generator, we performed the calculation of the payback period and comparison with the basic scheme (table. 4).

Table 4. Molar consumption of gasification products.

| Components | CH\textsubscript{4} | CO | H\textsubscript{2} | CO\textsubscript{2} | H\textsubscript{2}O | N\textsubscript{2} | SO\textsubscript{2} |
|------------|-----------------|----|-----------------|-----------------|-----------------|----------------|----------------|
| kmol/h     | 31.74           | 233.84 | 213.74 | 106.41 | 101.55 | 421.23 | 0 |

Table 4 presents a comparison of projects construction costs. Complex equipment under the basic scheme is 4.45 billion rubles [11]. According to the proposed scheme, the cost of the gas generator is 11.9 thousand rubles/kW [16], the cost of combined-cycle plant is $ 0.8 thousand/kW [17], and other facilities for construction include the cost of crusher [18].

As a result of the economic calculation, it turns out that the proposed scheme pays off in 5 years. At the same time, the cost of generated electricity is equal to 1.88 rubles/(kW·h).

Economic calculations have shown that the payback period of the investment of a combined-cycle gas turbine unit on biomass is about 5 years, which is less than that for the project carried out according to the basic scheme, with a payback period of 7 years.
4. Conclusions
The technological scheme of the combined-cycle plant based on biomass gasification has been developed. The advantages of the proposed scheme are the following:
- An increase in energy efficiency of the circuit due to a decrease in energy consumption for own needs (absence of a drying unit and an additional air compressor for a gas generator).
- Heating of compressed air in the new gas generator 4.
- Obtaining a certain pressure in the developed gas generator using an ejector 6.

An efficient circulating fluidized-bed gas generator with a heat exchanger has been developed, in which the efficiency of gasification of biomass is increased when using the physical heat of the generator gas in the heat exchanger to heat the air.

The efficiency of the proposed scheme is more than 50% when the electric power of the installation is 24 MW.

The software environment Aspen Plus 8 allowed us to simulate the developed system of gasification of wood waste, in which the difference between the results of calculation and modeling is less than 5%.

References
[1] Huang N, Zhao P, Ghosh S, Feduykhin A 2019 Applied Energy 240 pp 882-92
[2] Smyatskaya Y, Politaeva N, Toumi A, Olshanskaya L 2018 MATEC Web of Conferences 245 8004
[3] Mankonen A, Kaikko J, Vakkilainen E, Sergeev V 2018 MATEC Web of Conferences 245 07007
[4] Maksimova Y G, Vasil’ev D M, Zorina A S, Ovechkina G V, Maksimov A Y Applied Biochemistry and Microbiology 54(2) pp 173-8
[5] Namsaraev Z B, Gotovtsev P M, Komova A V, Vasilov R G 2018 Renewable and Sustainable Energy Reviews 81 pp 625-34
[6] Sultanguzin I A, Feduykhin A V, Kurzanov S Y, Gyulmaliev A M, Stepanova T A, Tumanovsky V A, Titova D P 2015 Thermal Engineering (English translation of Teploenergetika) 62(5) A008 pp 359-64
[7] Kirpichnikov I M and Fil N S 2012 Wood waste as a renewable source for the generation of heat and electric energy Bulletin of the South Ural State University, Series: Energy 16 pp 18–21
[8] Politaeva N A, Kuznetsova T A, Smyatskaya Y A, Trukhina E V and Atamanyuk I 2018 Energy Production from Chlorella Algae Biomass Under St. Petersburg Climatic Conditions Chem. Pet. Eng. 53 pp 11–12
[9] Zhao Y, Wang L, Huang L, Maximov M Y, Jin M, Zhang Y, Wang X and Zhou G 2017 Biomass-derived oxygen and nitrogen co-doped porous carbon with hierarchical architecture as sulfur hosts for high-performance lithium/sulfur batteries Nanomaterials 7
[10] Feduykhin A, Sultanguzin I, Gyul’Maliev A and Sergeev V 2017 Biomass pyrolysis and gasification comprehensive modeling for effective power generation at combined cycle power plant Eurasian Chem. J. 19 pp 245–53
[11] Feduykhin A V 2014 Development of systems for the combined generation of heat and electrical energy based on the study of the processes of pyrolysis and gasification of biomass dis. Cand. tech. Sciences (Ivanovo: ISEU)
[12] Moscow Timiryazev Agricultural Academy Zoo Engineering Faculty [Electronic resource] URL: http://www.activestudy.info/ximicheskij-sostav-drevesiny-i-kory-xarakteristika-organicheskix-veshhestv/
[13] Popov S K and Ippolitov V A 2016 Processes and installations for gasification of fuel: textbook (Moscow: Publishing House MEI)
[14] Popov S K, Svistunov I N and Ippolitov V A 2017 Simulation of high-temperature processes and installations in the environment Aspen Plus: textbook (Moscow: Publishing House MEI)
[15] Feduykhin A V, Sultangusin I A and Kurzanov S Yu 2016 Application of applied software for solving problems of industrial heat and power engineering: a tutorial on the courses Applied Software in Heat Power Engineering, Mathematical Modeling and Optimization of Heat
Power Engineering Systems, Numerical Simulation Methods, etc. in the direction of Heat Power Engineering and Heat Engineering (Moscow: Publishing House MEI)

[16] INTERREMAH URL: http://www.adaptika.ru/
[17] The center for online auctions URL: https://www.b2b-center.ru/info/experts.html?id=4102
[18] Tiu.ru URL: https://moskva.tiu.ru/Drobilka-drevesiny.html