Development and optimization of a two-stage gasifier for heat and power production

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Abstract. The major methods of biomass thermal conversion are combustion in excess oxygen, gasification in reduced oxygen, and pyrolysis in the absence of oxygen. The end products of these methods are heat, gas, liquid and solid fuels. From the point of view of energy production, none of these methods can be considered optimal. A two-stage thermal conversion of biomass based on pyrolysis as the first stage and pyrolysis products cracking as the second stage can be considered the optimal method for energy production that allows obtaining synthesis gas consisting of hydrogen and carbon monoxide and not containing liquid or solid particles. On the base of the two stage cracking technology, there was designed an experimental power plant of electric power up to 50 kW. The power plant consists of a thermal conversion module and a gas engine power generator adapted for operation on syngas. Purposes of the work were determination of an optimal operation temperature of the thermal conversion module and an optimal mass ratio of processed biomass and charcoal in cracking chamber of the thermal conversion module. Experiments on the pyrolysis products cracking at various temperatures show that the optimum cracking temperature is equal to 1000 °C. From the results of measuring the volume of gas produced in different mass ratios of charcoal and wood biomass processed, it follows that the maximum volume of the gas in the range of the mass ratio equal to 0.5–0.6.

1. Introduction
Combustion of biomass is used for either directly produce heat or for electricity production by generating steam which is then passed through a turbine generator [1]. The disadvantages of this method are the high NO\(_x\) emissions and also non-uniform characteristics of biomass as a fuel [2].

Gasification is the partial oxidation of biomass, as a result of which it is possible to obtain the gas combustible components of which are carbon monoxide and hydrogen [3]. This gas has a low calorific value because of large amount of nitrogen in the case of air gasification. The gas obtained by oxygen or steam gasification has higher calorific value but still contains carbon dioxide in the case of oxygen gasification and water in the case of steam gasification [4]. Furthermore, these methods require complicated gas clearing of tars and solid particles [5].

The pyrolysis process, especially fast pyrolysis, aimed at obtaining liquid products. The composition and quantity of these products and the possibility of their use as a fuel have now been well studied [6]. However, pyrolysis can be used to produce synthesis gas by a secondary cracking of liquid products. The advantage of this two-stage process in comparison with air gasification is the high calorific value of gas produced due to the absence of nonflammable...
nitrogen in its composition. Another advantage of the process is its cheapness in comparison with other gasification methods, such as oxygen or steam gasification.

Such a scheme with the partial oxidation and heterogeneous cracking of tars was used in two-stage gasifier developed by the Technical University of Denmark [7]. The gasifier called “Viking” gives almost complete tar conversion (less than 15 mg/Nm$^3$). The high tar removal of this gasifier is related to passing the volatiles through a partial oxidation zone followed by a char bed.

The two-stage method of biomass gasification offered by JIHT RAS [8] differs from the Viking gasifier scheme in absence of partial oxidation; thereby it is possible to obtain the synthesis gas with the maximum calorific value. On the base of the two stage cracking technology, there was designed a pilot power plant of electric power up to 50 kW. Scheme of the pilot power plant is shown at figure 1. The power plant consists of a thermal conversion module with a capacity of feedstock is not less than 50 kg/h and a gas engine power generator adapted for operation on syngas.

The thermal conversion module uses wood chips as feedstock and is heated by the flue gases generated by the combustion of wood pellets in the pellet furnace. A piston driven by a hydraulic cylinder delivers the wood chips into pyrolysis chamber which is a tube made of high-temperature steel with inner diameter of 50 mm and a length of 2000 mm. The temperature of the pyrolysis chamber wall varies along the length from 100 to 600 °C. Moving the reactor biomass is heated without access of oxygen and pyrolyzed. Speed of movement of the biomass is adjusted by changing the frequency of movement of the hydraulic cylinder.
Pyrolysis of the biomass produces biochar and condensable and noncondensable pyrolysis products in the gaseous form. The biochar falls into the cracking chamber of the reactor where it is warmed up to a temperature of 1000 °C. Condensable and noncondensable pyrolysis gases passing through the bed of biochar in the cracking chamber are converted into synthesis gas consisting mainly of hydrogen and carbon dioxide.

Cracking process can be homogeneous or heterogeneous. Homogeneous cracking takes place in the reactor volume due to infrared radiation from the hot walls. Heterogeneous cracking takes place on the surface of any material, in our case by filtration through hot char bed.

To determine the optimum size of the cracking chamber it is necessary to investigate the processes of homogeneous and heterogeneous of the pyrolysis products cracking in the reactor volume and on the surface of char, as well as to estimate the effectiveness of both cracking processes. For these purposes there was designed an experimental set-up simulating the operation of the pilot plant.

2. Experimental set-up
The experimental set-up (figure 2) consisted of a high-temperature two-chamber fixed-bed reactor and a system of extraction and analysis of gas and vapor forming as a result of heating an initial raw material.

The reactor was a stainless steel tube with an inside diameter of about 37 mm, which was placed within a two-section furnace with independent heaters for each section. The chambers were 300 mm length each. Raw material was placed into the chamber 1. There were series of experiments with different amount of char placed and different temperatures in the chamber 2. Gas yield dynamics during pyrolysis without secondary cracking was explored with empty chamber 2 at temperature of 20 °C.

To explore homogeneous and heterogeneous cracking, the chamber 1 was heated up to temperature 1000 °C that was held further at the constant level. After that the temperature of the bottom chamber was raised at the rate 10 °C/min. Process of homogeneous cracking was explored with empty chamber 2. To explore heterogeneous cracking, char obtained by pyrolysis of the same raw material was placed in the chamber 2 and heated up to 1000 °C.

Gases formed during pyrolysis of initial raw material passed through the porous carbon bed in the chamber 2. As a result of homogeneous and heterogeneous chemical reactions in the high-temperature zone, the pyrolysis gases decomposed into synthesis gas, which came into the
volume meter (eudiometer). The samples of the gas were chromatographed. Softwood pellets were used as a raw material for pyrolysis. Carbonized softwood pellets were used as the hot char filter.

3. Results and discussion
The results of measurements of the volume gas produced per 1 kg of softwood pellets during pyrolysis and two types of tars cracking are shown at figure 3. The results indicate that the heterogeneous cracking is much more effective than homogeneous and allows obtaining the maximum volume of the gas in the same reactor. This gas volume is up to 1.5 m$^3$ per 1 kg of wood biomass.

To determine the optimum temperature of the heterogeneous cracking chamber 2 has been filled with coal, which mass is twice the mass of material in the chamber 1. A series of experiments in which the volume of the product gas is measured at various temperatures in the chamber 2 was performed. The results of measurements are shown at figure 4.

As can be seen from the above data, the amount of produced gas increases with increasing temperature in the chamber 2 and reaches the maximum at temperature of 1000 °C. Further increase of the cracking temperature does not increase the volume of the gas, indicating complete decomposition of the pyrolysis products.

The next series of experiments aimed to determine the optimal mass ratio of the initial biomass ($m_1$) and the charcoal in the chamber 2 ($m_2$). For this purpose, the temperature of the chamber 2 was kept constant at 1000 °C. The mass of material in the chamber 1 was 30 g. The mass of coal in the chamber 2 was 2.5, 5, 10, 15, 20 and 30 g. In each experiment, volume of the gas obtained at given mass ratio was measured. The results of measurements are shown at figure 5.
Figure 4. Gas yield per one kg of raw material vs cracking temperature.

Table 1. Composition of the synthesis gas produced at different coal/biomass mass ratio.

| $m_1/m_2$ | $H_2$, % | CO, % | CO$_2$, % | CH$_4$, % | N$_2$, % |
|-----------|----------|-------|-----------|-----------|---------|
| pyrolysis | 32.6     | 22.4  | 24.1      | 16.3      | 4.6     |
| 0.00      | 43.7     | 36.2  | 10.3      | 7.9       | 1.9     |
| 0.08      | 46.8     | 38.7  | 6.6       | 6.1       | 1.8     |
| 0.17      | 49.4     | 40.7  | 4.9       | 4.1       | 0.9     |
| 0.33      | 50.2     | 42.4  | 3.1       | 2.5       | 1.8     |
| 0.50      | 52.7     | 43.2  | 1.4       | 1.5       | 1.2     |
| 0.67      | 53.2     | 43.6  | 0.9       | 1.2       | 1.1     |
| 1.00      | 54.4     | 43.6  | 0.3       | 0.9       | 0.8     |

From these data it follows that at a mass of coal in the chamber 2 at half the weight of processed biomass, the amount of the product gas becomes close to the maximum, indicating the complete decomposition of pyrolysis tars. This is confirmed by the data on the composition of the synthesis gas produced at different quantities of coal in the chamber 2, as it is shown in table 1.

For the mass ratio greater than 0.5 synthesis gas composition becomes constant, that indicating complete tar decomposition. Thus, using the charcoal filter is equal to one half of initial weight of the biomass may be considered as optimal to achieve the maximum degree of decomposition of the pyrolysis products. Further increase in coal mass filter does not increase the degree of decomposition and volume of the gas.
Figure 5. Gas yield per one kg of raw material during pyrolysis and subsequent cracking of tars at different mass ratio.

4. Conclusions
From the data received it follows that heterogeneous cracking of pyrolysis tars on the surface of charcoal is more effective than homogeneous cracking in volume of the reactor and allows receiving the maximum volume of synthesis gas in the same reactor.

Maximum conversion efficiency of pyrolysis products into synthesis gas is accomplished by heterogeneous cracking at temperature of 1000 °C.

From the results of measuring the volume of gas produced in different mass ratios of charcoal and biomass processed, it is clear that it reaches the maximum in the range of the mass ratio \( m_2/m_1 \) equal to 0.5–0.6.

Acknowledgments
This work was supported by the Ministry of the Russian Federation for Education and Science (project No. 14.607.21.0134, unique identifier RFMEFI60715X0134).

References
[1] Broek R 1996 Biomass Bioenergy 11 271–281
[2] Nussbaumer T 2003 Energy Fuels 17 1510–1521
[3] Lisý M 2008 16th European Biomass Conference pp 843–849
[4] Pengmei L 2007 Renewable Energy 32 2173–2185
[5] Dury A I 2009 Chemical Engineering Transactions 18 665–670
[6] Bridgwater A 2012 Biomass Bioenergy 38 68–94
[7] Henriksen U 2006 Energy 31 1542–1553
[8] Kosov V 2013 Materials and Processes for Energy: Communicating Current Research and Technological Developments pp 393–398