The two-stage technology of biomass conversion into synthesis gas

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The most effective way to convert biomass into energy is its conversion into combustible gas. However, the existing gasification technologies have several disadvantages.

For the last several years, in the Joint Institute for High Temperatures of Russian Academy of Sciences, the two-stage technology of biomass processing has been developing [1]. The technology is based on pyrolysis of biomass as the first stage. The second stage is high-temperature conversion of liquid fraction of the pyrolysis on the surface of porous charcoal matrix. Synthesis gas consisted of carbon monoxide and hydrogen is the main products of the technology.

The results of experimental investigations of composition and quantity of incondensable gases evolving during pyrolysis of wood and peat pellets in the temperature range 200–1000 °C, as well as composition and quantity of gases forming as a result of high-temperature cracking of tars are presented. It is shown that as a result of the pyrolysis and the subsequent cracking of emanating volatile products over a charcoal at temperature 1000 °C it is possible to receive about 1.4 m³ of gas with calorific value approximately 11.7 MJ/m³ from one kg of original raw material.

Keywords: biomass conversion; pyrolysis; syngas

1. Introduction

Interest to alternative sources of energy is growing all over the world. According to analysts of the European Union the share of energy produced from renewable resources in Europe in 2020 will exceed 40% and will increase in the future [2]. This will solve the problem of Europe's energy independence and reduce the negative impact of industrial energy production on the environment.

Biomass is the largest and the most important renewable energy source in the world. World production of biomass is estimated at 150-200 billion metric tons a year [3]. Biomass includes all variety of natural organics, agricultural wastes, industrial wastes, especially forestry and wood industry, paper mills, fast-growing plants, organic part of municipal waste.

Currently biomass provides approximately 14% of the total world energy consumption. About 25% of this energy resource falls on the industrial countries, which made a significant investment in environmental protection. The other 75% of the primary energy use of biomass is used for heat production for households in developing countries. Today, the share of biomass in the energy balance of a number of developing countries had a significant value: Nepal – 94%, Kenya – 95%, India – 50%, China – 33%, Brazil – 25%, Egypt – 20% [4, 5].

Biomass is the largest source of renewable energy sources consumed in the EU. Consumption of biomass was up 13% in 2010, accounting for 69% of the total consumption of renewables. Most of this was used for power generation and in households [6].

Biomass can be converted to energy in three ways: thermal conversion, chemical conversion, and biochemical conversion. In order to use the most effective of dry biomass thermochemical technologies such as burning, gasification and pyrolysis, which in spite of its effectiveness have some disadvantages.

The simplest method of obtaining energy from biomass is its combustion. The purpose of combustion is getting considerable amount of heat without any other commercial products. The flame temperature during the biomass combustion is between 800 to 1650 °C. Heat of reaction is from 16 to 24 MJ/kg of dried biomass depending on its type [7]. When the amount of oxygen is not enough for complete oxidation of combustible material, there is formation of carbon monoxide, hydrocarbons and other gases, and the heat of reaction decreases.

An important condition for complete combustion of fuel is its preparation, usually drying and pelletizing. In addition to the heat, combustion products are carbon dioxide, water, products of incomplete combustion which are most pollutants, and ash. All of this creates major problems for use of biomass as a source of heat in the industry.

Gasification is the most effective way to convert biomass is its conversion into combustible gas. However, the existing technologies of biomass gasification have several disadvantages. Air gasification is the easiest method to convert biomass into the gas. However, the resulting gas contains up to 60% nitrogen and 40% carbon dioxide. The calorific value of the gas is generally around 4–5 MJ/m³, which is too low for efficient use. Overall efficiency of gasification gas power plant is limited to 20% [8].

Oxygen and steam gasification allow increasing the calorific value of the gas which contains no nitrogen and a small amount of carbon dioxide. The maximum gas yield reaches 1.3 m³ per kg of raw material and its calorific value is about 11 MJ/m³ [9]. Steam gasification is the widespread process because of its simplicity. The main disadvantage of the process is concerned with necessity of steam generation, which reduces overall effectiveness of power plant. Use of oxygen for the purpose of gasification demands an air separation unit in technological chain that leads to rise in price of
the end product. It should also be noted that purification of the gas from tar and ash is an urgent problem for all methods of gasification.

Along with combustion and gasification, pyrolysis is an effective method of thermochemical processing of biomass, industrial and domestic waste and at the same time one of the least-developed technologies of bioenergy. Pyrolysis is the of thermal decomposition process organics without oxygen. It runs at relatively low temperatures (500–800 °C) as compared with the processes of gasification (800–1300 °C) and combustion (900–2000 °C).

Pyrolysis technology can produce gaseous, liquid and solid products [10]. Modern technologies of pyrolysis are focused to obtain a liquid product, so-called pyrolysis oil. Pyrolysis oil is a thick black tarry liquid close in composition to the biomass, and consists of a complex mixture of hydrocarbons with substantial water content (up to 30%) and having a calorific value of about 20 MJ/kg [11]. Pyrolysis oil theoretically can be used directly as a fuel, but its wide use as a furnace fuel or motor requires more complex processing technology. In addition, the pyrolysis products can be toxic and corrosive.

Increase in efficiency of the conversion of biomass into combustible gas can be achieved by combining of known methods with modern technologies. For the last several years, in the Joint Institute for High Temperatures of Russian Academy of Sciences, the two-stage technology of biomass processing has been developing. The technology is close to the scheme offered in [12] for processing of wood sawdust, and based on pyrolysis of biomass as the first stage. The second stage is high-temperature conversion of liquid fraction of the pyrolysis on the surface of porous charcoal matrix. Synthesis gas consisted from carbon monoxide and hydrogen is the main products of the technology. Our experiments have shown a significant increase of the volume of gas in the outlet of the reactor due to decomposition of condensable and non-condensable pyrolysis products. In comparison to pyrolysis, the volume of gas increased nearly 10 times at cracking temperature 1000 °C. At this temperature, the gas consists almost entirely of hydrogen and carbon monoxide in approximately equal parts in the zone of maximum gas release.

2. Experimental set-up

The experimental set-up (Figure 1) 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 two-section furnace with independent heaters for each section. The chambers were 300 mm length each. Raw material was placed into the bottom chamber. Char obtained by pyrolysis of the same raw material was placed in the top chamber. The depth of char bed was equal to 50 mm. Before experiments the top chamber 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.

Pyrolysis gases formed during pyrolysis of initial raw material passed through the porous carbon bed with the fixed temperature. As a result of homogeneous and heterogeneous chemical reactions in the high-temperature zone, a
decomposition of pyrolysis gases took place. Conversion degree depended both on the temperature in the top chamber and on the residence time in a high-temperature zone. Non-condensable gas came into the volume meter (eudiometer). The samples of the gas were chromatographed. Wood and peat pellets were used as initial raw material. Humidity of the samples was 6% and 10% for wood and peat respectively.

An additional set of experiments in which the top chamber of reactor was not heated up and was free of char were fulfilled. Comparison of the composition and the quantity of the gases formed at presence and absence of the char in the top chamber of the reactor gave the opportunity to compare efficiency of conversion of initial raw material into combustible gas under two considered regimes.

3. Experimental results and discussion

The results of chromatography of composition of the gases evolved during pyrolysis of peat pellets in the temperature range 100–1000 °C at the heating rate 10 °C/min are shown in Figure 2. During this series of experiments the top chamber of reactor was not heated up and was empty. Note that methane constituted the main part in the hydrocarbon mixture C\textsubscript{n}H\textsubscript{m}. From the data one can see that at temperature above 500 °C the carbon dioxide content substantially decreased whereas the content of combustible gases (methane, hydrogen and carbon monoxide) increased that led to increase of the calorific value of the product gas mixture. The overall gas yield was equal to 0.29 m\textsuperscript{3} per kg of initial raw material. The lower calorific value of product gas was equal to Q\textsubscript{ll} = 9.6 MJ/m\textsuperscript{3}. Extraction of the gas evolved in the temperature range 500–1000 °C (in accordance with data presented in Figure 2) leads to the appreciable increase of the calorific value of product gas up to 13 MJ/m\textsuperscript{3} but the gas yield decreases to 0.18 m\textsuperscript{3} per kg of initial raw materials.

![Figure 2](image_url)

**Fig.2** Gas yield per one kg of raw material during thermal processing of peat pellets vs. temperature of the bottom chamber for different regimes

Figure 3 shows the measurement gas volume per 1 kg of initial raw material produced during heating wood pellets (temperature T\textsubscript{1}) at the bottom chamber of the reactor at different fixed temperatures T\textsubscript{2} of the upper portion of the reactor. The same figure shows similar data obtained when pyrolysis without cracking of volatiles (the upper chamber is empty and T\textsubscript{2} = T\textsubscript{1}) took place.
From the presented data it follows that with increasing temperature in the upper chamber of the reactor the volume of gases increases. Simultaneously there is reduction of the liquid fraction.

At temperature $T_2 = 1000 \, ^\circ C$ the liquid fraction is absent that indicates its full conversion to the gas. Thus, during filtration of pyrolysis gases and vapours through the char bed there are not only the decomposition of high-molecular organic compounds, which under normal pyrolysis condense as tars, but the interaction of tars and water with the char resulting in the formation of hydrogen and carbon monoxide. This is confirmed by the loss of carbon mass balance in the upper chamber of the reactor. The mass of char formed in the bottom chamber did not depend on the temperature in the top chamber and was about 30% for peat pellets and 20% for wood pellets. Moreover it should be noticed that pyrolysis was characterized by linear dependence of gas yield on temperature in opposite of cracking scheme when the main volume of gas generated in the temperature range 250–500 $^\circ C$ that corresponded to the temperature range of liquid fraction formation during pyrolysis.

Figure 4 shows the results of chromatography of the gas composition during heating of the bottom chamber at two temperatures of the top chamber $T_2$. One can see that carbon dioxide and methane content in output gas decreased with the rise of temperature $T_2$. For temperature $T_2 = 1000 \, ^\circ C$ the content of carbon dioxide and methane didn’t exceed one percent. Temperature increase in the top chamber leads to disoxidation of CO$_2$ and heterogeneous pyrolysis of methane. It should be noticed that for the top chamber temperature $T_2 = 1000 \, ^\circ C$ the gas composition practically does not depend on the bottom chamber temperature at its changing in the range 250–500 $^\circ C$, i.e. in the main gas release area (Figure 3).

**Fig. 4 Composition of output gas at different temperatures of the top chamber**
Calorific values of the gas mixtures obtained by thermal processing of wood and peat pellets were calculated on the base of experimental data. Table 1 and Table 2 show content of the gas mixture obtained by thermal processing of peat and wood at different temperatures of the top chamber and their high and low calorific values.

**Table 1** Composition and calorific values of gas mixtures obtained from peat pellets

<table>
<thead>
<tr>
<th>$T_2$, °С</th>
<th>Volume fractions of combustible components</th>
<th>Calorific value, MJ/m³</th>
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<tbody>
<tr>
<td></td>
<td>$H_2$</td>
<td>CO</td>
</tr>
<tr>
<td>850</td>
<td>0.40</td>
<td>0.27</td>
</tr>
<tr>
<td>950</td>
<td>0.43</td>
<td>0.40</td>
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<tr>
<td>1000</td>
<td>0.49</td>
<td>0.41</td>
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</tbody>
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**Table 2** Composition and calorific values of gas mixtures obtained from wood pellets

<table>
<thead>
<tr>
<th>$T_2$, °С</th>
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</tr>
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<tbody>
<tr>
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<tr>
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<td>1000</td>
<td>0.46</td>
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</table>

Figure 5 shows dependence of high and low calorific value of gas mixtures obtained from one kilogram of wood and peat pellets as function of the bottom chamber temperature.

![Fig.5](image)

**Fig.5** Calorific value of the gas obtained per one kg of raw material by thermal conversion of liquid fraction of the pyrolysis

It is shown that the calorific value of gas mixture obtained by wood pellets processing exceeds the calorific value of gas mixture obtained by peat pellets processing to a very slight degree. Moreover the area of calorific value fast rise is quite narrower for the wood pellets than for the peat pellets. Other parts of the curves look very similar.

### 4. Implementation of the technology

The proposed technology of thermal conversion of biomass allows to create an autonomous source of heat and power based on cheap local bio-materials. In this case the main target product of the technology is synthesis gas to be used as fuel for autonomous energy complex based on the gas-piston engine. Schematic diagram of the energy complex is shown in Figure 6.
The main difference between the proposed scheme and known schemes of biomass gasification is principle of two-stage processing, including pyrolysis of the raw material and subsequent cracking of volatile pyrolysis products to produce the synthesis gas to be used as fuel gas.

5. Conclusions

The two-stage technology of various kinds biomass processing by pyrolysis and cracking of volatiles allows to produce synthesis gas with a calorific value of about 11 MJ/m$^3$. Conversion of volatile pyrolysis products allows significantly increase efficiency of existing technologies of thermal processing of biomass. Experimental data show the influence of regime parameters of the process on the composition and volume of gas mixtures. As a result of the pyrolysis and the subsequent cracking of pyrolysis volatile products it is possible to obtain up to 1.4 m$^3$ of synthesis gas consists of hydrogen and carbon monoxide in substantially equal parts.

References


