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Two-Stage Pyrolytic Conversion of Biomass

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Abstract

The widespread adoption of biomass as an energy fuel is hindered by a number of its significant drawbacks, such as low heating value, low ash melting point, low bulk density etc. Technological solutions that allow to fully overcome these shortcomings and ensure high economic performance have not yet been proposed, although there is a significant demand for them. A new technology for thermal processing of biomass into gas fuel, based on the pyrolysis process, has been developed at the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS). The degree of energy conversion of the processed raw materials in the proposed technology is about 75%. The gas fuel yield is $\sim$1.3 m^3/kg of biomass, and its heating value, on average, is 11 MJ/m^3. The content of the liquid phase in the energy gas obtained by the developed technology is not more than 50 mg/m^3. The gas produced by the technology under consideration on average consists of 90% hydrogen and carbon monoxide. According to existing standards, this gas can be used as a fuel for mini-CHP with gas-piston engines. A promising direction for using this gas is the production of liquid motor fuels.

Keywords: synthesis gas, pyrolysis, biomass processing, two-stage thermal conversion process, liquid fuel, biochar

1. Introduction

The development of distributed generation and the gradual decline in the share of traditional hydrocarbon energy sources in the global energy balance are sustainable trends of the 21st century. The decision to gradually refuse fossil fuels made by world's leading economies is caused by depletion of deposits cheap in the exploitation. The desire to reduce the environmental burden and to improve the energy security through the use of local energy resources also matters. Biomass has a number of advantages over other types of renewable energy resources as an alternative to fossil hydrocarbons (availability, all-seasonality), which is directly reflected in its contribution to energy production: 12.4% of world consumption in 2017 [1]. However, biomass also has a number of obvious disadvantages: low specific heating value, high hygroscopicity, low bulk density. Some types of

biomass are characterized by a low ash melting point, which makes it difficult for direct combustion in industrial plants. In addition, one of the most economically efficient way of converting thermal energy from solid biomass combustion into electrical energy for power plants with a capacity of less than 2 MW is the use of turbine CHP operating according to the Rankine cycle using a low-boiling coolant (ORC) and having an electrical efficiency of no more than 18% [2]. All these disadvantages can be largely overcome by converting biomass into liquid or gaseous fuels [3, 4]. Gasification is one of the most efficient and commercially viable methods of such processing used in industry today [5, 6]. At the same time, syngas obtained in air-blown gasifier is, firstly, strongly ballasted with nitrogen, which leads to a significant decrease in its higher heating value (4–6 MJ/m^3), and secondly, it contains a significant amount of high molecular weight organic compounds (the so-called "tar") [7]. With oxygen or steam gasification, which makes it possible to increase the heating value of the resulting gas mixture, an air separation unit or a steam generator must be provided in the technological chain, which leads to a significant increase in the cost of the final product. As concerned tar there are rather severe restrictions on its content in the gas mixtures receiving by biomass gasification and using as gaseous fuel. Presence of tar leads to fouling process equipments such as internal combustion engines and turbines. Various methods of tar removal are used both directly at the gasification stage and at the stage of purification of the resulting gas mixtures [8, 9]. The need for gas cleaning and its high cost are among the obstacles to the widespread introduction of gasification technologies.

A two-stage pyrolytic conversion is proposed as a method for producing pure mid-calorific synthesis gas. Two-stage pyrolytic conversion is a process that combines pyrolysis and subsequent high-temperature heterogeneous cracking of volatiles on biomass coke (**Figure 1**). As a result of this conversion, a high efficiency of energy conversion of raw materials (more than 70%) is achieved in comparison with conventional pyrolysis and gasification. In addition, a sufficiently high heating value of the resulting gas is provided (11–12 MJ/m^3) due to a decrease in the proportion of non-combustible components (for example, nitrogen, which is an integral component of the gas mixture obtained during air gasification).

The idea of using heterogeneous cracking as an additional stage in the processing of biomass into gaseous fuel in order to reduce the tar content was expressed in [10] and, later, was developed and used in the works of the Joint Institute for High Temperatures RAS (JIHT RAS) [11, 12] in relation to processing of wood, peat and straw. Similar approach was also implemented in the Viking gasifier developed at the Danish Technical University [13]. The proposed technology of two-stage pyrolytic conversion differs from the process implemented by "Viking" due to the absence of an oxidant supply to the reactor, which allows achieving the maximum heating value of the obtained synthesis gas. In the works of JIHT RAS, which will be discussed below, the process of converting biomass into gas was completely allothermal – the heat necessary for its implementation came from outside.

This chapter provides an overview of the results obtained in laboratory conditions for justification of the new technology conversion of biomass into synthesis gas and a description and characteristics of a pilot plant implementing the technology under consideration. The chapter has been designed so that the reader can get a comprehensive understanding of the two-stage pyrolytic conversion process, its effectiveness, features of practical realization and possible applications:

- Section 2 explains the nature of the process and contains recommendations regarding the selection of the main operating parameters noted in **Figure 1**.

- Section 3 contains characteristics of synthesis gas obtained by the method of two-stage pyrolytic conversion from 6 different types of biomass, as well as
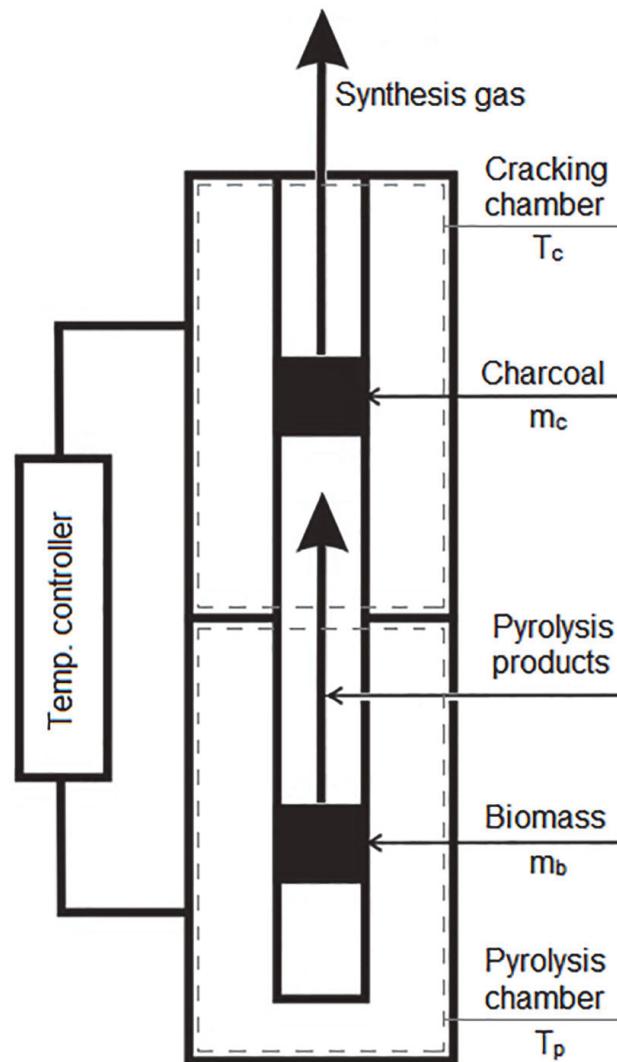
Figure 1.
Schematic diagram of the two-stage pyrolytic conversion process. T_p – Temperature in the pyrolysis chamber; T_c – Temperature in the cracking chamber; m_b – Mass of feedstock loaded into the reactor; m_c – Mass of charcoal loaded into the cracking chamber.

characteristics of product gas obtained from the same types of biomass by the method of traditional pyrolysis.

• Section 4 contains a description of the pilot installation for two-stage pyrolytic conversion, designed and built at the Joint Institute for High Temperatures RAS, and the characteristics of the gas produced by it. The section also includes an assessment of the energy efficiency of this installation and an analysis of technical solutions that can improve the efficiency of its operation.

• Section 5 describes the possible applications of gas produced by the two-stage pyrolytic conversion method.

2. Features of the two-stage pyrolytic conversion process and recommended operating parameters

2.1 The mass ratio of the coke residue in the cracking zone and the initial biomass

The condensing fraction of the pyrolysis products of woody biomass is a complex mixture of pyrogenetic moisture, acetic, formic and lactic acids, methanol,

furfural, levoglucosan, compounds of various classes (aldehydes, ketones, esters), etc. [14]. Heating pyrolysis products when passing through a porous coke residue leads to thermal decomposition of high-molecular substances (heterogeneous cracking), mainly with the formation of carbon monoxide and hydrogen. In addition, non-condensable pyrolysis products and pyrogenetic moisture vapor interact with the carbon of the coke residue with the formation of CO and H_2, which leads to a decrease in the mass of the coke residue. Obviously, the ratio of the masses of the feedstock and coke residue fed into the reactor of two-stage pyrolytic conversion should affect the yield of conversion products. The influence of this ratio was studied in detail experimentally by the authors in [15] for coniferous wood pellets, while in [16] later studies for dry oak sawdust are also included. The results of these experiments are shown in **Figure 2**. In both cases, the heating rate in the pyrolysis zone was 10 °C/min until the temperature reached 1000 °C.

The points in **Figure 2** correspond to the experimental data, while the lines are plotted by approximation. In accordance with the experimental results, the maximum yield of non-condensable gases in both cases corresponds to the mass ratio of the coke residue and the biomass sample m_c/m_b = 0.67. This ratio can be considered optimal for the given experimental conditions. With an increase in the rate of the feedstock heating, the optimal ratio m_c/m_b increases due to an increase of the mass flow rate of volatiles through the coke residue, and with a decrease in the rate of heating, it decreases. It is important to note that the weight loss of the coke residue in the experiments did not exceed some dozens of percent of the newly formed residue mass; therefore, the use of heterogeneous cracking does not require additional costs for the production or purchase of the coke residue.

2.2 The temperatures in the pyrolysis and cracking zones

In biomass processing by the two-stage pyrolytic conversion method, the first stage is conventional pyrolysis. The main change in the mass of raw materials and an increase in the volume of non-condensable gases formed as a result of the process occurs at a temperature in the pyrolysis zone T_p = 250–500 °C, corresponding to the range of formation of the liquid fraction [17]. However, T_p = 700 °C can be chosen
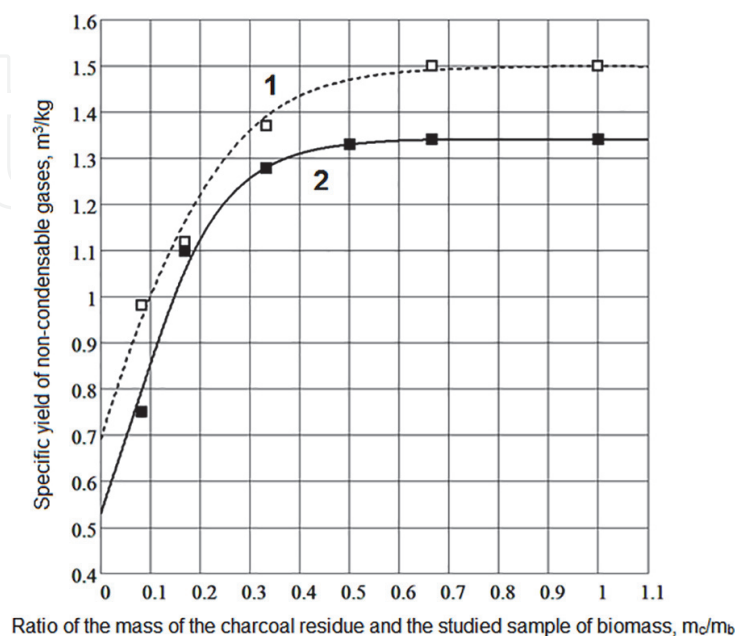

Figure 2.
Dependence of the specific yield of non-condensable gases (m^3/kg) on the ratio of the mass of the charcoal residue and the studied sample of biomass (m_c/m_b) for pellets from coniferous wood (1) and oak sawdust (2).

as the maximum pyrolysis temperature, which, according to [18], is the upper temperature limit for the formation of primary tar. With further heating, the formation of tar does not occur due to thermal destruction of biomass, but only from primary tar.

The dependence of the specific yield of non-condensable product gases on the temperature in the pyrolysis zone for woody biomass is shown in **Figure 3**.

In the process of two-stage conversion when the biomass pyrolysis stage is carried out in the temperature range of T_p = 250–500 °C, formation of gas has two main mechanisms: decomposition of vapors of condensable high-molecular compounds and three reactions proceeding in the forward direction:

$$C + H_2O \leftrightarrow CO + H_2; \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2; \tag{2}$$

$$C + CO_2 \leftrightarrow 2CO; \tag{3}$$

where (Eq. (1)) is the reaction of steam gasification of carbon on the coke residue, (Eq. (2)) is the water-gas shift reaction, (Eq. (3)) is the Boudouard reaction. In the temperature range of T_p = 500–700 °C, a further, relatively small increase in the volume of produced gases occurs, mainly due to the release of hydrogen from the carbonized feedstock in the pyrolysis zone.

The temperature in the cracking zone significantly affects the yield of non-condensable gases. Of greatest interest is temperature T_c = 1000 °C, since it was shown in [12] that at a temperature of T_c = 1000 °C and an interaction time of about 4 seconds in the cracking zone, almost complete conversion of condensing pyrolysis products into gas occurs, and CO_2 is almost completely converted to CO due to the developed surface and high reactivity of the coke residue. The experimentally obtained dependences of the yield of non-condensable gases on the temperature in the pyrolysis zone for different temperatures in the cracking zone [17] are shown in **Figure 4**. It can be seen from the figure that with an increase in T_c from 850 °C to 950 °C the increase of the gas yield is 0.285 m³/kg, and with an increase in T_c from 950 °C to 1000 °C the volume of produced non-condensable gases is increased by another 0.227 m³/kg. At the same time, as the temperature in the cracking zone
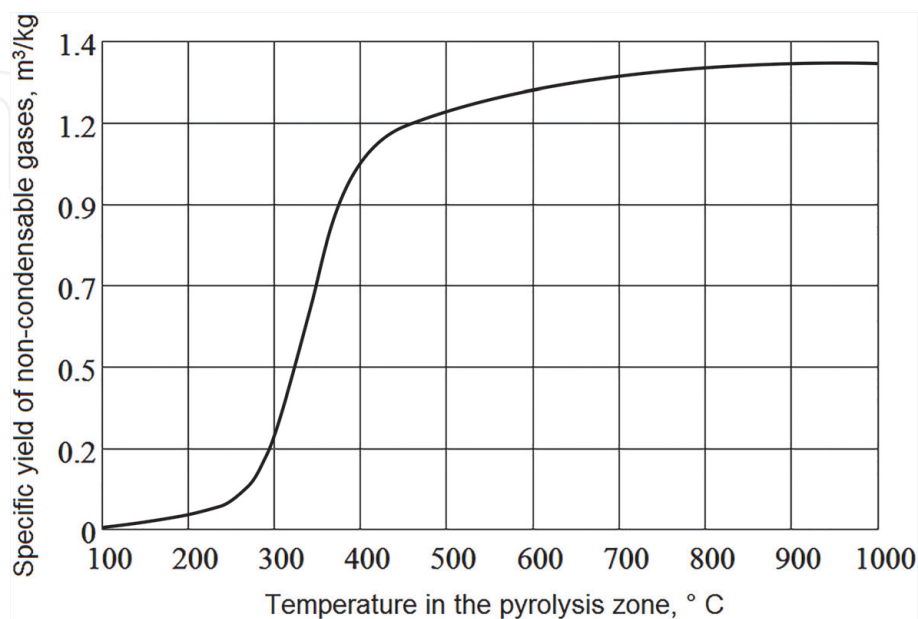

Figure 3.
Dependence of the specific yield of non-condensable gases (m³/kg) on the temperature in the pyrolysis zone at a fixed temperature in the cracking zone T_c = 1000 °C.
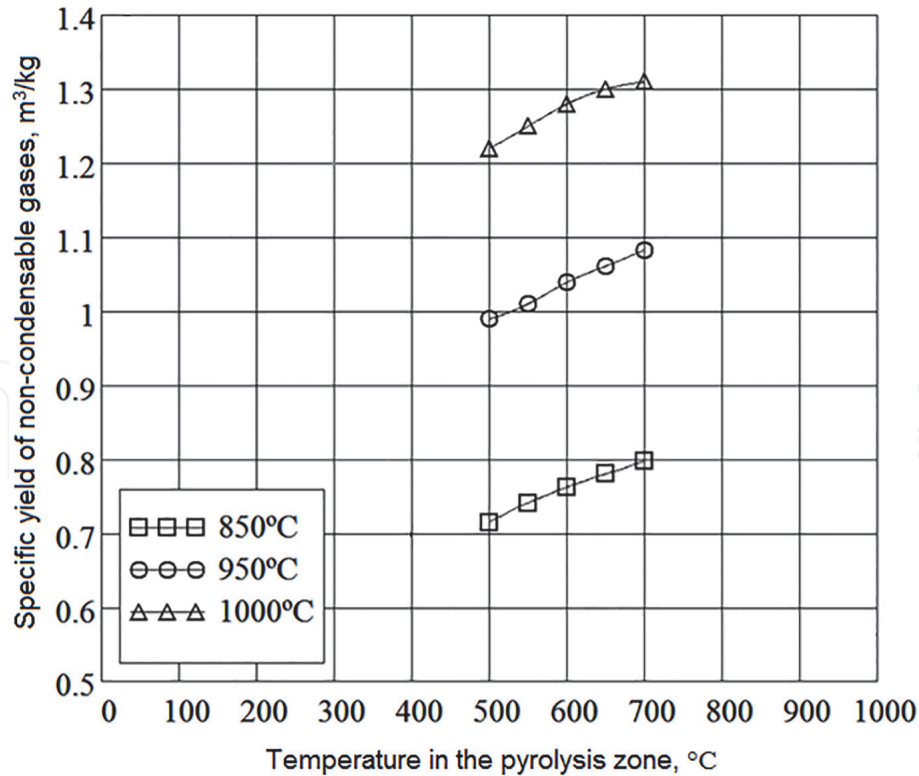
Figure 4.
Specific yield of non-condensable gases for different temperatures in the cracking zone (850 °C, 950 °C, 1000 °C) depending on the temperature in the pyrolysis zone.
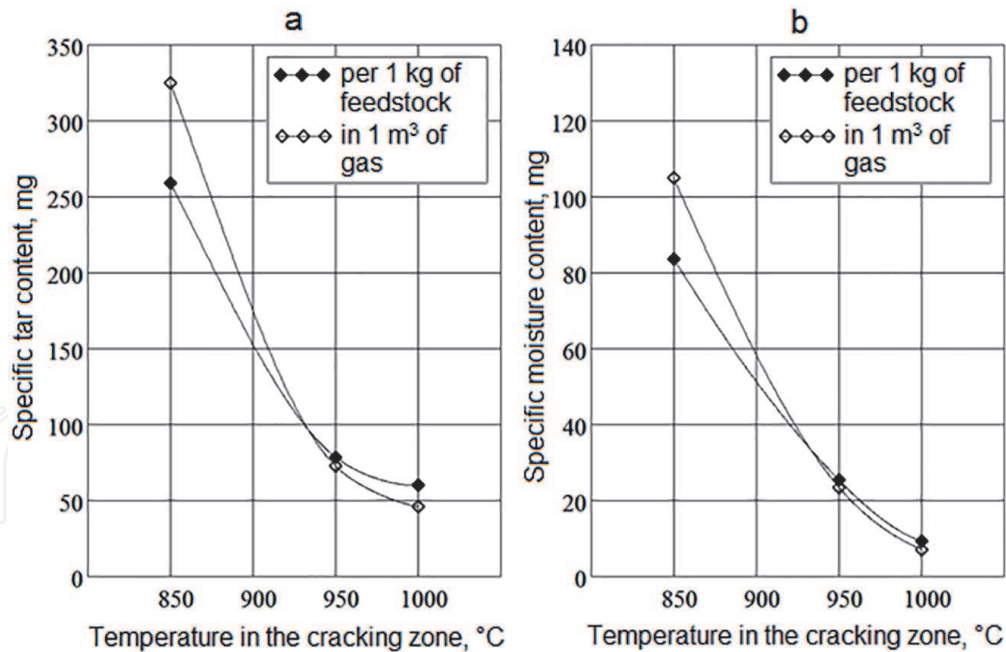

Figure 5.
Dependences of the specific content of tar (a) and moisture (b) in gas on temperature in the cracking zone T_c.

rises, a decrease in the content of tar and moisture in the resulting synthesis gas is also observed (**Figure 5**).

The tar content is an important characteristic of synthesis gas, since it largely determines the possibility of its use in internal combustion engines. The issue of the maximum permissible tar content remains controversial due to the small number of tests on engines operating on gas contaminated with tars. However, most of the authors of the works cited in [19] agree that a specific tar content of less than 100 mg/m³ is acceptable, and less than 50 mg/m³ is preferable for long-term engine

operation. Based on the dependences shown in **Figure 5**, it can be concluded that the content of tar in the gas obtained by the method of two-stage pyrolytic conversion will correspond to the permissible and preferable values in modes with $T_c \geq 930$ °C and $T_c \geq 985$ °C, respectively.

3. Characteristics of the synthesis gas obtained from various types of biomass and comparison of two-stage pyrolytic conversion with conventional pyrolysis

The process characteristics described in the previous section are derived from experiments carried out on woody biomass. However, the possibilities of processing other types of biomass are of great interest. This section is devoted to a brief description of the results of experiments on processing by the method of two-stage pyrolytic conversion of six types of biomass: wood pellets, peat pellets, straw pellets, sunflower husk pellets, pellets from poultry litter and wastewater sludge (WWS). These results are presented in more detail in [20].

Table 1 shows the characteristics of the considered types of biomass. The data on the elemental composition of pellets from sunflower husks were borrowed from [21].

The experimental setup had structure corresponding to the diagram shown in **Figure 1**. During the experiments, the temperature in the pyrolysis section gradually increased to 1000 °C with a heating rate of 10 °C/min. The temperature in the cracking section was 1000 °C during the entire experiment, and the time of passage of pyrolysis vapors and gases through it was no less than 4 s. The characteristics of the synthesis gas obtained as a result of a series of experiments are shown in **Table 2**. It should be noted that the synthesis gas obtained during the processing of wastewater sludge contains the largest amount of hydrogen, which makes this type of waste the most suitable raw material for the subsequent production of synthetic aviation fuel.

To compare the two-stage pyrolytic conversion with conventional pyrolysis, a series of experiments in which the temperature inside the cracking did not exceed 100 °C was carried out. Thus, the treatment was reduced to conventional pyrolysis. The characteristics of the gas mixture obtained as a result of these experiments are presented in **Table 3**.

Raw material	Moisture, wt %	Ash cont., wt %	Volatile fraction, wt %	Elemental composition, wt %					Higher heating value, MJ/kg	
		dry state		dry ash-free state						
	W	A	M_{vp}	C	H	N	O	S	Q_H^{exp}	Q_H^{cal}
Wood pellets	8.0	0.8	83.6	50.3	6.0	0.4	43.3	<0.05	20.6	19.8
Peat pellets	8.0	3.3	64.1	55.7	6.9	1.7	35.7	<0.05	21.9	23.6
Straw pellets	6.0	6.8	79.4	47.8	6.2	0.6	45.4	<0.05	19.6	19.0
Sunflower husk pellets	7.4	6.4	79.1	51.7	6.3		42.0		21.4	20.8
Litter pellets	16	13.8	82.6	48.0	6.4	5.9	39.0	0.7	20.4	20.1
WWS	2.7	22.7	89.1	51.7	7.5	8.5	26.0	1.5	25.0	25.9

Table 1.
Characteristics of the raw materials. The 'exp' index denotes the experimentally measured heating value, while the 'cal' index denotes the value obtained by calculation on the base of elemental composition data.

	Raw material		Wood pellets	Peat pellets	Straw pellets	Sunflower husk pellets	Litter pellets	WWS
Syngas yield m³/kg	exp	Initial state	1.39	1.39	1.35	1.39	1.3	1.04
		Dry ash-free state	1.3	1.34	1.37	1.39	1.25	1.29
	cal	Dry ash free state	1.28	1.29	1.33	1.29	1.31	1.27
Volume fraction of combustible components	H_2		0.46	0.49	0.4	0.43	0.46	0.53
	CO		0.46	0.41	0.38	0.37	0.37	0.27
	C_nH_m		0.00	0.01	0.00	0.00	0.01	0.05
Heating value, MJ/m³	higher		11.7	11.8	9.9	10.2	10.9	12.2
	lower		10.8	10.8	9.1	9.3	10.0	10.9
Energy conversion degree			0.74	0.72	0.69	0.66	0.67	0.63
Adiabatic temperature of combustion, °C			2040	2030	2000	2010	2020	1970
Crackling section filter			Wood charcoal	Carbon residue from peat pyrolysis	Carbon residue from straw pyrolysis	Carbon residue from sunflower husk pyrolysis	Wood charcoal	Wood charcoal

Table 2.
Characteristics of synthesis gas obtained by two-stage pyrolytic processing from different types of biomass.

Raw material		Wood pellets	Peat pellets	Straw pellets	Sunflower husk pellets	Litter pellets	WWS
Syngas yield, m³/kg (exp)	Initial state	0.26	0.29	0.26	0.38	0.26	0.22
	Dry ash-free state	0.28	0.33	0.30	0.44	0.36	0.29
Volume fraction of combustible components	H_2	0.28	0.23	0.20	0.18	0.20	0.24
	CO	0.26	0.19	0.17	0.16	0.23	0.07
	C_nH_m	0.16	0.13	0.11	0.09	0.06	0.18
Heating value, MJ/m³	higher	13.2	10.5	9.1	7.9	7.8	11.1
	lower	12.0	9.5	8.2	7.2	7.2	9.9
Energy conversion degree		0.18	0.16	0.14	0.16	0.14	0.13
Adiabatic temperature of combustion, °C		1860	1730	1720	1640	1710	1770

Table 3.
Characteristics of product gas obtained in conventional pyrolysis from different types of biomass.

Comparison of conventional pyrolysis with two-stage pyrolytic conversion in terms of the generated gas volume and the degree of energy conversion is shown in **Figure 6**. It is important to note that the degree of energy conversion was estimated exclusively for gaseous pyrolysis products.

From the presented data, it follows that the method of two-stage pyrolytic conversion makes it possible to efficiently process biomass of various types into synthesis gas with a calorific value of about 10–12 MJ/m³. The gas productivity of the process is several times higher than the gas productivity of conventional
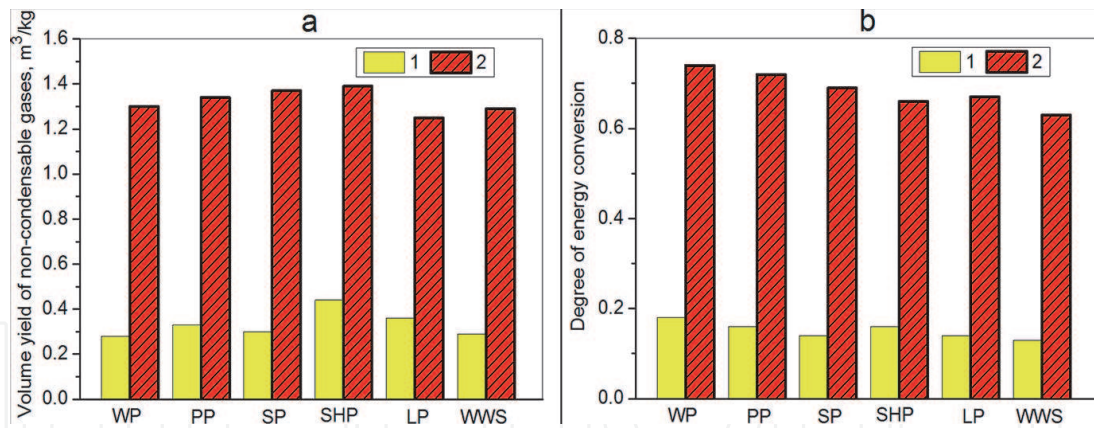
Figure 6.
Volume yield of gas per 1 kg of combustible mass of the feedstock (a) and the degree of energy conversion (b) at conventional (1) and two-stage pyrolytic processing (2) of different types of biomass: WP – Wood pellets, PP – Peat pellets, SP – Straw pellets, SHP – Sunflower husk pellets, LP – Litter pellets.

pyrolysis. The ratio of volume contents of hydrogen to carbon monoxide in the produced synthesis gas varies from 1:1 to 1:2 depending on the type of biomass. Moreover, the synthesis gas does not contain volatile pyrolysis products of high molecular weight, which makes this fuel cleaner than pyrolytic.

4. An experimental installation for the implementation of the two-stage pyrolytic conversion process and the results of its testing

Figure 7 shows a schematic diagram of a two-stage pyrolytic conversion module designed at the JIHT RAS.

The thermochemical conversion module operates in the following way. Wood biomass (sawdust, shavings) from the feedstock storage is fed in portions to the pyrolysis reactor using a reciprocating piston; the role of the lift mechanism is performed by a hydraulic cylinder connected to the pumping station through a hydraulic valve with electromagnetic control. At the entrance to the pyrolysis reactor, the biomass is compacted under the action of the force applied from the piston,
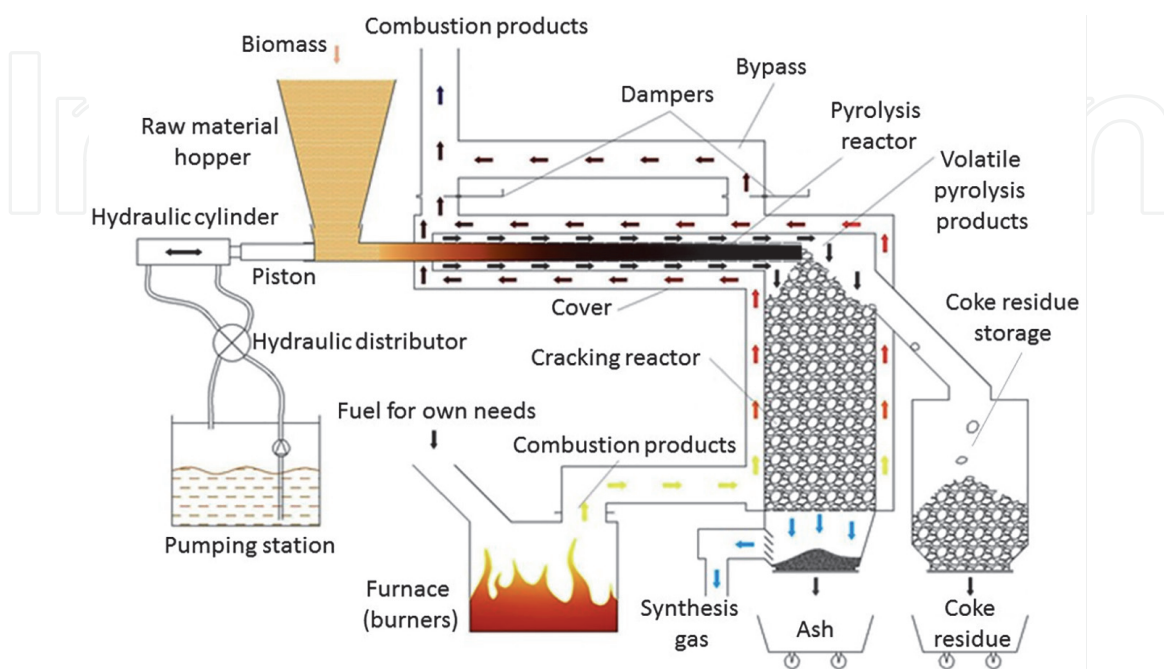

Figure 7.
Schematic diagram of a two-stage pyrolytic biomass conversion module.

creating an air-tight briquette that prevents the release of gaseous products to the outside, and then, in the form of a compressed briquette, moves through the pyrolysis reactor due to the arrival of new portions. Heat is supplied to the compacted biomass through the wall from the hot combustion products formed in the furnace or burner. To ensure the supply of the amount of thermal energy required to maintain the conversion process, any available fuel is burned, for example, natural gas or propane (used in experiments on separate modules of the installation), the initial biomass or coke residue of the processed biomass. In the pyrolysis reactor, the biomass is gradually warmed up to a temperature of about 500–700 °C, accompanied by the release of volatiles, which, through perforation in the wall of the pyrolysis reactor, enter the gas collectors, along which they move into a vertically located retort filled with coke residue of the processed biomass - a cracking reactor. The temperature of the coke residue in the cracking reactor can be maintained by supplying heat through the wall from the combustion products at a level of 1000 °C. Pyrolysis gases and vapors pass through a fixed high-temperature layer of coke residue, in which gases and high-molecular compounds (including tar) are converted into synthesis gas, which is then removed for cleaning, cooling and further use. As a result of chemical reactions, the coke residue in the cracking reactor is consumed, but is constantly replenished with coke residue coming from the pyrolysis reactor. The mass loss of coke residue in the cracking reactor is less than the mass of the newly formed coke residue. Therefore, a coke storage is provided in the thermochemical reactor, which can be periodically unloaded. The excess of the resulting coke residue can be used both in the process itself (to provide for own needs in thermal energy), and for other purposes. The outer casing of the thermochemical conversion module has a bypass and dampers that allow regulating the flow of combustion products in the pyrolysis zone, thereby ensuring the ability to maintain the required reactor temperature.

The pilot installation for two-stage pyrolytic conversion was implemented as a structure of 4 modules. The scheme of the module and the photograph of the installation are shown in **Figure 8**.
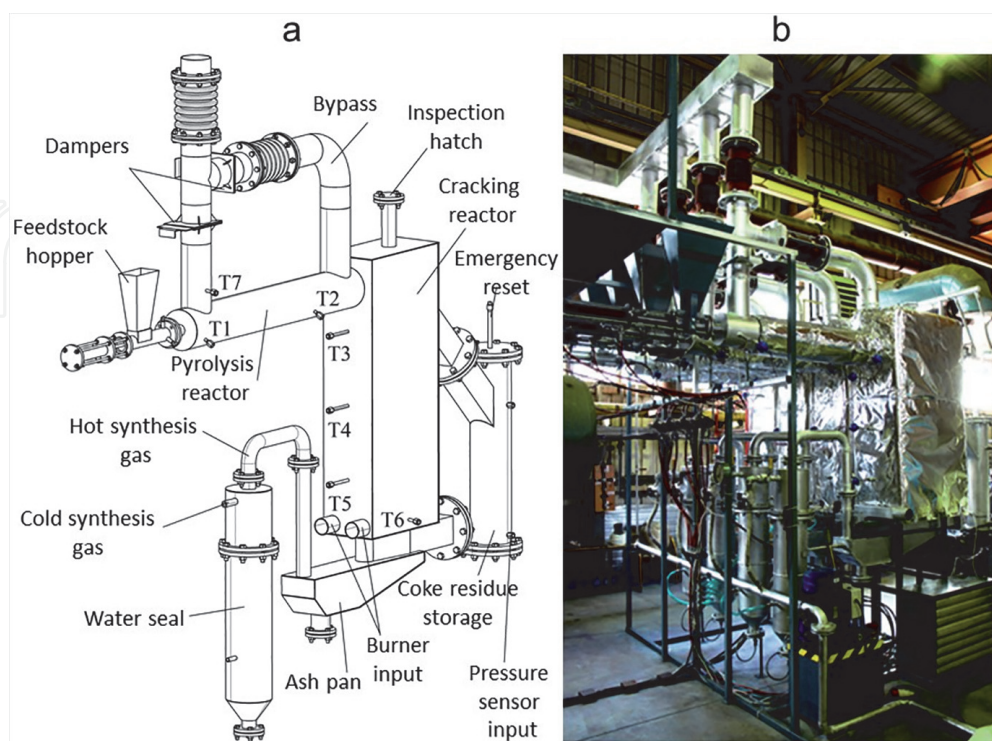

Figure 8.
Diagram of a thermochemical conversion module (a) and a photograph of an installation consisting of four modules (b).

The unit was tested for two modes of operation (mode A, mode B). The parameters characterizing the operating modes of the unit are presented in **Table 4**. The characteristics of woody biomass and coal residue obtained during the tests are presented in **Table 5**, and the characteristics of the resulting synthesis gas are presented in **Table 6**. Data on the calorific value of raw materials and two-stage conversion products obtained in mode A are presented in **Table 7**.

The energy balance of the installation can be calculated from the test results. The energy flows diagram of the installation is shown in **Figure 9**.

The general energy balance equation is as follows:

$$P_{BM} + P_{CP} - P_L = P_{SP}^{ch} + P_{SP}^{ph} + P_{GP}^{ch} + P_{GP}^{ph}, \tag{4}$$

where the superscript "ch" refers to chemical heat and the superscript "ph" refers to the physical heat of solid and gaseous products of the process. The results of calculating the components of the energy balance are shown in **Table 8**.

The degree of energy conversion of the installation was determined as follows:

$$\eta_{ec} = \frac{g_{SG} \cdot Q_{SG}^{net}}{Q_{BM}^{net}}, \tag{5}$$

where Q_{SG}^{net} is the lower heating value of synthesis gas, MJ/m^3; is the lower heating value of biomass, MJ/m^3; g_{SG} is the specific productivity of the unit for synthesis gas per 1 kg of feedstock, m^3/kg. According to the results of calculations, the degree of energy conversion was 79,8%.

Parameter	Dimen-sion	Mode	
Mode symbol		**A**	**B**
Biomass type		Oak sawdust	Pine shavings
Biomass consumption	kg/h	6,0	5,0
The mass of the coke residue in the cracking reactor	kg	8,6	8,6
Fuel type for own needs		Natural gas	Propane
Working value of gas pressure	bar	0,1 – 0,4(0,45)	0,4 – 2,0(2,2)
Fuel consumption for own needs in steady mode	m^3/h	3,22	1,08
Thermal power of burners in steady mode	kWt	30,0	27,4
Pumping station power	kWt	2,26	
Temperature parameters of pyrolysis and cracking reactors:			
At the entrance to the pyrolysis reactor (T1)	°C	300	250
At the outlet of the pyrolysis reactor (T2)	°C	660	500
At the entrance to the cracking reactor (T3)	°C	950	870
In the middle of a cracking reactor (T4)	°C	980	910
At the outlet of the cracking reactor (T5)	°C	1000	950
Combustion products inlet (T6)	°C	1100	1100
Combustion products outlet (T7)	°C	600	570

Table 4.
Operating parameters of the pilot installation during tests.

Parameter	Mass fraction[*], %	
	Oak sawdust	**Pine shavings**
Biomass parameters		
Total moisture	5,50 / - / -	8,80 / - / -
Ash content	0,50 / 0,53 / -	0,48 / 0,53 / -
Total carbon	46,96 / 49,69 / 49,95	47,68 / 52,28 / 52,56
Organic hydrogen	5,42 / 5,73 / 5,77	5,54 / 6,07 / 6,10
Oxygen	41,47 / 43,89 / 44,12	37,43 / 41,04 / 41,26
Nitrogen	0,14 / 0,15 / 0,15	0,05 / 0,06 / 0,06
Combustible sulfur	0,01 / 0,01 / 0,01	0,02 / 0,02 / 0,02
The release of volatile substances at 700°C	81,1 / 80,0 / 80,4	84,5 / 83,0 / 83,4
The release of volatile substances at 1000°C	83,6 / 82,7 / 83,1	87,9 / 86,8 / 87,3
Coke residue parameters		
Specific yield (per 1 kg of feedstock)	0,163	0,156
Ash content	3,05 / 3,05 / 0	4,01 / 4,01 / 0
Total carbon	94,39 / 94,39 / 97,36	92,48 / 92,48 / 96,34
Organic hydrogen	0,99 / 0,99 / 1,02	0,85 / 0,85 / 0,88
Oxygen	0,89 / 0,89 / 0,91	2,09 / 2,09 / 2,17
Nitrogen	0,68 / 0,68 / 0,70	0,56 / 0,56 / 0,58
Combustible sulfur	0,01 / 0,01 / 0,01	0,02 / 0,02 / 0,02

Table 5.
*Characteristics of woody biomass and coke residue. * In terms of working/ dry/dry ash-free condition.*

Parameter	Dimen-sion	Parameter value	
		Oak sawdust (A)	**Pine shavings (B)**
Synthesis gas volumetric flow	m³/h	7,66	6,50
Specific yield of the obtained synthesis gas	m³/kg	1,28	1,30
Synthesis gas chemical composition			
Hydrogen (H_2)	% vol.	50,4	49,2
Carbon monoxide (CO)		40,8	40,8
Carbon dioxide (CO_2)		5,5	5,0
Nitrogen (N_2)		1,5	1,8
Oxygen (O_2)		0,0	0,0
Hydrocarbons (C_nH_m), among them:		1,8	3,2
- methane (CH_4)	% of the total vol. of C_nH_m	90,7	91,8
- ethane (C_2H_6)		1,2	0,7
- ethene (C_2H_4)		1,1	0,8
- propane (C_3H_8)		4,2	2,7
- propene (C_3H_6)		0,2	0,1

Parameter	Dimen-sion	Parameter value	
		Oak sawdust (A)	Pine shavings (B)
- i-butane (C_4H_{10})		1,1	1,0
- n-butane (C_4H_{10})		0,6	1,0
- i-pentane (C_5H_{12})		0,2	0,4
- n-pentane (C_5H_{12})		0,7	1,5

Table 6.
Characteristics of synthesis gas obtained as a result of tests.

Parameter	Dimension	Value
Lower heating value of biomass	MJ/kg	16,9
Higher heating value of biomass	MJ/kg	18,2
Lower heating value of coke residue	MJ/kg	33,0
Higher heating value of coke residue	MJ/kg	33,2
Lower heating value of synthesis gas	MJ/ m^3	10,5
	MJ/kg	16,0
Higher heating value of synthesis gas	MJ/ m^3	11,5
	MJ/kg	17,5

Table 7.
Heating value of raw materials, coke residue and synthesis gas obtained as a result of tests in mode a.

The efficiency of the installation was calculated as follows:

$$\eta_{\sum} = \frac{G_{BM} \cdot g_{SG} \cdot Q_{SG}^{net}}{G_{BM} \cdot Q_{BM}^{net} + N_{PS} + G_{NG} \cdot Q_{NG}^{net}}, \tag{6}$$

where G_{BM} is the consumption of biomass, kg/s; N_{PS} is the power of the pump station, MW; G_{NG} – consumption of natural gas burned in the furnace, m^3/s; Q_{NG}^{net} – lower heating value of natural gas, MJ/m^3. According to the results of calculations, the efficiency was 37.1%.

Thus, the designed unit has a high efficiency of energy conversion of woody biomass into synthesis gas, but it has a low thermal efficiency. The main ways to increase efficiency are to increase the degree of using biomass energy and reduce heat losses with the flue gases [22, 23]. The problem of reducing heat losses with the flue gases can be solved both by increasing the efficiency of heat exchange processes inside the unit (improving the flow parts of heat exchangers by using developed fins and optimizing the geometry of the coolant channels), and by recuperating part of the thermal energy of flue gases for heating air, which then goes into the solid fuel furnace for combustion. The disadvantage of the latter solution is also the complication of the installation and an increase in electricity consumption due to the appearance of a heat exchanger and an air blower. A schematic diagram, including the proposed areas of modernization, is shown in **Figure 10**.

It is shown in [12] that when solving the problem of finding the optimal operating parameters of a modernized installation, its efficiency can be increased to 69.5%, but the efficiency of energy conversion of raw materials will decrease to 70.3%.
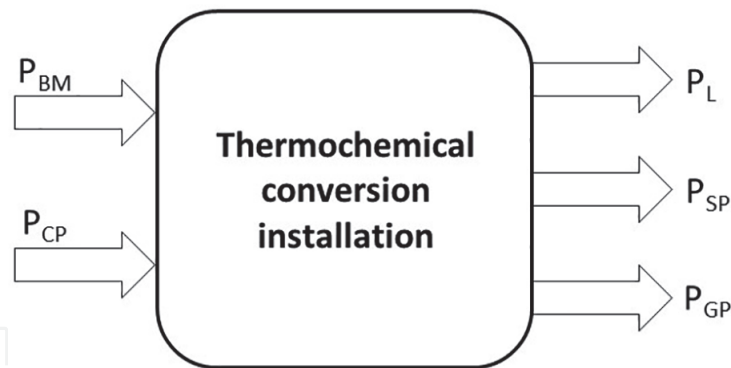
Figure 9.
Energy flows diagram of a thermochemical conversion installation. P_{BM} – Energy of biomass processed per unit of time; P_{CP} – Thermal power introduced by natural gas combustion products; P_L – Total heat losses of the installation; P_{SP} – Energy corresponding to the heat content of solid products produced per unit of time; P_{GP} – Energy corresponding to the heat content of gaseous products produced per unit of time.

Parameter	Designation	Quantity, kWt
Energy corresponding to the heat content of the biomass processed per unit of time	P_{BM}	30,3
Thermal power brought in by natural gas combustion products	P_{CP}	14,7
Thermal power of losses into the environment through the thermally insulated walls of pyrolysis and cracking reactors	P_L	8,1
Energy corresponding to the heat content of solid and gaseous products formed per unit of time (chemical and physical heat):		
• solid products, chemical heat	P_{SP}^{ch}	9,0
• solid products, physical heat	P_{SP}^{ph}	0,2
• gaseous products, chemical heat	P_{GP}^{ch}	24,5
• gaseous products, physical heat	P_{GP}^{ph}	2,8
Energy balance discrepancy	ΔP	0,4

Table 8.
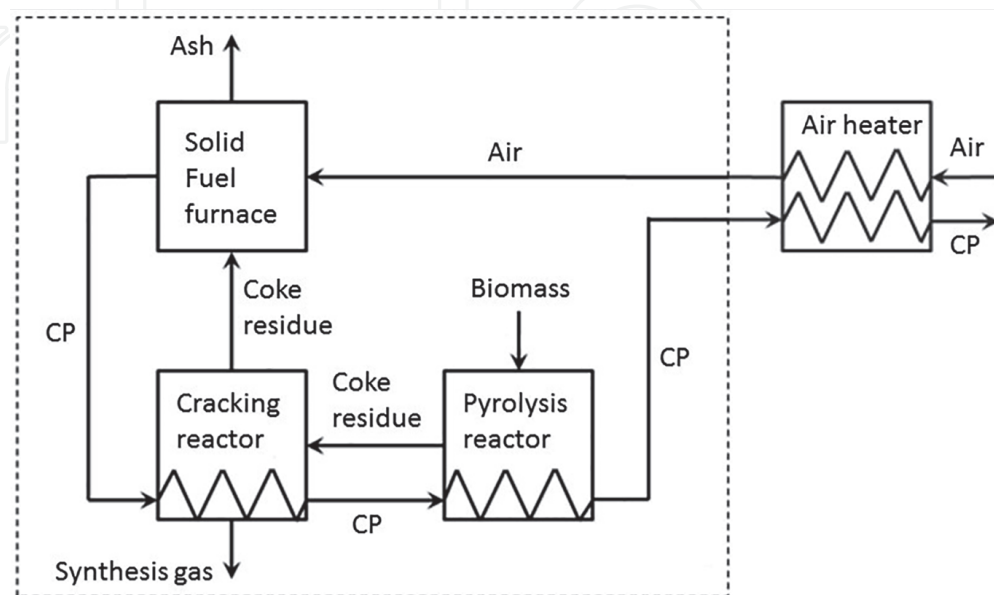*Energy balance of the pilot plant.*

Figure 10.
Schematic diagram of the modernized installation. CP – Combustion products.

5. Potential application areas for two-stage pyrolytic conversion

5.1 Cogeneration complex based on a gas piston engine

The schematic diagram of an autonomous cogeneration complex is shown in **Figure 11**. The diagram assumes parallel operation of 4 thermochemical conversion modules. The capacity of each module is 10–12 kg/h for the initial biomass or 12.8–15.4 m³/h for the synthesis gas.

The synthesis gas produced during the conversion of biomass is cleaned of solid particles (cleaning from tar is not required) in the filter and through the receiver enters the gas-piston engine (GPE). The rated power of the generator connected to the GPE is 75 kW. The combustion products of the GPE are cooled in a shell-and-tube heat exchanger to a temperature of 50 °C, after which they are removed into the atmosphere. In the same heat exchanger water is heated, which is then cooled in a heater (heat load up to 100 kW). The heater can be replaced by any other heat consumer.

The parameters of the energy complex are chosen in such a way as to ensure the possibility of testing it at the JIHT RAS stand. In the course of the tests carried out, the thermochemical conversion module was brought to the operating temperature mode, then the elastic gas tank was filled with synthesis gas, after which the GPE was started in the mode of the minimum load, which increased stepwise to 30 and then to 50 kW. During the tests, for each mode, we measured the flow rate of synthesis gas at the engine inlet, temperatures, pressures, and parameters of the electric generator. The engine running time at each load was 10 minutes. The results of measurements and calculations are presented in **Table 9**.

The tests carried out with one thermochemical conversion module have shown the possibility of implementing an autonomous cogeneration complex. The data obtained indicate that with the capacity of one module (in terms of feedstock – 12 kg/h), four thermochemical conversion modules will be able to provide gas to a power plant with a capacity of up to 50 kW. The thermal power in the cogeneration mode will be 54.4 kW.
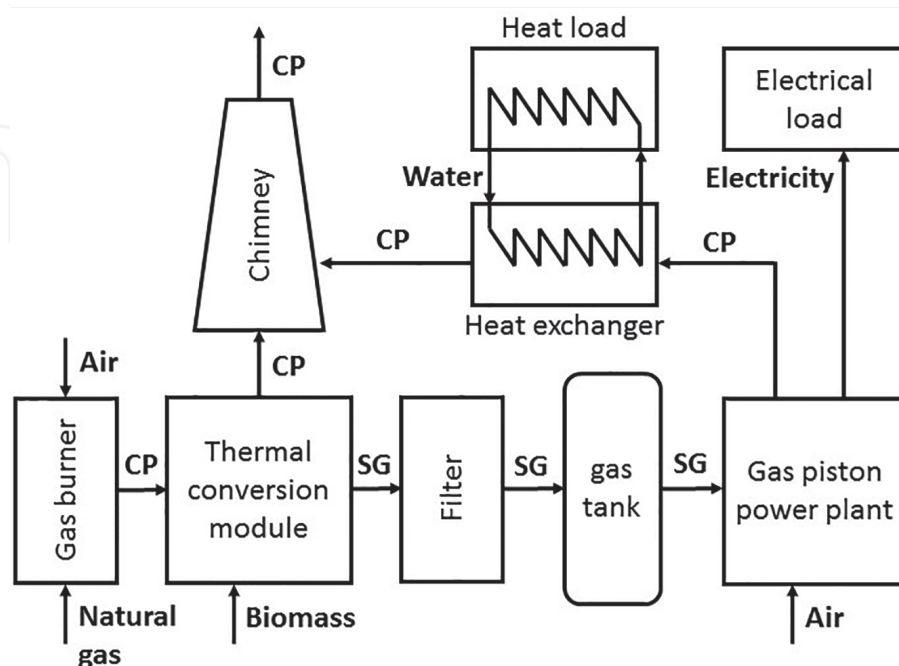

Figure 11.
Schematic diagram of a cogeneration energy-technological complex based on a gas piston unit. SG – Synthesis gas; CP – Combustion products.

No	Load current, A	Voltage, V	Electric Power, kW	Frequency Hz	Syngas consumption, m³/h	Thermal power, kW
1	133,9	224	30	50	39,1	35,3
2	219,3	228	50	50	56,2	54,4

Table 9.
Test results of the power engineering complex.

5.2 Substitution of liquid fuel in existing liquid fuel boilers

The synthesis gas obtained in the process of two-stage pyrolytic conversion can be used for partial replacement of diesel fuel in liquid fuel boilers. To study the co-firing of syngas and diesel fuel, a thermochemical conversion module was installed next to the boiler house. The schematic diagram of the heating complex is shown in **Figure 12**.

The heating complex uses a floor-standing cast iron boiler "RIELLO RTT 93" with an installed oil burner "CUENOD NC12H101". The nominal heat output of the boiler is 100 kW. The schematic diagram is provided for two modules for thermochemical conversion of biomass, which allow replacing up to 90% of diesel fuel with synthesis gas during continuous operation of the boiler at rated power. At the time of testing, one module and one elastic gas tank with a volume of 10 m³ were installed, which made it possible to carry out preliminary tests and evaluate the possibility of replacing liquid fuel with synthesis gas, since in fact the boiler operated in intermittent mode: after heating the direct supply water to the set temperature, the burner automatically turned off and remained off until the temperature of the direct supply water reached the lower threshold value, after which the burner re-ignited and the cycle was repeated.

For the co-combustion of diesel fuel and synthesis gas, a special nozzle was made on the flame head of a liquid fuel burner, which consists of two main elements - a supply pipe and a gas manifold with outlets after the air swirler (**Figure 13**). This
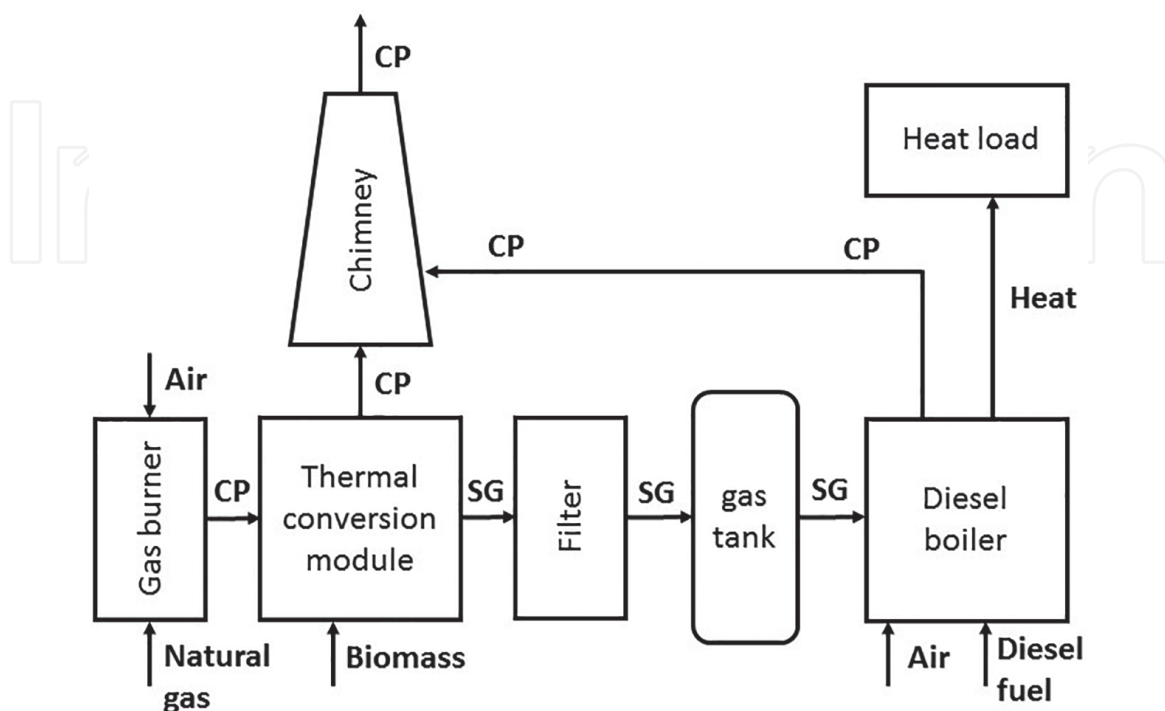

Figure 12.
Schematic diagram of the heating complex.

Figure 13.
Flame head of liquid fuel burner with nozzle for co-combustion of gaseous fuel.

allows synthesis gas to be fed into a turbulized air stream, which results in good mixing of gas and air. When it enters the boiler combustion chamber, the gas-air mixture burns out, while the liquid-fuel part of the burner, the power of which can be reduced to 10% of the nominal due to the installation of a low-flow nozzle, ensures guaranteed ignition of the mixture, preventing the occurrence of explosive situations. The total area of the openings for the gas outlet was selected experimentally (by measuring the gas flow rate) in such a way as to ensure the required gas performance of the burner in the operating range of excess pressures (5–30 mbar).

Heating complex tests included the following stages:

1. Bringing the thermochemical conversion module to the operating mode.

2. Filling an elastic gas tank with synthesis gas with subsequent determination of the composition of the syngas in the tank.

3. Start-up and subsequent operation of the boiler only on diesel fuel.

4. Boiler operation in the mode of combined combustion of diesel fuel and synthesis gas.

During testing of the heating complex, the temperature of the direct supply water was set on the boiler control panel and amounted to 58–62 °C. The tests were carried out for five modes of operation: three modes of operation on diesel fuel and two modes of co-combustion of diesel fuel and synthesis gas. Pine sawdust was used as the initial biofuel. The operating time in each mode was 10–15 minutes. Data on fuel consumption and parameters of combustion products in each mode are presented in **Table 10**.

Based on the data obtained as a result of the tests, the power and efficiency of the boiler were calculated in five operating modes (**Table 11**).

As tests have shown, the efficiency of the boiler in operating modes 4 and 5 turns out to be practically equal to the efficiency corresponding to the operation in the nominal mode, which indicates that there are no significant changes in the combustion conditions when diesel fuel is partially replaced by synthesis gas. Thus, the tests confirm the possibility of replacing liquid fuel in boiler houses with gaseous fuel obtained by the method of two-stage pyrolytic conversion.

Parameter	Dimension	Operating mode number				
		1	**2**	**3**	**4**	**5**
DF to SG ratio	% / %	100 / 0	100 / 0	100 / 0	90 / 10	80 / 20
Parameters of the oil part of the burner:						
Pressure of DF	Bar	11	9	7	9	7
DF consumption	kg/h	8,76	7,92	6,98	7,92	6,98
Parameters of the gas part of the burner:						
SG consumption	m^3/hч	0	0	0	3,6	7,4
	kg/h	0	0	0	2,29	4,72
Parameters of combustion products behind the boiler:						
Temperature	°C	297	292	286	299	303
O$_2$ content	% vol.	3,2	4,74	6,20	3,12	3,08
Air excess ratio	—	1,20	1,32	1,46	1,19	1,19

Table 10.
Fuel consumption and parameters of combustion products during testing of the heating complex. DF – Diesel fuel; SG – Synthesis gas.

Parameter	Dimension	Operating mode number				
		1	**2**	**3**	**4**	**5**
Thermal power	kW	90,4	80,9	70,5	90,7	90,4
Efficiency	%	87,2	86,3	85,3	87,2	87,1

Table 11.
Power and efficiency of the boiler at different operating modes.

The efficiency of the heating complex can be increased if the combustion products formed in the boiler are sent to the thermochemical conversion module. In a similar way, the efficiency of the energy technology complex shown in **Figure 11** can be increased by using the combustion products generated in the GPE in the thermochemical conversion module.

5.3 Production of synthetic aviation fuel

The authors of [24, 25] have shown that synthesis gas obtained by two-stage thermal conversion of woody biomass during experiments can be used to synthesize dimethyl ether (DME) and methanol, which serve as the basis for the production of the base component of aviation fuel. Studies have shown that the synthesis of DME and methanol from lean synthesis gas with an H$_2$:CO ratio of 0.95–1.25 can be efficiently carried out with a two-layer loading of a methanol catalyst and γ-A$_{12}$O$_3$.

The volumetric content of individual gases, as well as various inclusions in the composition of the synthesis gas used for the production of DME and methanol, have a significant impact on both the efficiency of synthesis and the quality of the products obtained. Tar, moisture, solid particles, nitrogen and sulfur compounds in synthesis gas are undesirable impurities that reduce the catalyst life and deteriorate the quality of synthesis products. In the production of synthesis gas from woody feedstock by the method of two-stage pyrolytic conversion, gas purification is significantly simplified in comparison with the gas obtained from air gasification.

6. Conclusions

Two-stage pyrolytic conversion is a method for obtaining gaseous fuel with a calorific value of about 11 MJ/m^3 from biomass. The process includes two stages: pyrolysis of the feedstock and subsequent heterogeneous cracking of pyrolysis products when they are passed through a carbon packing. As a result, synthesis gas is formed, as well as a coal residue, which can be further used in the coal packing in the cracking reactor, as a fuel for own heat demand or for other applications.

The optimum (in terms of the specific yield of non-condensable gases) temperature in the pyrolysis zone is 500–700 °C, while the optimum temperature in the cracking zone is 1000 °C. The minimum mass of coal in the cracking reactor to achieve the maximum yield of non-condensable gases should be at least 67% of the mass of the feedstock fed to the pyrolysis reactor, provided that the heating rate in the pyrolysis reactor is 10 °C/min.

Experiments on the processing of six types of biomass (pellets from wood, peat, straw, sunflower husks and poultry litter, as well as wastewater sludge) by the method of two-stage pyrolytic conversion showed that each of the considered types of biomass can be used as raw material for synthesis gas production. The gas productivity of the process is several times higher than the gas productivity of conventional pyrolysis. The ratio of volumes of hydrogen to carbon monoxide in the produced synthesis gas varies from 1:1 to 1:2 depending on the type of biomass, while it does not contain volatile pyrolysis products with high molecular weight, which makes it possible to use it as fuel for internal combustion engines.

An experimental installation was built at the JIHT RAS, which implements the process of two-stage pyrolytic conversion. The unit provides the degree of energy conversion of the initial biomass into synthesis gas up to 79.8%. However, it has a low thermal efficiency: only 37.1%. This characteristic can be increased up to 69.5% with the heat recovery from flue gases.

Tests have confirmed that the synthesis gas obtained in the process of two-stage pyrolytic conversion can be used as motor fuel for internal combustion engines, as well as for partial replacement of diesel fuel in liquid fuel boilers. Moreover, it can be used as a raw material for the production of liquid aviation fuel. The best suited for this is the synthesis gas obtained during the processing of wastewater sludge due to its high hydrogen content.

Acknowledgements

Nomenclature

CHP   combined heat and power (plant);
ORC   organic Rankine cycle;
WWS   wastewater sludge;
SG   synthesis gas;
CP   combustion products;
GPE   gas piston engine;
DF   diesel fuel;
DME   dimethyl ether.

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