Composition and energy value research of pyrolise gases

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Abstract. Energy values of gaseous pyrolysis products of typical forest and aquatic plant biomass of Europe are investigated. Theoretical research of main characteristics of samples of typical plant biomass of Europe such as pine, thorn, microcystis, elodea is produced. Methodology and planning of experimental studies of process of pyrolysis of plant biomass are formulated. Experimental researches of composition of gas pyrolysis products of different types of plant biomass for different temperatures were carried according to laboratory conditions. Pyrolysis of plant biomass was carried out using a specially designed and manufactured pyrolysis plant the main part of which is a pyrolysis reactor. Installation made by our department is intended for slow pyrolysis. In research for determine presence and percentage of product yield qualitative and quantitative gas chromatography assays were used. The lower calorific value of gaseous pyrolysis products of samples of typical forest and aquatic plant biomass of Ukraine are calculated. As a result of calculations it was determined that during pyrolysis of aquatic plants and algae mixture of the obtained gases had the highest values of lower calorific value: 17,10-17,15 MJ/kg - for microcystis and 16,45-16,50 MJ/kg - for elodea. Gas obtained from pyrolysis of pine wood had the highest values of lower calorific value in the range of 13,8 to 13,85 MJ/kg. The lower calorific value of pyrogas obtained from thorn samples ranged from 12,6 MJ/kg to12,65 MJ/kg.

1. Introduction
Research of systems for converting biomass into various types of fuels for internal combustion engines have been conducted in Europe during many years. But despite possibility of using thermal decomposition of biomass as a substitute for natural gas and liquid motor fuels, as well as possibility of intensive reproduction of wood, there is currently no reason to say that these promising technologies provide replacement of at least 10% of traditional energy in Europe. One of the problems is that the scientific bases of high-temperature conversion of bio-raw material for the purpose of its further usage in various industries of Europe are not sufficiently developed at present.

Existing experimental data of biomass pyrolysis conditions and modes are insufficient to implement technologies that ensure economic biomass thermal conversion processes efficiency. Expediency and necessity of research for a large nomenclature of biomass varieties of processes occurring when biomass is heated to temperatures of physical and chemical transformations is obvious. Establishing regularities of these transformations in thermal decomposition of biomass can become basis for creating economic efficiency directions for usage of biofuels in technological installations in Europe.
2. Literary sources analysis and problem statement

2.1. Biomaterials for biofuels

A number of authors believe that biomass provides energy about 15% of consumers in the world at present. About a quarter of biomass energy is from industrialized countries, and the remaining 75% is from developing countries [1]. Obviously, bioenergy cannot completely replace fossil fuels. However, using it can partially reduce CO₂ emissions and replace oil. Wood is a CO₂-neutral fuel provided that trees grow as much as they cut down. In addition, labor is required for logging, transformation, and conversion of wood into thermal energy. Development of forest industry for energy purposes contributes to employment of local people and supports social and economic activity in rural and forested areas of Ukraine.

Structural components of biomass consist of basic chemical structural blocks of wood: cellulose, hemicellulose, and lignin. For this reason, the non-food biomass fraction is called lignocellulosic biomass. Wood components of lignocellulosic biomass are interwoven into complex composite matrices that create different structural components (e.g., tree trunk, corn stalks). Cellulose and hemicellulose are consolidation of biomass structure [2].

Type of biomass mainly depends on the sum of each of these components. In general, proportion of biomass components varies depending on the types of biomass. Biomass consists mainly of carbon, hydrogen, and oxygen but after total combustion water and carbon dioxide will remain [3]. Resulting water and water vapor contain a lot of latent heat that is released during condensation. Almost all types of lignocellulosic raw materials of biomass have a calorific value in range of 15-19 MJ / kg, and its value for most wood materials is 15-17 MJ / kg. The main component of wood is cellulose. It occupies about 45% of the mass in hard and soft wood [4].

Cellulose is a strong, unbranched polymer of glucose contained in the plant cell wall. This long chain molecule, often from 5,000 to 15,000 glucose rings, is polymerized into one cellulose molecule \((C_6H_{10}O_5)_n\), where \(n\) is the length of the cellulose polymer. Cellulose fibres are incorporated like woven mats into biomass and its chemical structure [5].

Hemicellulose is also found in the walls of the plant cell. It is composed of highly branched polymers such as glucose and other sugars, many of which contain five carbon atoms. Hemicellulose is characterized by a lower molecular weight than cellulose. It consists of only 500-3000 units of sugar and has a shorter chain than cellulose. Surrogate molecule for hemicellulose is \(C_4H_5.9O_3.3\), this formula was proposed in [6].

Lignin occupies the space of the plant cell wall, filling volume around the branches and chains of hemicellulose and cellulose. It is covalently bound to hemicellulose resulting in a lignocellulosic matrix and therefore entire final structure of the plant. Lignin can be represented as a combination of two chemical groups: \(C_9\)-group and \(OCH_3\), the methoxy (MeO) group. Molecular formula for lignin is written as: \(C_9H_{16}O_2(OCH_3)_r\), where \(r\) is the ratio of the methoxy group and phenylpropanoid group. This ratio depends on the raw material [7].

2.2. Products of pyrolysis

The pyrolysis gas mixture consists of several combustible gases: CO₂, CO, H₂, CH₄, hydrocarbons, traces of N₂, C₂-C₆, and sulfates. The amount of gas depends on many factors, including the type of reactor, feedstock and residue processing. As a rule, such gas has a calorific value of about 13-15 MJ / m³ (natural gas - about 37 MJ / m³) [8].

Pyrolysis gas with a high content of hydrocarbon components (resulting in high calorific value) is generally used as an energy source. Purified pyrolysis gas can be used as an energy source in furnaces, as fuel for industrial steam boilers, and as gaseous fuel in internal combustion engines and gas turbines [9].

Pyrolysis of compost for production of syngas with an explicit \(H_2 / CO = 3\) or \(H_2 / CO = 2\) was investigated in the work [10]. Composts were obtained from hybrid (perennial) grasses and nonhybrid (perennial) grasses. Exceptionally large higher heating values of pyrolysis gas very close to of
feedstock were obtained for compost made from brome (16.23 MJ / kg), hybrid Becva (16.45 MJ / kg), and tall fescue (17.43 MJ / kg).

Experimental results of slow, fast, and catalytic pyrolysis of five lignocellulosic residues (corncobs and corn stalks, sunflower residues, olive kernels and olive tree prunings) are reported in paper [11]. Pyrolysis took place in two different reactor configurations: a captive sample wire mesh reactor for fast pyrolysis and a fixed bed reactor for non-catalytic and catalytic pyrolysis. Comparison of the experimental results showed that pyrolysis in the captive sample reactor produced more energy than in the fixed bed reactor (15.40 MJ / kg) while the fixed bed reactor configuration seemed to favor the production of liquid products (13.80 MJ / kg). Pyrolysis results were assessed and recommendations for the further usage of their products were made.

Fast pyrolysis of cellulose, xylan, and lignin was experimentally conducted between 350 and 650 °C in a tube furnace and the effect of temperature on pyrolysis products (char, noncondensable gas, and bio-oil) was investigated [12]. The yields of char, noncondensable gas, and bio-oil were quantified using gas chromatography and gas chromatography with mass spectrometry. Noncondensable gas mainly consists of CO, CH\textsubscript{4}, CO\textsubscript{2}, and H\textsubscript{2}.

The char yields for the three components decrease with an increase in temperature, and the gas yields and bio-oil yields increase with an increase in temperature, reach maximum at a certain temperature and then decrease after that temperature. Maximum energy for cellulose, xylan, and lignin are 13.43 MJ / kg, 13.92 MJ / kg, and 14.22 MJ / kg respectively; and their corresponding temperatures are 400, 450, and 500 °C respectively. To investigate a relationship between biomass and three major components (hemicellulose, cellulose, and lignin) pyrolysis of three typical biomass samples (rice straw, corn stalk, and peanut vine) was also studied.

If the pyrolysis vapor is cooled rapidly, a dark brown liquid is called bio-oil or bio-petroleum. Bio-oil obtained from biomass is a complex mixture of water (usually 20-30 % by weight depending on the feedstock), as well as carboxylic acids, carbohydrates, etc. [13]. Bio-oil contains different amounts of organic acids and it causes corrosion of materials (e.g. steel and aluminum). However, various chemicals contained in bio-oil can be extracted and used for the chemical and food industries. According to [14], the chemical that is currently emerging from bio-oil includes polyphenols (used for the production of resin), calcium and magnesium, acetates, and others (used in the food industry). Accordingly, bio-oil may have different uses. According to [15], bio-oil can be a major product of the pyrolysis process.

In order to produce biofuels, bio-oil needs to be modified. On average, bio-oils have low, compared to gasoline (44 MJ / kg) and diesel (42 MJ / kg), calorific value (about 20 MJ / kg) [16]. However, it was found that the bio-oil they obtained without processing could be used as fuel for industrial steam boilers and furnaces. It is transportable and can be stored in large quantities [17].

Therefore, it is not necessity to use it immediately upon receipt. Energy derived from biofuels is commonly referred to as "green energy". It can be used as a "clean" fuel for the production of electricity and heat from small stationary diesel engines, gas turbines, and boilers. In addition, the range of chemicals that can be extracted or obtained, including food aromatic compounds, resins of agrochemicals, mineral fertilizers, as well as compounds that require the use of emission control [18].

Oxidized residue, or so-called biochar, is the third product of biomass pyrolysis. Biochar has properties similar to coal in many respects. Biochar contributes to formation of aromatic polycyclic hydrocarbons (surfactants) during the pyrolysis of biomass, especially at low temperatures, with a calorific value of about 26 MJ / kg [19].

This charcoal property also makes it an interesting energy product. Authors [20] found that biochar obtained during the pyrolysis of energy coal can be used as an additive in the source fuel or for its replacement, as well as in the form of briquettes for local fuel. Activated charcoal can be made from virtually any carbon carrier, but the most commonly used feedstock is wood and coal. One of the major industries of activated carbon is water purification, air filters for industrial use and motor transport. Bio coal can replace oil and can be enriched with activated carbon [21].
3. **Formulation of the problem**

Thus, large-scale studies of pyrolysis processes have been carried out at the moment. But the problem is that there are currently no reliable mathematical models to describe the processes of pyrolysis of different types of plant biomass. For further research at the Ivano-Frankivsk National University of Oil and Gas (Ukr.) it is envisaged to use mixtures of natural and pyrolysis gases in gas-converted diesel engines. Therefore, in order to establish combustion heat of an alternative gas fuel for a gas-converted diesel engine, it is necessary to carry out experimental studies of components of pyrolysis gas in the specified ranges of change in the basic technological parameters.

4. **Formation of the purposes**

The purpose of the work is to study composition and energy value of gaseous pyrolysis products of various plant biomasses in Europe.

For solution of this problem the following tasks are outlined:
- to investigate experimentally composition of gaseous pyrolysis products of various types of plant biomass at different temperatures;
- to establish lower calorific value of gaseous pyrolysis products of samples of typical forest and aquatic plant biomass of Europe.

5. **Presentation of the main research material**

5.1. **General characteristics of plant biomass in Europe**

Approximately 40 % of European territory is covered by mixed forests. Natural vegetation consists of forest, grassland, and marsh species. Large areas are occupied by mixed and coniferous forests, pine, pine-oak, oak-hornbeam, and alder forests grow here. Approximately 35 % of the territory of Europe is covered by the forest-steppe zone. The forest-steppe is dominated by deciduous forests, mainly oak forests (rocky oaks and common oaks); of bushes: turf, hornbeam; of herbs: kavela, tipchak. More than 20 % of Europe's territory is the steppe zone. Vegetation: fluffy oak, field maple; from shrubs: hornbeam, wild rose; of herbs: alpine, sedge. About 5 % of territory is a mountain area. Vegetation: thousand berry, water nut, European cedar pine, common pine, juniper, white ash.

5.2. **Characteristics of investigated plant biomass species**

5.2.1. **Pine (Pinus sylvestris)**. Pine occupies about 5.5 million hectares or 14 % of the total forest area in Europe. Density of its wood ranges at 420-600 kg / m³. Pine is popular for manufacture of furniture, plywood, veneer, and is also suitable for production of briquettes of charcoal and activated carbon, as it has a high calorific value.

5.2.2. **Thorn prickly (Prunus spinosa)**. Thorn is a branched bush up to 2 m high. Extremely widespread in Europe. The core is brown, hard, heavy (specific weight - 700 kg / m³). It is used for a variety of purposes, including firewood, feed and organic fertilizers.

5.2.3. **Elodea**. Elodea or "water plague" is a genus of perennial aquatic plants of the Hydrocharitacea family, one of the most abundant aquatic plants in Europe and the Earth. This plant is extremely adaptable to any aquatic environment, is extremely unpretentious, and has extremely high rates of biomass increase: up to 5 % per day.

5.2.4. **Microcystis blue-green (Microcystis aeruginosa)**. *Microcystis blue-green is an algae of the genus Microcystis of the Microcystice family of the Chroococcales division of the blue-green algae (Cyanophyta). It is extremely widespread in Europe, and it is the predominant species of algae in fresh water, very common in seawater, and in moist soils.

5.3. **Planning of experimental studies of the pyrolysis process**
The purpose of the experimental studies is to establish the basic laws of obtaining components of pyrolysis gas in the process of controlled thermal decomposition of vegetable biomass, to use it as a fuel in gas mixtures for gas-converted diesel engines. In this case, it is advisable to allocate as a result of studies relevant to each material systems of parameters that determine the output of the final products. The solution to this problem is possible when implementing a multifactorial experiment with the reproduction of the basic conditions of the process under study.

Making a research plan according to the well-known provisions of theory of experimental design creates conditions for increasing the reliability of measurement results and reducing in many cases the volume of experimental studies or bench tests. But usage of modern methods of planning experimental studies (for example, drawing up factorial plans) requires a certain minimum of information about the links between the studied factors. Analysis of literature devoted to this problem [7-20] showed that there is no reliable information about the nature of thermal decomposition of plant biomass. It can only be stated that the output of the final pyrolysis products is influenced by temperature, rate of heating of raw materials, type of plant biomass. But the factorial plan guarantees that as a result of the minimum number of experiments reliable values of the coefficients in the regression equations are obtained only if the order of the regressive equation is known before the experiments begin. Moreover, conducting experiments using factor plans is only possible with sufficiently specific theoretical ideas about the process under study.

If the nature of dependencies between the main factors studied does not known in advance then usage of a conventional factor plan may lead to erroneous results. For example, with regard to the investigated processes of thermal decomposition of plant biomass it is possible to have local experiments to obtain dependence of the fraction of liquid or gaseous products on temperature. Therefore, for example, usage of first-order models in drawing up the plans of the experiment will be unreasonable, based on physical ideas about possible options for development of processes of thermal conversion of plant biomass. Accordingly, the most correct would be to use in the design of the experiment plans of a classic multifactorial scheme of sequential experiments in a selected space of factors. However, experiments should be performed not gradually but randomly according to the general theory of experiment planning, where implementation of independent factors vary in order to exclude influence of external uncontrolled factors on the results of the experiment randomly.

Planning researches the following tasks should be set:
- create conditions for estimating random errors of measurements;
- to ensure minimum values of systematic errors and to eliminate gross errors;
- to ensure stability of the properties of the samples of the investigated varieties of plant biomass throughout the series of experiments;
- ensuring minimum deviations of parameters characterizing the conditions of the experiments (humidity, pressure and temperature in the pyrolysis installations);
- ensuring the adequacy of reproduction of the characteristics of the samples from study to study.

According to results of analysis of research works [1-6] it is possible to make a reasonable conclusion that in terms of output of pyrolysis gas the main input parameter is composition of wood biomass. The purpose of the purpose in the planned experiments was to select composition of the final gaseous products. The main variables determining this composition are temperature of biomass samples at the end of the experiment, temperature change interval, heating rate, and biomass composition. The choice of range of temperature changes was carried out by the method of successive approximations when conditions of complete conversion were reached. Values of heating rate were chosen based on real capabilities of the plants for industrial thermal conversion of plant biomass. Temperature change intervals were chosen based on conditions to ensure maximum accuracy of the experimental results. The research used the main varieties of plant biomass that are promising for use in Ukraine. Also, when choosing a species of plants, the goal was to obtain the maximum possible range of change in its structure as a raw material, to draw conclusions about the effect of individual properties of biomass on the output of pyrolysis gas.
Constant initial temperature of the samples was maintained during the experiments. All experiments were carried out in a closed heated room at an air temperature of 291-294 K. To record the sample temperatures, chromel-copel thermocouples were used. The number of experiments for fixed factors was selected at least five.

The lower calorific value of the pyrolysis gas $Q_{H, PG}$ (MJ/kg) was determined by formula:

$$
Q_{H, PG} = V_{CO} \cdot Q_{H, CO} + V_{CH4} \cdot Q_{H, CH4} + V_{H2} \cdot Q_{H, H2}, \quad MJ/kg
$$

where $V_{CO}$, $V_{CH4}$, $V_{H2}$ - volumetric parts of carbon monoxide, methane, and hydrogen in the pyrolysis gas;

$Q_{H, CO}$, $Q_{H, CH4}$, $Q_{H, H2}$ - lower calorific value of carbon monoxide, methane and hydrogen (CO = 10,11 MJ/kg, CH4 = 50,0 MJ/kg, H2 = 120,01 MJ/kg).

5.4. Research methodology

Materials selected for the study were four types of plant biomass typical of Europe. Before experiments, the plants were dried to reduce moisture content. The size of individual plant particles was approximately 5-10 mm by length and 1-3 mm by thickness.

Pyrolysis of plant biomass was carried out using pyrolysis plant the main part of which is a pyrolysis reactor. The plant consists of a reactor with a pyrolysis gas sampler (Fig. 1a), a compressor for pumping pyrolysis gas into the reactor cylinders, and pyrolysis gas cylinders (Fig. 1b). The plant is intended for slow pyrolysis. The reactor has a heating circuit that is connected to the 220 V network.

Amperage was changed by an electric regulator for maintain the set temperature. The temperatures were monitored by means of chromel-copel thermocouples with an error of ± 2.0 ° C. After beginning of output of pyrolysis gas a portion of gas was discharged to heat the reactor instead of electric heating circuit. Amount of gas was changed by a gas valve for maintain the set temperature. Capacitor was made as a container with a helical tube. Water with temperature of 12-30 ° C was used as coolant which was periodically updated as it was heated in the cooled tank. Amount of plant biomass loaded once into the reactor was 5000 ± 1 gram. The duration of the pyrolysis (experiment) time was 2-3 hours depending on the set heating temperature.

Conditions of the experiment corresponded to different set temperatures of pyrolysis and types of investigated vegetable raw materials. Plant biomass was pre-dried before pyrolysis (Fig. 2a). Further, dried biomass was crushed (Fig. 2b), loaded into pyrolysis apparatus, and heated.
Resulting pyrolysis gas was fed into the cooler with water and then into the gas bag. From the gas bag by means of a compressor pyrolysis gas was pumped into the high-pressure cylinders. The liquefied condensed product was collected in a pyrolysis fluid collector. The yield of various obtained products was determined by weighing the solid residue (biochar) and the pyrolysis fluid collected during the experiment.

Difference between the loaded biomass and the masses of coal and pyrolysis fluid was the amount of pyrolysis gas. Mass of pyrolysis gas was simultaneously controlled by weighing the gas cylinders before and after filling them. The output of pyrolysis gas was also determined as a percentage of the weight of the feedstock. The gases obtained during pyrolysis were analyzed for composition on a gas chromatograph NeoCHROM Class B.

To exclude experimental typical errors of serial studies experiments were conducted according to a randomized classical plan with constant control of all parameters necessary to calculate random and systematic measurement errors. In order to ensure repeatability of the results of the experiments, experiments at constant factors were performed several times until the product yield fractions were obtained with a scattering not higher than 2.0 %.

5.5. Analysis of pyrolysis gases
In this study gas chromatography assays were used to determine the presence and percentage yield of the product. Gas chromatography for analyzing the qualitative and quantitative composition of gases has several advantages: required sample volumes (~ 1 cm³), short exposure time (about ten minutes), high accuracy, speed and economy.

NeoCHROM Class B gas chromatograph was used to analyze the qualitative and quantitative composition of the gases obtained from pyrolysis process of plant biomass samples. Gas chromatography is an analytical method for the isolation of compounds based on their sorption separation. Determination of composition of the mixture may be based on determining the peak area or peak height of the compound. This method allows to obtain quantitative and qualitative information for each compound present in the analyzed gas phase sample. During the experiments automatic sampling and injection using internal normalization method was used. This is a calibration method commonly used in gas chromatography. The method is based on measuring the area of each peak in the chromatogram. Total area is normalized by 100 % and each peak is indicated as a percentage of the total area.

Gas obtained from wood biomass samples from the gas cylinder was introduced into the receiving tank and analyzed by NeoCHROM Class B gas chromatograph. Carrier gas was hydrogen and the gas obtained consisted mainly of CO, CO₂, CH₄, H₂, and air. Volumetric concentrations were calculated by external standard method based on a linear relationship between concentrations and area of the
standard mixture as measured by the chromatograph. Gas chromatograph was calibrated with a standard mixture before determining the gas composition. The following parameters were set in the hardware system of the NeoCHROM Class B gas chromatograph: detector temperature - 100 °C (thermal conductivity detector); injector temperature - 80 °C; column temperature - 60 °C; type of column - with polysorb-1 filler; carrier gas - hydrogen; flow rate of carrier gas - 40 l/min.

5.6. Results of experimental studies of composition of pyrolysis gas
During experimental studies of plant biomass pyrolysis products obtained consisted of solid biochar, pyrolysis fluid, and pyrolysis gas. Yield and composition of final pyrolysis products were significantly dependent on the experimental conditions. Effect of biomass characteristics and pyrolysis temperature on the composition of pyrolysis products and heat of gas combustion was investigated.

Thermal decomposition of source biomass materials takes place during pyrolysis process. As already mentioned material of plant biomass consists mainly of three types of polymers: cellulose, hemicellulose, and lignin. Cellulose during heating mainly releases CO, CO$_2$, H$_2$; hemicellulose releases CO$_2$, H$_2$O and some hydrocarbons, and lignin - CO, CO$_2$, CH$_4$ [4-5].

During the studies gas obtained from pyrolysis of vegetable biomass was collected in a gas cylinder and analyzed in a NeoCHROM Class B gas chromatograph. During pyrolysis gas experiments carbon monoxide (carbon monoxide) CO, carbon dioxide (carbon dioxide) CO$_2$, oxygen O$_2$, hydrogen H$_2$, nitrogen N$_2$, and methane CH$_4$ were recorded. Distribution of gas components obtained for different types of plant biomass at different end pyrolysis temperatures is presented in Fig. 3-4. During the experiments aforementioned plant biomass was used: pine, thorn, microcystis, elodea.

![Figure 3. Dependence of gas mixture composition on temperature obtained during pyrolysis of pine (a) and thorn (b)](image)

6. Results and Discussion
Studies have shown that increasing the temperature contributes to the intensive release of methane CH$_4$. Methane formation was due to decomposition of lignin as its concentration increased during decomposition process at high temperatures.

Methane formation is due to the separation of methoxyl groups. The air content decreases. It is established that at temperatures of 200-350 °C gas mixture mainly consists of CO and CO$_2$ and also contains N$_2$ and O$_2$. Origin of CO and CO$_2$ mainly depends on the decomposition of cellulose and hemicellulose. Formation of CO and CO$_2$ at a higher temperature is caused by decomposition of lignin. At temperatures between 200 and 600 °C CO content decreases slightly and CO$_2$ content remains approximately stable.
Figure 4. Dependence of gas mixture composition on temperature obtained during pyrolysis of microcystis (a) and elodea (b).

At temperatures of about 700 °C, methane content for pine reached 20.3 %, carbon monoxide - 36.8 %, hydrogen was less than 0.1 % (Fig. 3). At 700 °C, methane content for terrain was 17.9 %, carbon monoxide - 36.7 %, hydrogen was also less than 0.1 % (Fig. 3).

At temperatures near 700 °C methane content for microcystis reached 21.2 %, hydrogen - 2.1 %, and carbon monoxide - 39.8 % (Fig. 4). At 700 °C, methane content for elodea was 20.7 %, hydrogen - 1.9 %, and carbon monoxide - 38.1 % (Fig. 4).

The lower calorific value of pyrogas obtained from the thorn samples was in range of 12.55–12.62 MJ / kg. Gas obtained from pyrolysis of pine wood had the highest values of lower calorific value in range from 13.75 to 13.90 MJ / kg. The results of these researches sufficiently correlate with the results obtained in [22-25].

7. Conclusions

Studies have shown that the largest amount of methane (20.1-21.0 % of the volume of gas obtained) was found in gas mixtures formed during the pyrolysis of aquatic plant and algae (elodea and microcystis) at temperatures in the range of 600-700 °C. Maximum amount of CO (45.9-48.1 % of the volume of gas obtained) was obtained by pyrolysis of pine wood at temperatures of about 200-300 °C. The biggest amount of CO₂ (31.8-32.9 % of the volume of gas obtained) was found in gas mixtures formed during thorn pyrolysis at temperatures of 200-500 °C. Hydrogen content during the experiments was recorded during pyrolysis of aquatic plants and algae (elodea and microcystis) within 0.5-2.1 % with a tendency to increase with increasing temperature. It has also been found that nitrogen and oxygen content decreases with increasing temperature.

As a result of calculations it was determined that during pyrolysis of aquatic plants and algae (elodea and microcystis) mixture of obtained gases had the highest values of lower calorific value: 17.12 ± 0.2 MJ / kg - for microcystis and 16.48 ± 0.3 MJ / kg - for elodea. Gas with a lower calorific value of 11–15 MJ / kg is considered to be a medium-calorie gas fuel and can be used directly in internal combustion engines [26, 27]. Therefore, purpose of further studies is to use the resulting pyrolysis gas in mixtures with methane (propane-butane) for gas-converted diesel engines.

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