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# Features of Pyrolysis of Plant Biomass at Excessive Pressure

*Sergey Vasilevich and Dmitry Degterov*

## Abstract

The paper describes methods for producing charcoal (highly porous carbon materials) based on plant (wood) raw materials, and the equipment used to implement these processes, the use of activated carbons. The paper describes results of an experimental study of the effect of pressure on the formation of charcoal in the pyrolysis of birch chips. The experimental investigation was carried out at pressures of 0.1, 0.3, 0.5, 0.7 MPa. To investigate the effect of pressure on the pyrolysis process, a laboratory bench was designed and constructed. It was found that increasing the pressure from 0.1 MPa to 0.7 MPa increases the yield of charcoal from 25.1 to 32.4% by weight (relative to the dry weight of the starting material) and the carbon content from 89.1% by weight at 0.1 MPa to 96.4% by weight at 0.7 MPa. The calorific value of charcoal decreases from 34.86 MJ/kg at a pressure of 0.1 MPa to 30.23 MJ/kg at a pressure of 0.7 MPa. This is due to the release of oxygen-containing components, which have a higher calorific value than pure carbon, from the porous coal structure. Reduction of the charcoal heat combustion with a decrease in the amount of oxygen-containing components confirms conclusion that their calorific value exceeds the calorific value of pure carbon.

**Keywords:** pyrolysis, birch chips, pressure, laboratory reactor, charcoal

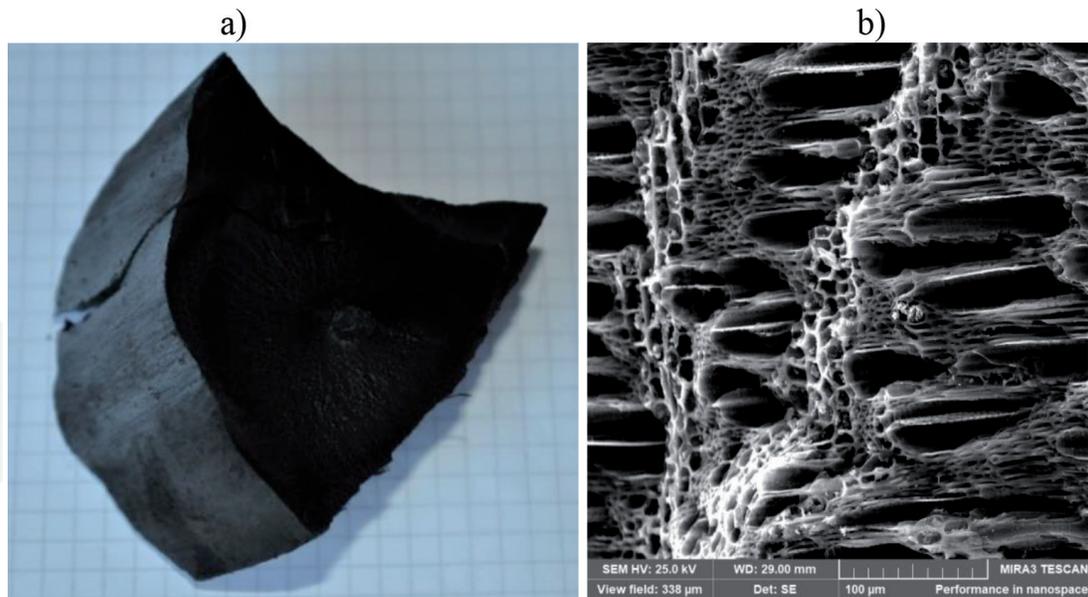
## 1. Introduction

Charcoal (**Figure 1**) is a solid porous pyrolysis product of plant biomass (thermal decomposition without oxygen access), which is formed along with liquid products (resins) and combustible gases. Charcoal is used as a high quality renewable solid fuel (calorific value 30–35 MJ/kg), as well as in industry, for example, in the production of technical silicon [1].

Currently, the use of charcoal in the production of carbon sorbents is expanding, which are used in various technologies of adsorption purification and separation [2, 3].

The density of wood has a significant effect on the strength of coal, which can vary significantly both from breed to breed, and in different parts of the wood. **Table 1** shows the average physical characteristics of oak and birch wood, which are most often used in Belarus for the production of high-quality charcoal.

The yield of charcoal during pyrolysis increases as the size of the pieces of wood increases, while the yield of almost all liquid products decreases. Depending on the size of the wood raw material, it is possible to achieve different densities of its packing in the working chamber. Depending on the size of the wood raw material, it is possible to achieve different densities of its packing in the working chamber.



**Figure 1.**  
General view (a) and micrograph (b) of charcoal.

Wood species	Birch	Oak
Density in an absolutely dry state, kg/m <sup>3</sup>	520	550
Cellulose content, %	45,8	37,1
Content of hemicellulose, %	26,0	28,8
Lignin content, %	21,2	22,5
Heat capacity, J/kg K	1700	
Calorific value, kWh/kg	4,0	
Thermal conductivity across the fibers, mW/m K	150	200
Charcoal output, kg/m <sup>3</sup>	150	160

**Table 1.**  
Physical parameters of raw materials for the production of charcoal [2].

Type of firewood	Coniferous firewood, m			Deciduous firewood, m		
	0,25	1,0	3,0	0,25	1,0	3,0
Round 3–10 cm thick	0,79	0,69	0,61	0,75	0,63	0,55
Round 11–14 cm thick	0,81	0,72	0,66	0,80	0,70	0,62
Chipped up to 15 cm thick	0,77	0,70	0,63	0,76	0,68	0,60
A mixture of round and chipped	0,77	0,70	0,65	0,76	0,68	0,63

**Table 2.**  
Coefficients of full wood content [1].

The full wood ratio determines the volume fraction of wood in a densely folded woodpile. The values of the fullness coefficient for firewood of different sizes are presented in **Table 2**. Assuming that birch chopped firewood 0.5 m long is used for coal production, we will use the value of the wood content factor 0.72 in the calculations.

The process of wood pyrolysis essentially depends on the initial moisture content. This value varies in very wide ranges: from 60 to 65% for freshly sawn raw

materials to 15% for air-dry wood. The optimal level of relative humidity of wood intended for pyrolysis is in the range of 15–25%. With a higher humidity, in addition to an increase in fuel consumption and a decrease in the productivity of devices, the mechanical strength of coal decreases. In this regard, the raw material must be pre-dried. With natural drying of wood, a 12-month supply of raw materials is technically justified. With artificial drying, the supply of wood must be at least 3 months [1].

Depending on the calcination temperature and its duration, the content of non-volatile carbon in the coal varies. Tables 2.3 and 2.4 show examples of the distribution of elements in the original wood and decomposition products for the calcination depths, as a result of which the content of non-volatile carbon in coal is 84 and 94%. The data are given in terms of absolutely dry wood. As follows from these tables, an increase in the content of non-volatile carbon leads to a decrease in the yield of coal and an increase in the duration of the process. Thus, the calcination of the coal should only be carried out to the extent required by the customer. For domestic purposes, coal with a non-volatile carbon content of 77–82% is optimal.

Traditionally, charcoal is produced in the process of slow pyrolysis at heating rates of 5–7 K/min and temperatures of 623–873 K. The duration of the pyrolysis process is 1–14 days, depending on the unit productivity. The mass yield of coal is 20–33%. In the world, such equipment produces from 26 to 100 million tons of charcoal per year with a growth trend of about 3% per year [1]. A consequence of the high duration and low efficiency of the process is a significantly higher cost of charcoal in comparison with fossil coal.

Usually, when charring, either direct heating with a hot gas stream flowing through the bed and washing the surface of individual pieces is used, or indirect heating through the wall of the apparatus.

**Table 3** shows the classification of charcoal burning equipment according to various criteria affecting the thermal regimes and the speed of the pyrolysis process [2].

**Figure 2** shows various types of equipment for the production of charcoal: (a) Combustion furnace VMR (USA) (Duty cycle: 48 hours. Chamber volume: 14 m<sup>3</sup>. Loading: 10 m<sup>3</sup>. Temperature ~ 450°C. Coal output: 1000 kg (≈30%)); (b) experimental reactor Antala (University of Hawaii, USA) (max. Coal yield ≈ 40%. cycle no more than 1.5 hours. Heating of raw materials in a sealed reactor leads to volatility and pressure rise to 7–10 bar at 350°C); (c) UVP-5US mobile incinerator (CIS) (Working cycle: 8–12 hours. Retort volume: 4.5 m<sup>3</sup>. Coal output: 30–32%.); (d) charcoal kiln unitary enterprise “ECO-CARBON” (Ukraine) (Working cycle: 18–34 hours. Consumption of firewood for the furnace up to 0.2 m<sup>3</sup>/day).

The main stages of the charcoal production process are: drying, endothermic pyrolysis, exothermic pyrolysis, calcination and cooling.

During the drying process, the wood is heated to a temperature of 100–120°C and the water evaporates. Due to the fact that with excessively intensive drying, vapors tear wood, the temperature of the heat carrier in known technologies does not exceed 200–220°C (average temperature in the chamber). At the same time, while the wood is not dry, its temperature (at normal pressure) remains about 100–120°C. The composition of the wood is practically unchanged. Drying is usually divided into two stages. At the first stage (heating and actual drying), the relative humidity is brought to 5%. The second stage – drying is carried out already in the pyrolysis process.

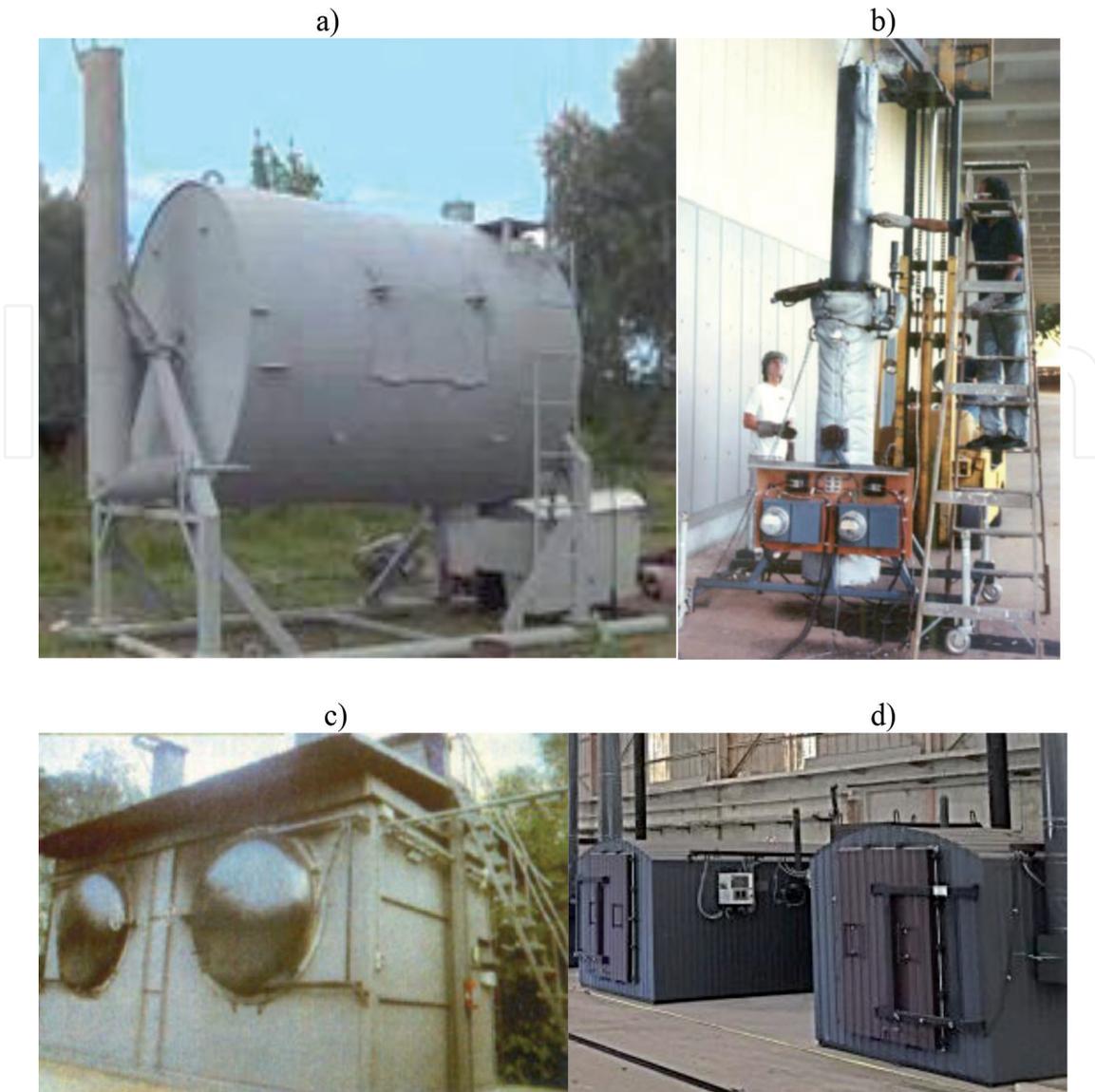
The stage of endothermic pyrolysis includes heating wood before the decomposition of hemicelluloses, removal of bound moisture, decomposition of hemicelluloses and individual lignin fragments, heating to the temperature of exothermic pyrolysis.

Criterion	Modifications
By orientation	Horizontal
	Inclined
	Vertical
Capturing liquid products	Without capturing
	Partial capture
	With catching
	With combustion of ASG
By material	Steel (retorts)
	Concrete, etc.
	Brick (oven)
By mobility	Stationary
	Collapsible
	Mobile
By the way of heat supply	With internal heat carrier
	Through the wall
Combined with other operations	Drying, pyrolysis, cooling
	Pyrolysis only
	Drying and pyrolysis
	Pyrolysis and cooling
	Combination with activation
By the method of moving raw materials	Due to the movement of the working area or pushing device
	Under own weight
	In withdrawable devices
	Stationary
	In trolleys
By type of raw material	Unseparated logs
	Chopped firewood
	Sawdust briquettes
	Waste
By mode of operation	Periodic
	Semi-continuous
	Continuous

**Table 3.**  
*Systematization of charcoal burning equipment [2].*

Exothermic decomposition of wood occurs in the temperature range from 275 to 450°C. At this stage, there is an intensive decomposition of cellulose and lignin, secondary polymerization reactions occur, and resins are formed. The free heat of exothermic pyrolysis is 1000–1150 kJ per 1 kg of wood.

The beginning of intensive decomposition of cellulose and wood corresponds to a temperature of 280–290°C, lignin decomposes at a temperature of about 350–450°C.



**Figure 2.**  
*Equipment for the production of charcoal: (a) combustion furnace VMR (USA); (b) experimental reactor Antala (University of Hawaii, USA); (c) UVP-5US mobile incinerator (CIS); (d) charcoal kiln unitary enterprise "EKO-CARBON" (Ukraine).*

At this stage, it is necessary to provide intensive heat removal to prevent the possibility of an uncontrolled process. The gases generated by pyrolysis can be used for combustion in the combustion chamber. In the event of an excessive temperature rise, intensive removal of the temperature is required. The completion of wood pyrolysis is most often determined by the absence of active combustion of pyrolysis gas in the combustion chamber.

Calcination is necessary to remove from the carbon skeleton the residues of volatile substances retained by adsorption. At the same time, the content of non-volatile carbon in coal increases and the mass yield of charcoal decreases. In the course of calcination, the structure of coal also changes – functional groups containing oxygen and hydrogen are split off from it, and the bonds between carbon atoms change.

In the course of calcination, endothermic and exothermic reactions proceed in parallel, the total balance of the stage is endothermic. However, with a high degree of accuracy, it can be assumed that the heat consumption during the calcination process is necessary only for heating the charcoal.

During the cooling process, the temperature of the charcoal is lowered to 120°C. This process is most efficiently carried out using steam. Lower temperatures can be

achieved using cold, non-condensable pyrolysis gases. After coal is unloaded from the reactor, it cools completely without oxygen.

Of the many factors that determine the yield and composition of biomass pyrolysis products, the main ones are the final process temperature and pressure in the apparatus, the heating rate of the material, the type of heat carrier used, the method of heat exchange and the presence of chemical additives, as well as the type and quality of raw materials.

It is known that the process of pyrolysis of plant biomass is influenced by various parameters, such as temperature, composition and structure of raw materials, moisture content of raw materials, environmental pressure, etc.

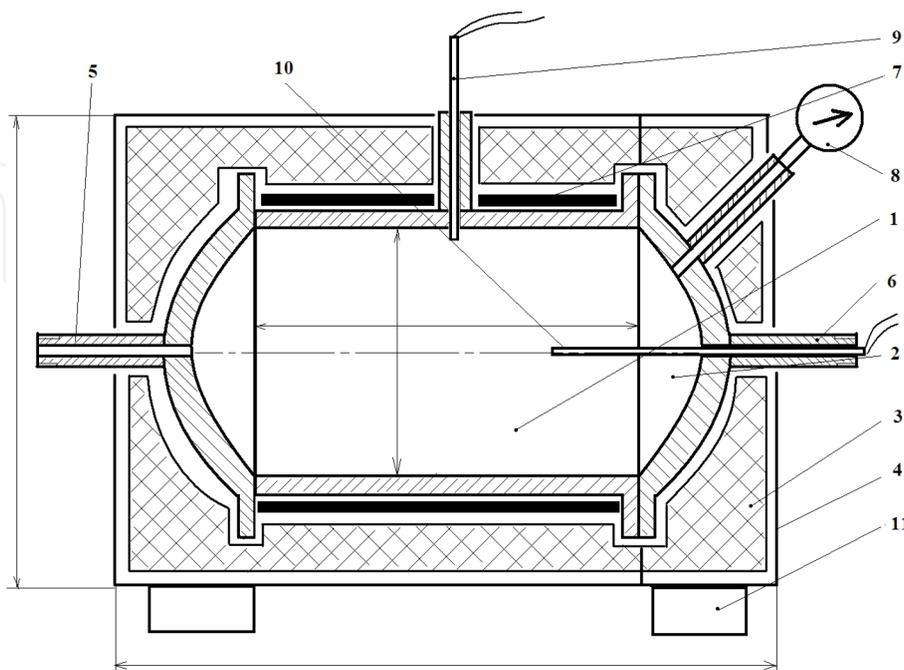
The influence of pressure on the process of wood pyrolysis has been studied for quite a long time [4–8].

Klason et al. [4, 5] more than 100 years ago, studying the pyrolysis of cellulose and woody biomass at a temperature of 400°C, found that the formation of charcoal is due to the occurrence of primary and secondary chemical processes. According to these authors, as a result of the course of primary processes, the formation of charcoal and a large amount of various hydrocarbons occurs, which then decompose with the formation of charcoal and volatile components CO<sub>2</sub>, CO, H<sub>2</sub>, etc. pyrolysis, the yield of charcoal is increased.

The results of Klason et al. [4, 5] were later confirmed in studies of pyrolysis of various types of biomass and various conditions of this process [6–8].

Despite extensive studies of the influence of pressure and other factors on the formation of charcoal in the process of pyrolysis of biomass, the chemical mechanism of the influence of pressure has not yet been clarified, which necessitates a study of this effect when developing an effective technology for the production of charcoal from biomass.

A laboratory reactor for the thermochemical conversion of wood was developed and constructed to work out the modes of the process of obtaining charcoal. The diagram of the reactor is shown in **Figure 3**.



**Figure 3.**  
*Schematic of a laboratory reactor.*



**Figure 4.**  
*Laboratory bench for the production of charcoal.*

The main elements of the laboratory reactor are housing 1, cover 2, thermal insulation 3, casing 4, fittings 5–6, electric heater 7, monometer 8, thermocouples 9–10, support legs 11.

The general view of the reactor is shown in **Figure 4**.

The raw material used was birch wood in the form of firewood and chips.

The design of the reactor allows pyrolysis of biomass both at atmospheric and overpressure. For this, fitting 5 was plugged, and an adjustable safety valve was attached to fitting 6 instead of thermocouple 10, which was triggered at a pressure of 0.3–0.7 MPa.

## 2. Description of experiments

To reveal the effect of excess pressure on the yield of solid pyrolysis products (charcoal), experimental studies of the pyrolysis of wood chips with a particle size of 17x8x6 mm were carried out at atmospheric and excess pressure, at various temperatures and pyrolysis times. The moisture content of the wood is 14.2%. The density of the wood is 506.4 kg/m<sup>3</sup>, the ash content is 0.23%. The moisture content was determined using a FAUNA-M moisture meter (manufactured by OOO Lenta, RF). **Table 4** shows the elemental composition of the wood raw material used. Measurement error of elemental composition 0.1%.

During pyrolysis without overpressure, raw wood was placed in a reactor. Then thermocouple 10 was placed in the wood layer (**Figure 3**). After that, the electric heater 7 was turned on. The temperature inside the wood was determined using a thermocouple 10. At the moment when the temperature exceeds 110°C, it can be concluded that the drying process is complete. Thus, the drying time of the chips was determined.

After that, the temperature in the reactor increased to 400°C. The thermocouple 10 was used to measure the temperature inside the reactor.

Component	C	O	Si	Al
Content, %	54,9	44,8	0,2	0,1

**Table 4.**  
*Elemental composition of used wood raw materials.*

The process of cooling the obtained charcoal was carried out in a natural way (with the heater turned off) and with the supply of water through the choke 5. In this case, the change in temperature inside the coal layer was recorded and the time of their cooling was determined.

When pyrolysis of wood with excess pressure increases with temperature inside the reactor, the release of gaseous products begins, which accumulate in the reactor, creating excess pressure. When the required pressure is reached, the valve is activated, and the excess of gaseous pyrolysis products leaves the reactor, which allows maintaining a constant operating pressure in the reactor.

Experiments were carried out at a pressure inside the reactor of 0.1, 0.3, 0.5, 0.7 MPa. The amount of energy consumed for the coal production process was the same for all experiments and amounted to 34.89 MJ.

**Figure 5** shows a general view of the resulting charcoal.

There was no excess pressure in the reactor (pyrolysis gases were freely leaving the reactor). The total pyrolysis time was 600 minutes (10 hours). The mass yield of coal was 25.1% (29.2% on dry weight of wood). The calorific value of coal is 34.86 MJ/kg. The calorific value was determined on a V-08MA “K” calorimeter.

In the course of the experiments, it was revealed that with the same consumed energy, the temperature inside the reactor during pyrolysis with excess pressure is higher than at atmospheric pressure. This is due to the fact that the thermal energy released during the operation of the heater accumulates inside the reactor until it begins to be consumed in the drying process or endothermic pyrolysis. However, under excess pressure, these reactions proceed at higher temperatures. For example, at a pressure of 0.1 MPa, an active process of moisture evaporation was observed at a temperature of 104 C, and at a pressure of 0.7 MPa - 185 C. This agrees with the reference data on the dependence of the temperature of water evaporation on pressure.

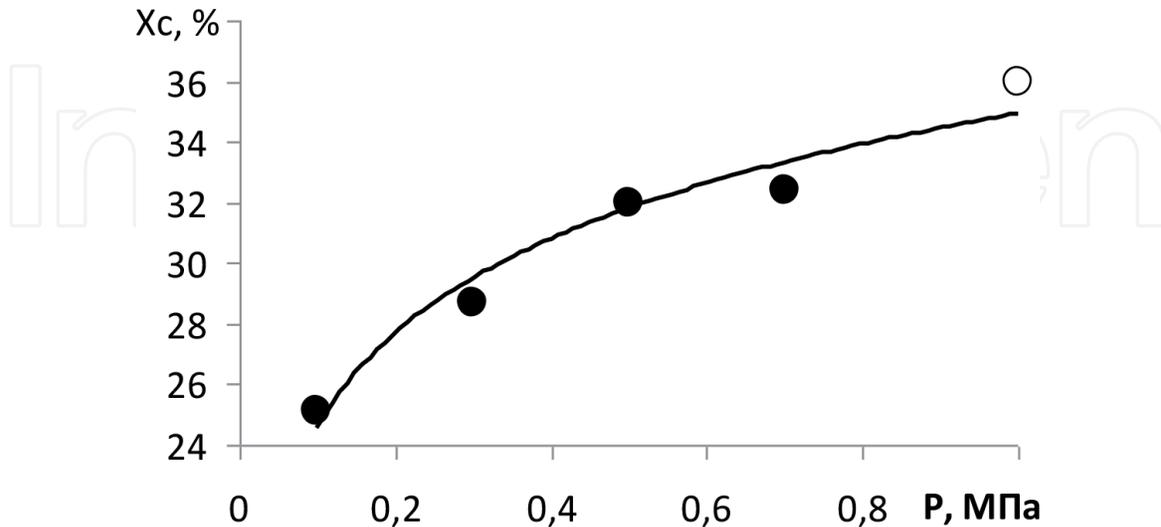
The mass yield of coal was 27.8% (32.4% per dry weight of wood with a thermodynamically equilibrium solid carbon yield of 41–42% in the pressure range



**Figure 5.**  
*General view of the resulting charcoal.*

Pressure, MPa	0,1	0,3	0,5	0,7
X <sub>c</sub> , %	25,11	28,68	31,96	32,40

**Table 5.**  
 Dependence of the mass yield of charcoal on the pressure in the reactor.



**Figure 6.**  
 Graph of the dependence of the mass yield of charcoal on the pressure in the reactor.

of 0.12–0.7 MPa). This is 1.12 times more than in the experiment without excess pressure. The calorific value of coal is 30.23 MJ/kg.

The operating time in all experiments is the same, the voltage on the heater was also constant, which means that the amount of energy expended on coal production is the same (34.9 MJ).

**Table 5** and **Figure 6** shows the dependence of the mass yield of charcoal to dry mass on the pressure in the reactor.

The mass yield of charcoal to dry matter was determined by the expression

$$X_c = \frac{M_c \cdot 100}{M_0 \cdot \left(1 - \frac{W}{100}\right)},$$

where  $M_c$  – mass of coal, g;

$M_0$  – mass of the feedstock, g;

$W$  – moisture content of the feedstock, %.

In **Figure 6**, the dark symbols are the data obtained by the authors, and the light symbol is the data obtained at the University of Hawaii (USA) [9] at a pressure of 1 MPa.

An increase in pressure leads to an increase in the residence time of gaseous pyrolysis products in the reactor and their contact with the feedstock and coal, i.e. brings the conditions in the reactor to equilibrium.

**Table 6** shows the values of the calorific value of the obtained charcoal at various pressures.

**Table 6** shows that with increasing pressure in the reactor, the calorific value of the resulting charcoal decreases. This can be explained by the fact that coal contains tar, the calorific value is higher than that of pure coal. We have determined that the

Pressure, MPa	0,1	0,3	0,5	0,7
Q <sub>c</sub> , MJ/kg	34,86	33,69	31,04	30,23

**Table 6.**  
Dependence of the calorific value of charcoal on the pressure in the reactor.

The elements	Raw wood	Coal			
		1 atmosphere	3 atmospheres	5 atmospheres	7 atmospheres
C, %	54,9	89,1	95,3	94,02	96,4
O, %	44,8	8,4	4,0	5,66	2,9
Si, %	0,2	0,2	0,1	0,01	—
Al, %	0,1	—	—	0,03	—
Ca, %	—	1,3	0,4	0,1	0,3
K, %	—	0,3	0,1	0,03	0,2
Mg, %	—	0,2	—	0,03	0,1
Mn, %	—	0,2	—	0,05	—
P, %	—	0,1	—	0,02	—
S, %	—	—	—	—	—
Fe, %	—	—	—	0,04	—

**Table 7.**  
Data of elemental composition for charcoal obtained at various pressures. Measurement error of elemental composition 0.1%.

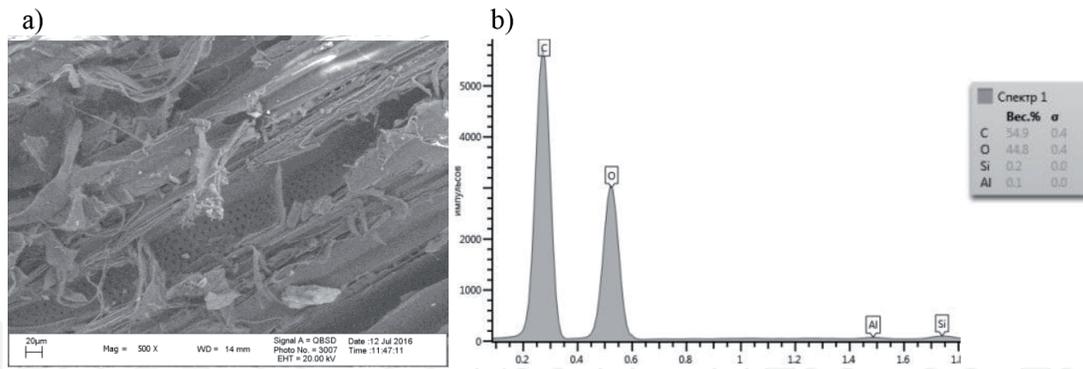
calorific value of pure coal (without tar) is 27.01 MJ/kg. It is close to the value of the calorific value of the coal obtained by us at a pressure of 0.7 MPa. High purity activated carbon was taken as a reference. At the same time, pyrolysis resins have a higher calorific value. Therefore, the presence of resins increases the calorific value of the resulting product, but decreases its quality. Based on this, we can conclude that with increasing pressure, the quality of coal increases.

This is also confirmed by the results of the elemental analysis of the obtained products. **Table 7** shows the elemental composition data for charcoal obtained at various pressures. The elemental composition was determined by X-ray spectral microanalysis using an Oxford Instruments X-MaxN energy dispersive analyzer operating in conjunction with a LEO1455VP scanning electron microscope with a sensitivity of 0.1 at.%.

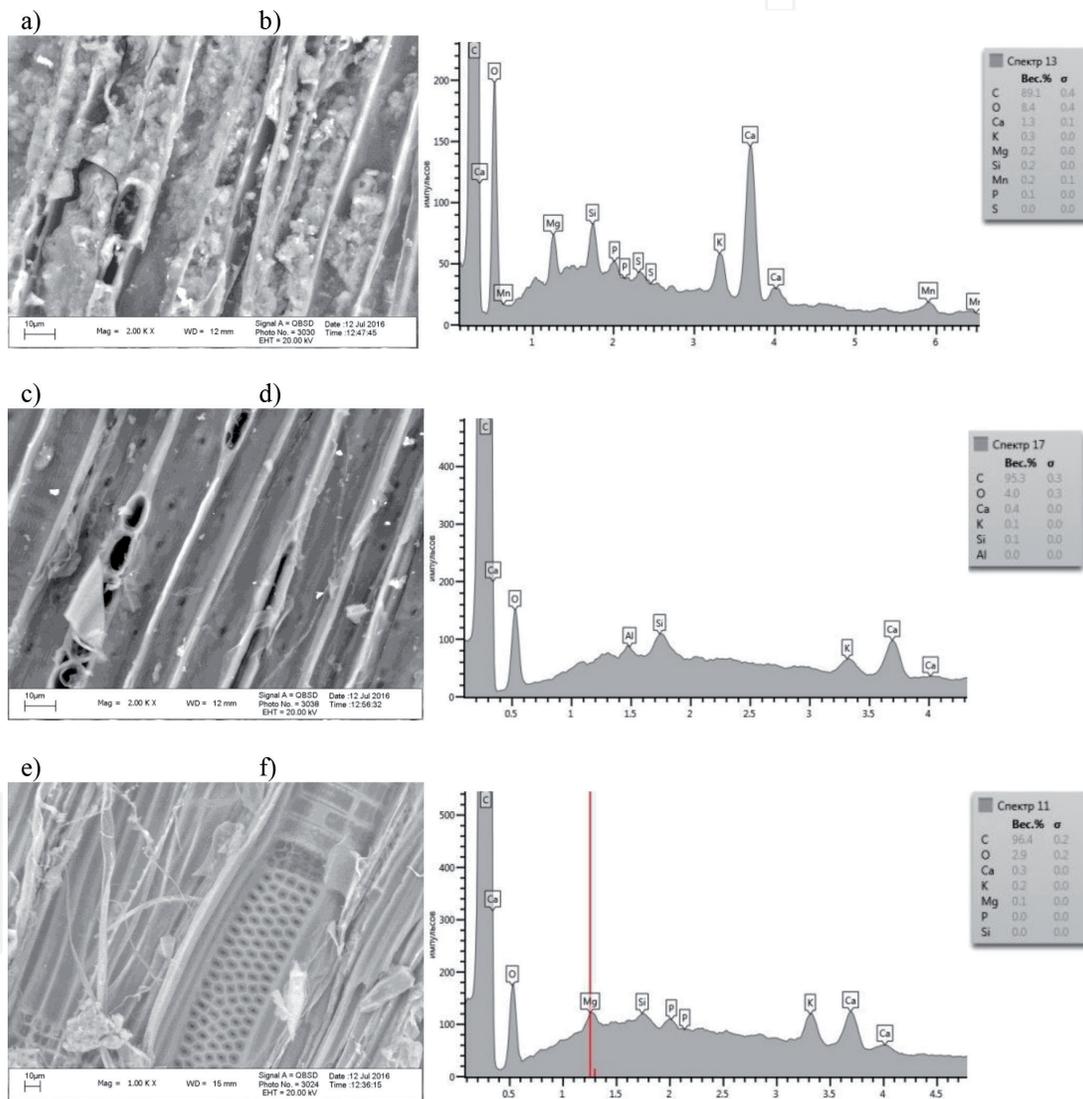
**Figure 7** shows a micrograph of the used wood and a graph of the elemental composition.

**Figure 8** shows micrographs (left) and graphs of the elemental composition (right) of charcoal obtained at a pressure of 0.1 MPa (a, b), 0.3 MPa (c, d), 0.7 MPa (e, f).

As can be seen from **Figure 8**, the charcoal composition obtained at a pressure of 0.1 MPa contains amorphous resinous inclusions (**Figure 8a**). At a pressure of 0.3 MPa, inclusions are absent (**Figure 8c**). At a pressure of 0.7 MPa, the general view of coal under a microscope coincides with wood (**Figures 7a** and **8e**). This indicates the complete preservation of the cellular structure of wood during its pyrolysis under a pressure of 0.7 MPa.



**Figure 7.**  
 Micrograph (a) of used wood and graph of elemental composition (b).



**Figure 8.**  
 Micrographs (left) and graphs of the elemental composition (right) of charcoal obtained at a pressure of 0.1 MPa (a, b), 0.3 MPa (c, d), 0.7 MPa (e, f).

As noted above, in the case of pyrolysis of birch chips at higher pressures, the temperature in the chip layer reaches the plateau-like area at higher temperatures. An increase in temperature in the layer of chips promotes the process of desorption of oxygen-containing components from the pores of the resulting charcoal and to an increase in the carbon content in it.

**Table 7** shows that with an increase in pressure from 0.1 MPa to 0.7 MPa, the oxygen content in charcoal decreases from 8.4% by weight. up to 2.9% weight. In this case, the carbon content increases from 89.1% by weight. up to 96.4% weight.

According to the authors of [4–8], such a change in the yield of charcoal and the carbon content in it is due to the occurrence of secondary chemical reactions, in which the decomposition of the primary pyrolysis products occurs with the formation of charcoal and volatile components. The positive effect of pressure in this case is due to the difficulty of the diffusion release of the components formed during the decomposition of the wood pulp. This hypothesis was confirmed by us through experimental studies of the influence of the difficulty in the yield of gaseous pyrolysis products on the quantitative yield and composition of the obtained coals.

### 3. Description of the experimental setup

The authors have developed and manufactured an experimental plant for the pyrolysis of plant biomass under pressure, which makes it possible to obtain a highly porous carbon material, the parameters of which (sorption capacity, total pore volume, bulk density, elemental composition) meet the requirements for activated carbon.

During the development of the installation, the technological scheme of thermal steam activation was adopted. In this case, the installation consists of three blocks shown in **Figure 9**.

The arrows show the movement of the steam. Each unit is equipped with a pressure relief valve. On block 1 - for 8 atmospheres, on blocks 2 and 3 - for 10 atmospheres (to ensure, first of all, the movement of steam into the pyrolysis chamber and activation). Each block is made in the form of cylinders with an inner diameter of 0.1 m. The blocks (chambers) are interconnected by adapters in the form of tubes with an inner diameter of 0.02 m. The thickness of the walls of the chambers and adapters is 0.005 m.

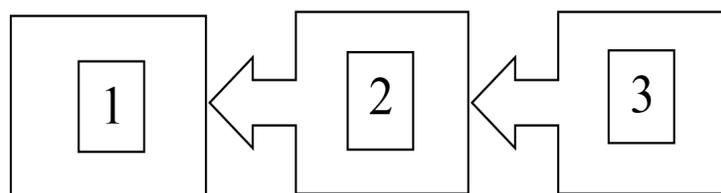
The installation diagram is shown in **Figure 10**.

The experimental setup works as follows.

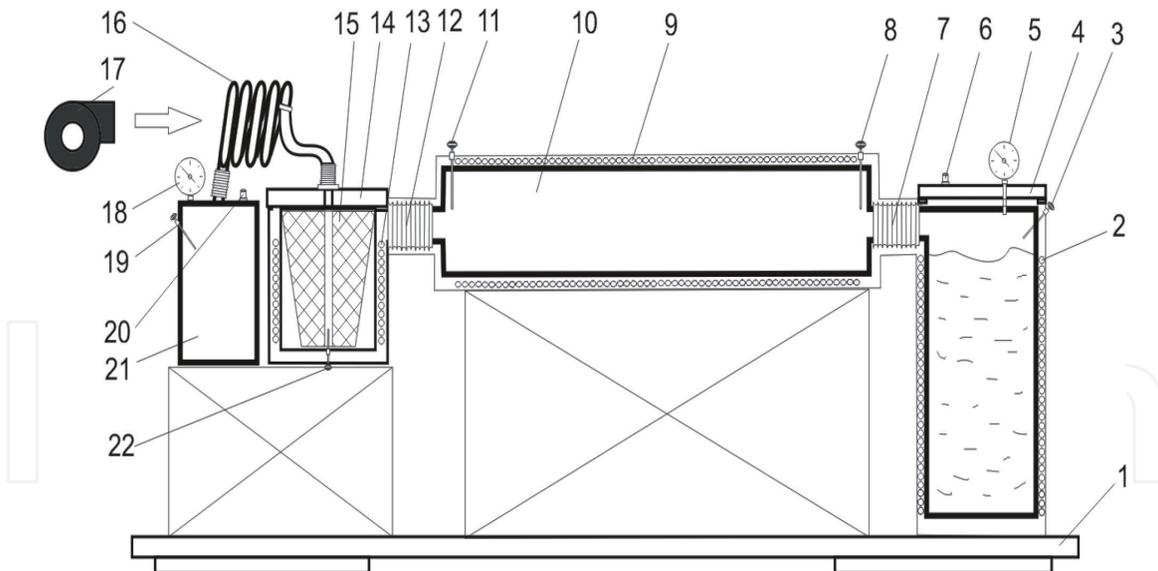
At the beginning of work, wood raw material is loaded into basket 15 (see **Figure 10**) and placed into the cavity of the pyrolysis and activation chamber.

After loading the basket, the pyrolysis and activation chamber is hermetically closed by the chamber lid 14, having previously installed a brass O-ring. Water with a volume of 2 liters is poured into the steam generator and hermetically closed with a lid. After that, the serviceability of the devices and the reliability of the fastening of the installation elements are checked. Then the fan 17, the temperature controller “Sosna-002” and the heaters 2, 9 and 13 on the steam generator, superheater and pyrolysis and activation chamber are turned on.

The required pressure in the installation is maintained by valves 6 and 20 installed on the steam generator and cooler.



**Figure 9.** Block diagram of the experimental setup. (1) pyrolysis and activation chamber, (2) superheater, and (3) steam generator.



**Figure 10.**  
 Diagram of the experimental setup.

The general view of the installation is shown in **Figure 11**.

A general view of the loaded basket is shown in **Figure 12**.

To control the pressure level, pressure gauges are installed on the steam generator and cooler.

The temperature regime in the installation is maintained through the use of electric heaters on the steam generator, superheater and pyrolysis and activation chamber. The temperatures in the chambers are controlled using thermocouples 3, 8, 11 and 19 (see **Figure 10**) installed in the steam generator, superheater, in the pyrolysis chamber and in the cooler.



**Figure 11.**  
 General view of the experimental setup.



**Figure 12.**  
*Loading the basket into the pyrolysis chamber and activation.*



**Figure 13.**  
*General view of the cooler.*

The gaseous products of the conversion, together with the superheated steam during thermal expansion, create an overpressure in the installation. In the case when the pressure exceeds the operating pressure (8 atm), the surplus of gaseous products leaves the unit through the safety valves.

Heavy hydrocarbons released in the pyrolysis and activation chamber during the operation of the unit enter the cooler (**Figure 13**) through the heat exchanger. In the cooler, heavy hydrocarbons and steam are condensed. To remove them, the cooler is equipped with an outlet pipe and a valve.

To intensify the process of cooling the exhaust gaseous products and ensure their condensation, a fan is installed that creates an air flow to enhance heat transfer.

#### 4. Description of the experiment

During the experiment, birch wood chips with a fraction size of 35x8x4 mm were used as raw materials. The humidity was 9.6% (determined by the EVLAS-2 M device). Ash content 0.11%. The density of the wood is 380.95 kg/m<sup>3</sup>. The bulk density of the chips was 187.27 kg/m<sup>3</sup>. The calorific value of wood raw material is 17269.79 kJ/kg. The mass of wood in the basket was 200.2 g.

After loading the raw material and turning on the heater, the pyrolysis and activation chamber was brought to a thermal regime corresponding to the onset of pyrolysis (250 C). After that (55 minutes after the start of the experiment), the heaters on the steam generator and the superheater were turned on. At the same time, at the end of the pyrolysis of plant biomass (wood chips), superheated steam began to flow in the pyrolysis and activation chamber. Pyrolysis started 55 minutes after the heaters were turned on and lasted 75 minutes. The maximum pyrolysis temperature was 650 C. At the end of the pyrolysis, calcination and simultaneous activation with superheated steam for 2 hours and 30 minutes took place. The superheated steam temperature was 760 C. The total process time was 4 hours and 40 minutes. At the end of the work, the heaters were turned off. After cooling all the elements of the installation and, as a consequence, reducing the pressure to atmospheric, the lid of the pyrolysis and activation chamber was opened and the basket with samples of the finished solid product was removed.

The general view of the obtained solid pyrolysis products is shown in **Figure 14**. The mass yield of solid products was 15.5%.

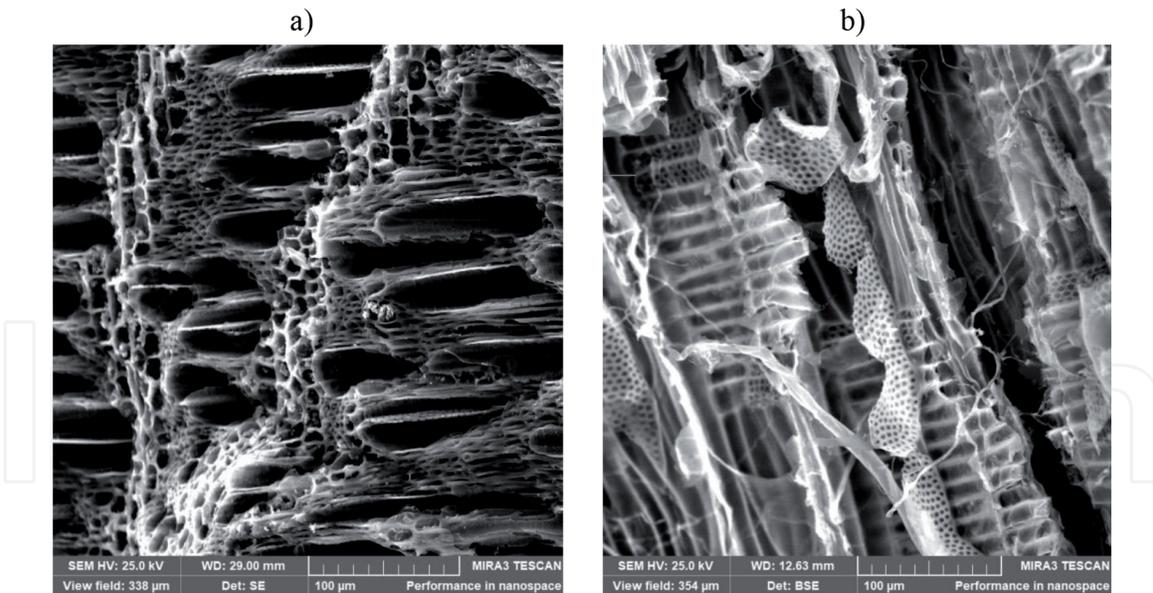
After that, the basket was again loaded with wood chips and installed in the pyrolysis chamber. At the same time, the valves were removed so that during the operation of the installation in the chambers the pressure was close to atmospheric.

Then the experiment was repeated and solid pyrolysis products were obtained, the mass yield of which was 9.4%.

It can be seen that at a pressure of 8 atm, the mass yield of solid products is higher than at atmospheric pressure. This confirms the results previously obtained by the authors and described in [10, 11].



**Figure 14.**  
*General view of solid products of wood chips conversion.*



**Figure 15.** Micrographs of samples of solid pyrolysis products obtained at a pressure of 1 atm. (a) and 8 atm. (b).

The elements	Raw wood	Coal	
		1 atmosphere	8 atmospheres
C, %	55,18	88,3	93,7
O, %	44,52	8,1	3,1
Si, %	0,15	0,7	2,0
Al, %	0,08	0,5	0,3
Ca, %	0,01	1,1	—
K, %	0,05	0,3	0,4
Mg, %	0,01	0,4	0,3
Mn, %	—	0,1	—
P, %	—	0,2	—
S, %	—	0,1	0,2
Fe, %	0,1	0,2	—

**Table 8.** Elemental composition of raw materials and charcoal obtained at different pressures.

Investigations of the composition and properties of solid conversion products were carried out. **Figure 15** shows micrographs of samples of solid pyrolysis products obtained at a pressure of 1 atm. (a) and 8 atm. (b).

The figure shows that in the sample obtained at a pressure of 8 atm. More pores are observed on the surface than in the sample obtained at a pressure of 1 atm.

The elemental composition of the samples is shown in **Table 8**. Measurement error of elemental composition 0.1%.

The table shows that the carbon content in the sample obtained at a pressure of 8 atm. Higher than in the sample obtained at atmospheric pressure. This is consistent with the results of the studies described in [10, 11].

The bulk density of the obtained solid product was 70.85 kg/m<sup>3</sup>.

The total pore volume is 3.985 cm<sup>3</sup>/g.

The values of the specific surface of the samples were determined. For solid pyrolysis products obtained at 1 atm., These indicators were: 50.31 m<sup>2</sup>/g. For the products obtained at 8 atm., They are equal to: 664.99 m<sup>2</sup>/g. The iodine content in the samples of solid pyrolysis products was not observed.

All characteristics of the obtained solid products of thermochemical conversion of wood meet the requirements of the standards for activated carbon.

The results of testing an experimental installation for thermochemical conversion of plant biomass under pressure showed the effectiveness of using such equipment to obtain highly porous carbon materials, the parameters of which meet the requirements for activated carbon. The biomass pyrolysis temperature was 650 °C, the superheated steam temperature was 760°C. The total time of the activated carbon production process was 4 hours and 40 minutes. Activation time 2 hours 30 minutes. The mass yield of the obtained solid product corresponds to 15.5%. According to the indicators revealed, the resulting product meets the requirements of the standards, which makes it possible to draw a conclusion about the possibility of using the selected technological scheme for creating industrial samples of pyrolysis equipment for producing activated carbons from woody biomass.

## **5. Conclusion**

The paper describes the methods of obtaining wood (highly porous carbon materials) based on plant (wood) raw materials, and the equipment used to implement these processes, the use of charcoal. The conclusion is made about the advantage of obtaining charcoal under excess pressure.

An experimental study of pyrolysis of birch chips on a laboratory bench in the pressure range from 0.1 to 0.7 MPa showed that an increase in pressure at which pyrolysis is carried out promotes an increase in the mass yield of charcoal and an increase in the carbon content in it. At the same time, there is a decrease in the calorific value of the resulting charcoal, which is due to the release of oxygen-containing components from the porous structure of coal, which have a higher calorific value in comparison with pure carbon.

A description of the developed and manufactured experimental setup is presented, which consists of a steam generator, a superheater, a pyrolysis and activation chamber, a cooler with a heat exchanger with forced convection, which are interconnected sections. Experiments were carried out confirming that excessive pressure increases the mass yield of solid products of thermochemical conversion of plant biomass. Were determined the physical parameters of the obtained solid products of pyrolysis and physical activation at an excess pressure of 0.8 MPa.

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