

TORREFACTION OR PYROLYSIS OF BIOMASS. PROSPECTS FOR UKRAINE

Received Mar. 31, 2025; accepted Jun. 27, 2025

Available online Jun. 30, 2025

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The article considers the processes of torrefaction and pyrolysis of biomass typical for Ukraine. The advantages of torrefied fuel and directions of its application are given. Technical problems that arise in industrial installations are separately considered (self-heating and self-ignition of the torrefied product, adsorption and condensation of liquid substances, the danger of self-ignition of torrefied gas). During the granulation of torrefied biomass, energy consumption increases 3 times compared to untreated biomass. Due to dry friction, abrasive wear of the matrix increases. The cost price of torrefied pellets is higher than that of fossil coal. Based on these considerations, it is assumed that torrefaction plants in Ukraine can be built with foreign equipment. The state of charcoal production in Ukraine has been analysed. A forecast has been made regarding further growth of its volumes. The production of biochar by the oxidative method for metallurgy and agriculture (biochar) is considered. Specific biochar rich in nutrients can be produced from granulated chicken manure and sewage sludge. A technological scheme for the continuous co-production of torrefied fuel and biochar has been developed. The use of oxidative pyrolysis reactors for creating cogeneration plants that produce both electrical and thermal energy from biomass has been considered.

Keywords: torrefaction, types of reactors, dry pyrolysis, oxidative pyrolysis, biochar.¹ Cand. of Science (Tech.)
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ТОРРЕФІКАЦІЯ ЧИ ПІРОЛІЗ БІОМАСИ. ПЕРСПЕКТИВИ ДЛЯ УКРАЇНИ

Отримано 31 бер. 2025 р.; рекомендовано до публікації 27 черв. 2025 р.

Доступно онлайн 30 черв. 2025 р.

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Розглянуто процеси торрефікації та піролізу біомаси, використовуваної в Україні. Наведено переваги торрефікованого палива та сфери його застосування. Окремо розглянуті проблеми технічного характеру, які виникають на промислових установках (самонагрівання та самозаймання торрефікованого продукту, адсорбція та конденсація рідких речовин, небезпека самозаймання торр. газу). При грануляції торрефікованої біомаси витрати енергії збільшуються в 3 рази в порівнянні з необробленою

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біомасою. Внаслідок сухого тертя збільшується абразивне зношення матриці. Собівартість торрефікованих пелет є вищою, ніж викопного вугілля. Передбачається, що в Україні установки торрефікації можуть бути побудовані на закордонному обладнанні. Проаналізовано стан виробництва деревного вугілля в Україні. Зроблено прогноз щодо подальшого нарощування його обсягів. Розглянуто виробництво біовугілля методом окиснювального піролізу для металургії та сільського господарства (біочар). Специфічний біочар, насичений поживними речовинами, можна виробляти з гранульованого курячого посліду та каналізаційного мулу. Розроблена технологічна схема безперервного сумісного виробництва торрефікованого палива й біовугілля з рослинної біомаси. Розглянуто використання реакторів окиснювального піролізу для створення когенераційних установок з виробництва електричної й теплової енергії з біомаси.

Ключові слова: торрефікація, типи реакторів, сухий піроліз, окиснювальний піроліз, біочар.

Introduction

The search for new types of energy capable of replacing fossil fuels with renewable sources has led to an increase in both fundamental and applied research, primarily focused on the potential for regenerating natural resources, as the current energy system is based mainly on the use of fossil fuels. Biomass plays a vital role, as it can be used to produce solid fuel, combustible liquids, and biogas. Moreover, biomass helps to offset the intermittency of solar and wind power generation. Therefore, a backup form of energy production is needed—one that can ensure continuity of energy supply when required. Biomass can be considered the first energy source that humanity learned to utilise, initially for combustion and later for producing charcoal (biochar). In addition, biomass serves as a means of storing and accumulating solar energy through the process of photosynthesis. However, unlike fossil fuels, biomass has several disadvantages, such as low energy density, high moisture content, low calorific value, expensive logistics, etc. These drawbacks, however, can be reduced or eliminated through the use of physical, biological, and thermochemical biomass processing technologies.

This article examines thermochemical technologies for converting biomass into a solid carbonaceous residue (biochar) as the main product and combustible (pyrolysis) gas as a by-product. The relevance of biochar production is driven by the fact that the EU acquis restricts the use of fossil fuels by the provisions of the Paris Climate Agreement and the earlier Kyoto Protocol. At the same time, the use of biochar is being encouraged at coal-fired thermal power plants and boiler stations. In terms of fuel properties, biochar is comparable to fossil coal. It has a brittle structure, is easily crushed and ground using existing power plant equipment and can be used for flame combustion without the need to reconstruct the heat supply system.

The aim of this study is to conduct a comparative analysis of thermal biomass conversion methods—torrefaction and pyrolysis—in order to assess their potential for application in Ukraine. To achieve this goal, the following four **objectives** must be addressed:

1. To analyse available state-of-the-art thermochemical technologies for converting biomass into biochar;

2. To explore the feasibility of biomass torrefaction using the method of oxidative pyrolysis;
3. To provide recommendations for biochar production in Ukraine;
4. To develop a technology for the combined production of biochar and torrefied biofuel.

Materials and Methods of Torrefaction

It is known that lignocellulosic biomass typically consists of three main components: cellulose, hemicellulose, and lignin. The chemical composition of dry woody and plant biomass is approximately the same and consists of carbon (50%), oxygen (42%), hydrogen (7%), and ash (1%). Studies have shown that hemicellulose decomposes in the temperature range of 210–320 °C, cellulose at 300–390 °C, and lignin at 200–550 °C. When biomass is heated in the absence of air or with limited oxygen access, chemical depolymerisation of hemicellulose, cellulose, and lignin occurs, resulting in the formation of biochar with a high carbon content of up to 92–95%, which is nearly pure carbon. This phenomenon was noticed by our ancestors, who began producing biochar from wood by burning it in earth-covered piles. However, biochar was not initially used as fuel but rather as a soil amendment (biochar) to improve soil structure and increase its fertility. Over 1,000 years ago, entire fields of biochar-enriched soil (Terra Preta) appeared in the Amazon Basin, and they have retained high fertility to this day [1]. Thus, the first use of biochar was likely agricultural. In those ancient times, there also arose the need for smelting and heat treatment of various metals. As a fuel, they used biochar made from wood. Over the centuries, the process of biochar production was refined and developed into an industrial technology and became known as pyrolysis. According to the regulatory document [2], pyrolysis is an irreversible thermal decomposition process of fuel in the absence of air. According to various sources, biomass pyrolysis occurs within a temperature range of 200 °C to 900 °C and lasts from several seconds to more than a day, depending on the size and moisture content of the raw material. The process occurring at 200–320 °C is referred to as mild pyrolysis (torrefaction or bertinisation). Currently, the term "torrefaction" is the most commonly used.

Medium-temperature pyrolysis, also known as pyrolysis, occurs at temperatures ranging from 300 to 600 °C and is a widely used industrial process for producing charcoal for energy applications. High-temperature pyrolysis, occurring at 600–900 °C and sometimes up to 1,000 °C, enables the production of biochar with a high sorption capacity.

Although torrefaction has been known for quite a long time (over 100 years), the practical use of torrefied biomass has historically been very limited. For example, firewood was torrefied and then used to heat the homes of wealthy households. In recent decades, interest in torrefaction has grown—about 40 years ago—due to the restrictions on CO₂ emissions from fossil fuels. Biomass, as is well known, is a CO₂-neutral fuel. Currently, plant-based biomass is

considered the primary feedstock for torrefaction, and its availability is many times greater than that of woody raw materials [3, 4]. This includes readily available materials such as sunflower husks, buckwheat hulls, rice husks, and screenings from grain elevators.

Another promising source is baled agricultural residues—including straw from grain and rapeseed crops, baled corn, sunflower and miscanthus stalks, and bedding manure—amounting to millions of tons annually [3]. Thus, Ukraine possesses sufficient plant biomass resources to establish industrial production of torrefied biofuel.

Fig. 1 shows the block diagram of the torrefaction process, and Fig. 2 presents the technological scheme [5].

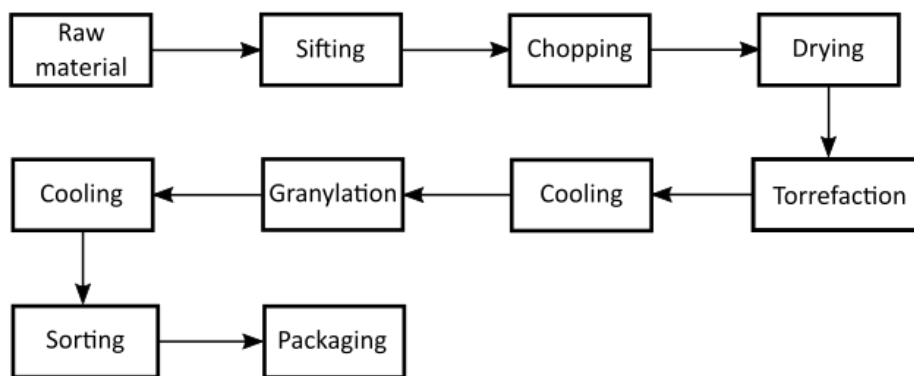


Fig. 1. The torrefaction flowchart

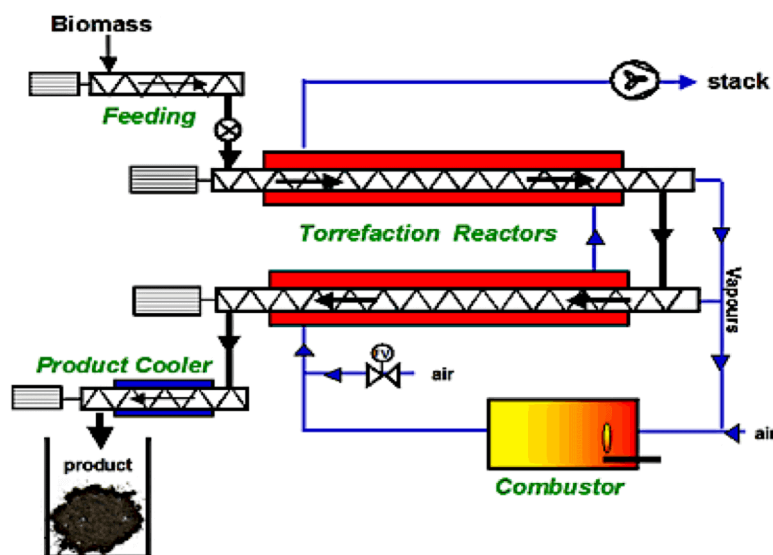


Fig. 2. The technological scheme of torrefaction

Types of torrefaction reactors. The main element of the flow chart is the torrefaction reactor.

A rotary drum reactor is the most common type of continuous reactor, where the feedstock can be heated either externally—through the reactor wall—or directly within the reactor using an inert (oxygen-free) gas stream.

Most often, the drum in which the biomass is transported is heated from the outside, without direct contact between the hot flue gas stream and the feedstock. Heat transfer occurs through thermal conduction. The residence time of the feedstock can be adjusted by controlling the rotation speed of the drum.

Torrefaction reactor with a fluidised bed: Moist biomass is placed on a grate, while hot inert gas is injected from below through the biomass layer. At a sufficient gas velocity, the biomass is lifted above the grate and behaves like a fluid. This results in a uniform temperature distribution throughout the biomass bed.

Microwave reactor. The microwave torrefaction reactor uses high-frequency electromagnetic waves. These waves create vibration of water molecules inside the biomass, which leads to an increase in its temperature to a predetermined value [6]. The torrefaction process takes place in the temperature range of 200–320 °C, at which most of the hemicellulose is destroyed while cellulose and lignin are only partially. In the process of torrefaction, moisture evaporates, and volatile substances are formed – torrefaction gas (torr. gas). At the same time, the mass of raw materials is reduced by 20–30%, and 10% of the energy intensity of raw materials is converted into torrefaction gas. As a result of a significant decrease in the mass of raw materials, in comparison with the loss of energy, the combustion heat of the torrefied product increases by 10–15 % compared to the initial raw material.

The main advantages of torrefied fuel [7]

The calorific value is 20–21.6 MJ/kg, hydrophobicity, less volatile substances are released during combustion, and logistics costs are reduced when transporting torrefied pellets with a high volumetric density of up to 750 kg/m³. Typically, torrefied fuel is mixed with fossil coal in coal warehouses and then enters the fuel feeding system.

Parameters affecting the torrefaction process [8–13]

Temperature and residence time. The residence time mainly affects the decomposition of hemicellulose. The characteristics of the final product are more influenced by temperature than residence time. The rate of heating used during the torrefaction process affects the secondary dehydration reactions that determine the final distribution of solid, liquid and gaseous products.

Raw material particle size. The discrepancy between the particle size of the input raw material and the moisture content leads to variation in heat transfer and, as a result, uneven heating. The smallest pieces will turn into charcoal, while the larger pieces will not be fully baked.

Industrial development of torrefaction

The results of numerous studies on laboratory plants for torrefaction of different types of biomass do not yet guarantee the capacity, continuity and reliability of torrefied biomass production in pilot plants, and even more so in industrial ones. The main reason is the difficulty of scaling, since many problems cannot be predicted, as they arise when processes occur on a larger scale [14]. According to source [15] when torrefying Yunnan pine at a temperature of 300 °C, the yield of the solid phase was 46.27 % (wt), torr. gas 33.62% (wt.), liquid fraction nearly 20% (wt.). The composition of torr. gas obtained by torrefaction of corn stalks

at a temperature of 300 °C is as follows: hydrogen – 31.82%, CO – 19.97%, CO₂ – 20.70%. Lower calorific value – 17.83 MJ/m³ [16].

Torrefaction gases contain H₂, CO, CO₂, CH₄ and a variety of condensing components such as acetic acid, formic acid, methanol, furfural, hydroxyacetone and water. They are highly reactive and can quickly polymerise into bio-oils. These bio-oils are adsorbed in the reactor on the surface of torrefied biomass particles. After unloading and cooling, the bio-oil particles condense and flow out of the storage containers for the torrefied product.

A significant issue associated with torrefied products is the phenomenon of self-heating and spontaneous combustion [14]. For example, at an atmospheric air temperature of +95 °C, torrefied material can begin to ignite and burn without a visible flame. There have been documented cases of self-heating and ignition of torrefied pellets stored in outdoor piles—even during rainy weather. To eliminate the risk of spontaneous combustion, a two-stage torrefaction technology for sunflower husks was proposed in [17]. This method involves torrefaction in a hearth-type reactor at a temperature of 250 °C, followed by cooling of the resulting product using atomised water. The cooling process occurs at a temperature above 120 °C. Upon contact with the hot product, the water instantly turns into steam, as the latent heat of vaporisation is exceeded. The water consumption for cooling is about 0.3 L per kilogram of biomass. The proposed torrefaction technology ensures rapid and reliable cooling of the torrefied product while simultaneously suppressing the exothermic processes that may occur in the hot material, thereby increasing the fire safety of the torrefaction process. The torrefied product does not require drying, as the water fully evaporates upon contact with the hot material, and the resulting steam mixes with the torrefaction gas and is expelled from the reactor.

The key problem observed during pelletising torrefied biomass is high energy costs due to product friction. Compared to pelleting of raw biomass, they increase almost 3 times, from 50–60 kW·h/t to 150 kW·h/t. Also, the quality of torrefied pellets (strength, density, surface structure, moisture resistance) turned out to be lower than expected.

The service life of the matrix when using torrefied material is shorter because it is harder than raw biomass.

For the above and other reasons, many biomass torrefaction projects have failed, as evidenced by various news stories on the Internet. There are no examples of torrefied pellets being transported in open gondola cars. The cost of torrefied pellets is still higher than that of coal.

Thus, in the world, biomass torrefaction is in the initial stage of commercial implementation. For example, the well-known Austrian company "Polytechnic" is building the largest wood chip-based plant in Europe in Finland, with a capacity of 60,000 tons. In the future, such plants, which run on plant biomass, can be built in Ukraine, as is the case with biogas plants that use foreign equipment.

Unfortunately, domestic biomass torrefaction studies are at the stage of laboratory installations.

For example, we conducted an experimental test into the possibility of torrefying pellets by oxidative pyrolysis. To conduct experimental research, a laboratory installation was created, the scheme of which is shown in Fig. 3. The unit operates under positive pressure (Fig. 3, a).

Thermocouples T_1 – T_4 of type K are installed at the height of the reactor to measure temperature. The thermocouples were connected to a 4-position multimeter.

In the installation under vacuum (Fig. 3 b), there is no gas meter 4. To cool the torr. gas to a temperature acceptable for the operation of the fan, the receiver 4' is installed.

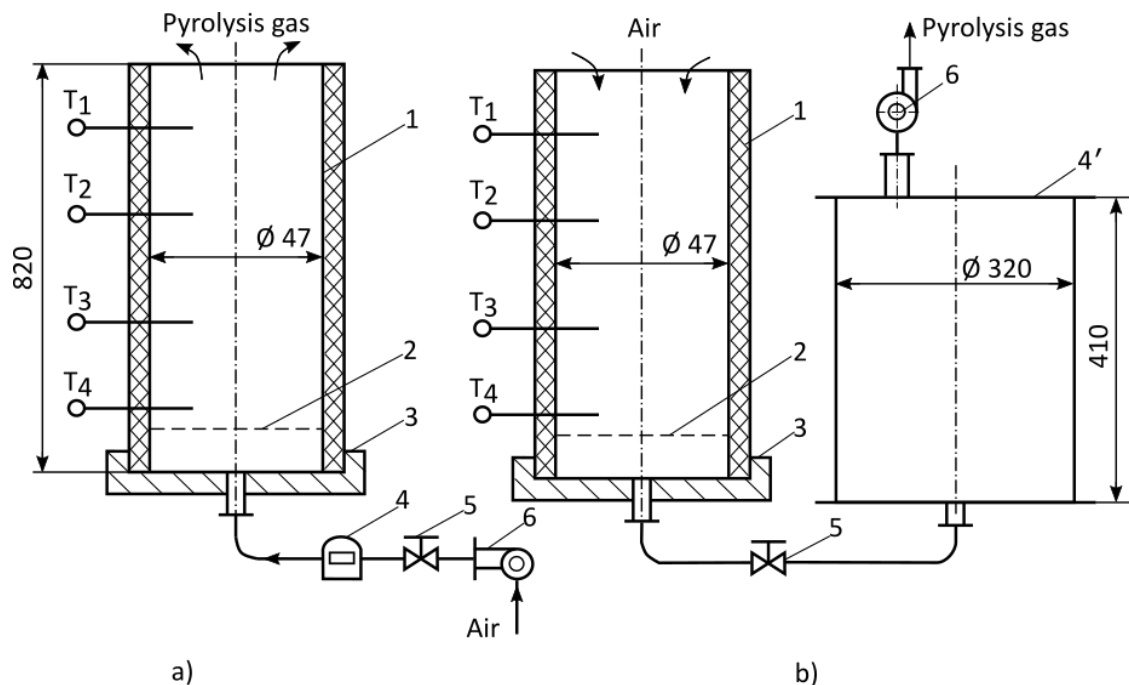


Fig. 3. The scheme of a laboratory installation for biofuel torrefaction

a) under air pressure; b) under vacuum

1 – reactor with thermal insulation; 2 – grate; 3 – cover; 4 – gas meter; 5 – valve; 6 – fan; 4' – receiver

Experimental studies on a pressurised air unit (Fig. 3, a). Wood pellets with a diameter of 8 mm and a moisture content of <10% were loaded into the reactor. The weight of the pellets was 900 g. The air supply fan 6 was turned on, and the top layer of pellets was ignited using a gas burner. When the temperature reached 450 °C on the thermocouple T_1 , the burner was turned off. A combustion zone of torrefaction gas was formed in the reactor, moving downward against the flow of air supplied by the fan. The amount of air was regulated by a damper and measured using a gas meter. At a temperature of 450 °C, the process of oxidative pyrolysis of the pellets occurred, resulting in the formation of biochar. By reducing the air supply to the reactor, the temperature in the combustion zone of torr. gas was gradually reduced to a maximum torrefaction temperature of 320 °C.

As the air supply was reduced, the combustion of the torrefaction gas gradually diminished, and smoke began to emerge from the open top of the reactor. The temperature recorded by thermocouple T_1 dropped to 280–320 °C, and the process came to a halt. When the air supply was increased, the temperature at T_1 rose again to 420–450 °C, and the torrefaction gas burned smokelessly. Five test runs

of the system were conducted, which showed that torrefaction does not occur at a temperature of 320 °C.

Experimental studies on a unit under vacuum (Fig. 3 b).

An advantage of this setup is its ability to operate in a continuous mode. The startup procedure is as follows: a layer of red-hot pellets is placed onto the grate of the reactor. The fan is then turned on, drawing air into the reactor through its open top. 800 g of pellets with a diameter of 8 mm and a moisture content below 10% are loaded into the reactor. A combustion zone of torrefaction gas forms and moves upward against the incoming air stream. When the temperature measured by thermocouple T_4 reaches 450–500 °C, the air supply is reduced. With further reduction of the air flow, the temperature at T_3 stabilises at around 320 °C, as observed in previous tests. At this temperature, smoke is emitted from the fan instead of torrefaction gas. The temperature at T_4 then begins to drop below 320 °C, and the torrefaction process halts. To resume the process, the damper is opened, drawing in more air into the reactor. The process restarts at a temperature of 420–470 °C, corresponding to low-temperature oxidative pyrolysis.

It is assumed that at a torrefaction temperature of 320 °C using the oxidative pyrolysis method, the torrefaction gas contains a high proportion of nitrogen, carbon dioxide, and water vapour (non-combustible components), and too few combustible compounds (carbon monoxide, hydrogen, methane). As a result, it cannot sustain combustion on its own. Therefore, there is no internal heat source, and torrefaction does not occur. Thus, torrefaction of biofuel is best conducted using the dry pyrolysis method.

Charcoal production in Ukraine. Charcoal is produced by dry pyrolysis (indirect heating of raw materials through the retort wall). The amount of charcoal produced per capita is extremely small, approx. 0.1 kg/year. In industrialised countries, this figure is up to 20 kg/year, for example, in Japan. According to the portal of charcoal producers, 247 charcoal producers are registered in Ukraine.

Perechyn Timber Chemical Plant is the largest producer of wood and coal products in Ukraine (up to 4,000 tons per month). Coal production takes place in two vertical retorts. All pyrolysis gases are burned in the waste heat boiler.

In addition to the official producers of charcoal, handicraft production flourishes in Ukraine in all forest-rich regions – from Sumy to Uzhhorod. The cycle of burning a batch of coal is lengthy, while illegal producers often do not use equipment that reduces harmful emissions, given its high cost. Primitive charcoal production could turn Ukraine into Haiti, where illegal charcoal production has led to an environmental disaster yet has not enriched the inhabitants.

There is a great demand for charcoal worldwide, so most of its producers focus on exporting it due to its high price and low requirements for its quality. Overseas, this product is mainly used as raw materials for further processing.

According to the State Customs Service, in 2023, Ukraine exported 122 thousand tons of charcoal and imported 957 tons.

The most important for biochar consumers are its mechanical strength, electrical resistance, calorific value and porosity. Table 1 shows the tentative composition of charcoal.

Table 1. Elemental composition of charcoal

Pyrolysis temperature, °C	Output, %	Content of elements, %		
		C	H	O
100	100	47.4	6.5	46.1
200	92.6	58.4	6.1	36.5
400	39.2	76.1	4.9	19.0
600	28.6	93.8	2.6	3.6
800	26.7	95.7	1.0	3.3

Further increases in charcoal production are predicted, both by expanding the operating enterprises and constructing new ones.

Biochar production by the oxidative pyrolysis method. By dry pyrolysis technology, only one product is manufactured – charcoal. The pyrolysis gas generated during the process is used to meet the system's own technological needs. To improve the energy efficiency of the process, a method known as oxidative pyrolysis was proposed nearly 40 years ago. This method yields two products: biochar and pyrolysis gas. The term biochar refers to charcoal made from woody or plant-based biomass. In addition to the term oxidative pyrolysis, the literature also uses the term partial gasification [18, 19]. This technology is based on the effect of a “reverse thermal wave” in the fuel bed. The fundamental difference between oxidative pyrolysis and dry pyrolysis is that in oxidative pyrolysis, the fuel is evenly heated inside the reactor with limited air access, due to the combustion of part of the pyrolysis gas. The optimal particle size for biofuel in oxidative pyrolysis is 10–40 mm (such as wood chips, pellets, and briquettes), and the optimal moisture content is up to 20%.

For the first time in Ukraine, the technology of oxidative pyrolysis was studied at the National Metallurgical Academy

(Dnipro-based) by a research team led by Dr. Tech. Sci. Hubynskyi M.V. [20]. The processing of sunflower husks and walnut shells into biochar was investigated as a raw material to produce high-calorific fuel briquettes. Currently, research is being conducted to develop methods for using carbon materials derived from plant biomass in metallurgical processes. This will help reduce the metallurgy sector's dependence on fossil fuels. The production cost of biomass-based coke will be lower than that of fossil coal coke. The cheapest types of biofuel are sunflower husks and cereal straw.

At the Institute of Gas of NAS of Ukraine, under the supervision of Ph.D. in Technical Sciences Panyh K.Y., cogeneration units for the production of electric and thermal energy from biomass are being developed based on oxidative pyrolysis technology. For instance, the Institute is testing an industrial unit powered by wood pellets with an electrical capacity of 25 kW. Due to improvements in technology, the tar content has been reduced to 0.1 g/m³ of pyrolysis gas. Such gas is fully suitable for use in gas-piston engines. Another product of biomass thermal processing—biochar—is used to produce fuel briquettes using a roller press. The unit operates in batch mode; therefore, to ensure continuous electricity generation, several pyrolysis reactors are required [19]. Based on the developments of the Institute of

Gas, the company “Biosmartex” in Rivne offers cogeneration units with a capacity of 4,000 kW (electric) and 3,900 kW (thermal). Fuel consumption is 3,000 kg/h, and the biochar yield is 20% [21].

At the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, under the supervision of Ph.D. in Technical Sciences Klyus S.V., a technology was developed for producing organic fertilisers from large-scale waste, namely poultry litter and sewage sludge [22]. Poultry litter is classified as Class IV hazardous waste. According to Article 246 of the Tax Code of Ukraine (as amended July 1, 2019), the rate for waste disposal is set at 5 UAH/ton. Poultry farms that can utilize poultry litter by any method or sell it directly to consumers are exempt from taxation. In Ukraine, the volume of poultry litter amounts to approximately 5 million tons per year (about 10% of the European figure).

To facilitate the successful utilisation of bedding-based poultry litter, some poultry farms install pelletising lines. The pellets have a diameter of 8–10 mm and a moisture content of up to 30%. Due to their unpleasant odour, the pellets are packaged in sealed bags. We conducted a test

processing of these pellets using the oxidative pyrolysis method. At a temperature of 400–600 °C, carbonised biochar (an organic fertiliser) is obtained, with a nutrient content comparable to simple superphosphate. Additionally, thermal processing of pellets made from sewage sludge from the Bortnychi Aeration Station in Kyiv was carried out on a pilot-industrial unit. The carbonised sludge also contains nutrients and can be used as fertiliser [22].

Thus, carbonised waste—poultry litter and sewage sludge—can be considered a specific type of biochar enriched with nutrients. The discussed applications of oxidative pyrolysis technology for biomass show good potential for industrial implementation in Ukraine.

Development of a technology for the combined production of biochar and torrefied biofuel.

The gas produced during oxidative pyrolysis has a low calorific value. Therefore, it is often burned as production waste. To enable the beneficial use of pyrolysis gas, a basic scheme has been developed for a continuous-operation unit for the combined production of biochar and torrefied biofuel (Fig. 4).

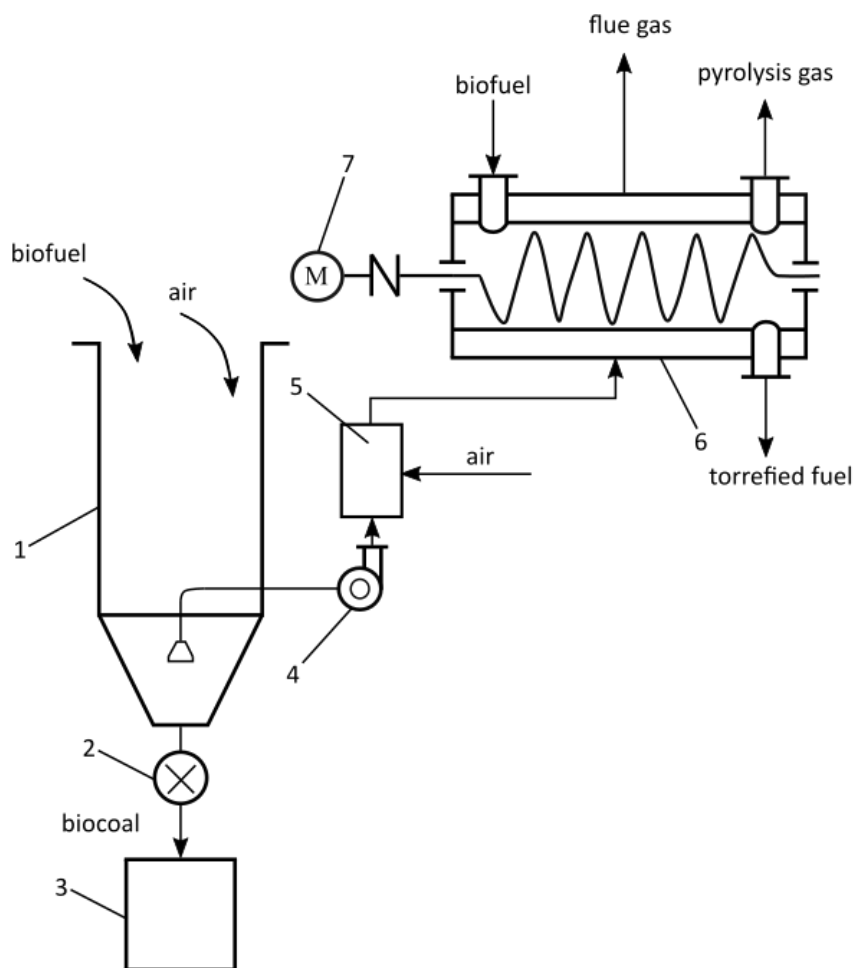


Fig. 4. The Scheme of installation of continuous operation

1 – oxidative pyrolysis reactor; 2 – gateway shutter; 3 – collection of biochar; 4 – smokehole;
5 – combustion chamber; 6 – auger torrefier; 7 – engine

The unit operates as follows. First, biochar is loaded into the oxidative pyrolysis reactor (1), with the upper layer being ignited. Then, the lock valve (2) is switched off, allowing part of the biochar from reactor (1) to enter the collector (3), while fresh biofuel in the form of pellets, wood chips, or briquettes is fed into reactor (1) to replace it. Due to the vacuum created by the exhaust fan (4), air is drawn into the reactor (1), initiating the oxidative pyrolysis process. The discharge of biochar and the feeding of biofuel into reactor (1) are then synchronised. [23].

The pyrolysis gas generated in reactor 1 flows into the combustion chamber (5), where it is burned with air. The resulting flue gases are directed into the jacket of the screw torrefier (6), heating it to the required temperature (max 320 °C). Finely dispersed biomass (pellets, wood chips, grain cleaning waste, etc.) is fed into the body of the torrefier through a conveyor system and a lock valve. This biomass is heated, torrefied, and transported by the screw to the discharge hatch. Torrefaction gas, which contains no nitrogen, is formed inside the torrefier. After appropriate purification, this gas can be used as boiler fuel. The flue gas from the jacket of torrefier 6 is released into the atmosphere. By combining the oxidative pyrolysis reactor and the screw torrefier in a single technological scheme, the following products are obtained: biochar, torrefied biofuel, and torrefaction gas. The overall energy efficiency is increased by utilising the pyrolysis gas to heat the torrefier.

Conclusions

Biomass torrefaction is presented as a process capable of improving the combustion properties of biomass. However, this technology is still in the early stages of industrial implementation in developed countries. It is anticipated that torrefaction units in Ukraine could be built using imported equipment, as in the case with biogas installations.

Based on the results of experimental studies, the torrefaction of wood pellets using the method of oxidative pyrolysis has shown that the process is physically impossible, even at the highest torrefaction temperature of 320 °C. The torrefaction gas does not contain a sufficient amount of combustible components to sustain combustion, causing the torrefaction process to stop.

A promising direction for Ukraine is the use of oxidative pyrolysis of biomass to produce biochar from plant waste, poultry litter, and sewage sludge. In particular, biochar can be used in metallurgy, while agricultural biochar can be applied in farming. At the Institute of Gas of NAS of Ukraine, cogeneration units for generating electric and thermal energy have been developed based on oxidative pyrolysis reactors.

An energy-efficient technological scheme is proposed that combines the operation of an oxidative pyrolysis reactor for biochar production and a screw-type torrefier for the production of torrefied biofuel. The knowledge and experience accumulated by Ukrainian scientists and engineers are already being implemented in demonstration projects and are expected to be scaled up for industrial use.

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