VOLUME 20, ISSUE 1, 2019

# International Journal of Energy for a CLEAN Environment

Editors-in-Chief
Kuruvilla John
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ASTFE
American Society
of Thermal and Fluids Engineers

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New York • Connecticut

*International Journal of Energy for a Clean Environment* 20(2):113–134 (2019)

# PERSPECTIVES FOR DEVELOPING AND USING THE TORREFACTION TECHNOLOGY IN UKRAINE

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*Ukraine refers to countries that only partially provide themselves with traditional types of energy resources, and it is forced to import about 65% of fossil fuels. This article shows the possibility of increasing the biomass energy using through introduction of torrefaction technology as a relatively new process that allows converting raw material to highly efficient fuels with properties close to fossil fuels increasing amount of processing of raw materials geography of its delivery, reducing the cost of transportation, storage what will be enable to save traditional fuel and energy resources, diversify sources of energy supplies, strengthen energy independence of the state and improve the environment. There are a number of applications for torrefaction products, the most promising of which are: combustion in pellet boilers, cofiring with coal, gasification of raw biomass for fuel production, and the production of composite wood-based materials. Estimation of the efficiency of considered technologies is carried out.*

**KEY WORDS**: *torrefaction technology, bioenergy, biofuels, cellulose, hemicellulose, lignin, pyrolysis*

## 1. INTRODUCTION

The alternative energy development and the search for new energy sources are the main global trends of the 21st century. Their manifestation is facilitated by the local exhaustion of natural resources, the possible emergence of the energy crisis, the negative impact of conventional energy on the environment and threats of regional environmental disasters (Kryshtopa et al., 2018). It should be noted that renewable energy sources have recently become one of the important criteria for the sustainable development of the world community.

The reserves of fossil fuels in Ukraine are limited. Therefore, in order to meet the existing demand, about 65% of the required amount has to be imported. This creates the main problem for the energy security of the country (Daly, 2014). So, the use of renewable energy sources is one of the most important directions in Ukraine's energy policy, aimed at saving traditional fuel and energy resources and improving the state of the environment. Increasing the volume of renewable energy sources used in Ukraine's energy balance will raise the diversification level of energy sources which will contribute to strengthening the country's energy independence.

Taking into account the agricultural orientation of the state's economy, bioenergy is one of the most prospective components of its renewable energy. Ukraine has significant land resources. On January 1, 2009, its land fund amounted to 60,354.8 thousand hectares or almost 6% of Europe's territory. In particular, the agricultural land was about 19% of the total European land area, including arable land, which made up almost 27%. The Ukrainian index of agricultural land per capita is the highest among the European countries – 0.9 ha, including 0.7 ha of arable land (compared to the average European indices of 0.44 ha and 0.25 ha, respectively). The area of Chernozems (Food and Agriculture Organization of the United Nations, 2006) in Ukraine ranges from 15.6 to 17.4 million hectares according to various estimates or makes up about 8% of world reserves (State Land Policy in Ukraine: State and Development Strategy, 2009).

Ukraine has a sufficient amount of biomass, available for energy production—about 29 million tons of coal equivalent, as estimated in 2015 (Geletukha and Zhelezna, 2017). The structure of energy potential is shown in Fig. 1.

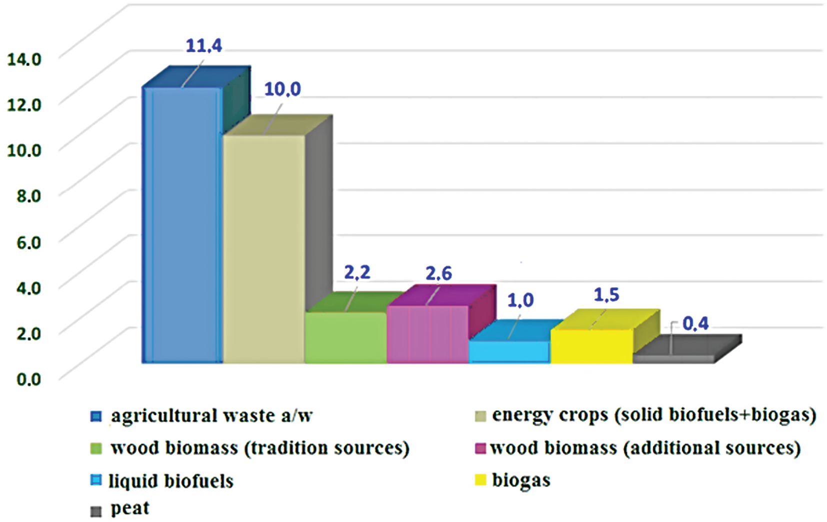

**FIG. 1:** Structure of the energy potential of biomass in Ukraine [based on the results of Geletukha and Zhelezna (2017)]

The main components of the potential are energy crops, which have been grown for industrial purposes in Ukraine recently, and the primary agricultural wastes (straw, production wastes of maize, grains, sunflower, etc.). These production wastes of agricultural crops are widely used as fuel itself and as additives to the existing commercial fuels (Kryshtopa et al., 2018). In general, the economic potential of agricultural waste is almost 11.4 million tons of coal equivalent per year and of energy crops—10 million tons of coal equivalent per year.

It should be mentioned that Ukrainian scientists work on the cultivation of new energy crops. In particular, the scientists of the National Botanic Garden of the National Academy of Sciences of Ukraine have created a valuable gene pool of palmate millet, sugar sorghum, misconstrues, and millet dumplings which are characterized by early ripening, drought tolerance, and high yield of seeds or phytomass, high carbohydrate content in grain or in aboveground mass (Blum et al., 2014).

Unlike other renewable energy sources, the biomass is a universal energy source which can be used for both the production of electric and thermal energy as well as biofuel for transport purposes (Panchuk et al., 2017). At the same time, low energy density (8–14 MJ/kg), the instability of granulometric composition, particles size (10–100 mm), wide dispersion of moisture content (25–60%), and low bulk density (60–200 kg/m$^3$) are the main problems of the biomass transportation and storage (Makarov et al., 2013).

Some disadvantages of biomass can be eliminated by mechanical processing—granulation, resulting in solid granules (pellets) in the form of cylinders, 6–25 mm in diameter and 5–80-mm long (Van Loo and Koppejan, 2003). They have the average moisture content of 8–10% and the bulk density of 630 kg/m$^3$. However, due to their high hygroscopicity, fuel pellets require special conditions of transportation and storage. In the case of moisture ingress, they quickly swell and disintegrate into the original biomass particles (Alakangas and Paju, 2002).

One of the ways to increase the consumer properties of biomass is the process of torrefaction (Makarov et al., 2013). So, the present paper is devoted to brief review and analysis of the applicability of the torrefaction in the Ukraine.

## 2. THE PURPOSE OF RESEARCH AND PROBLEM STATEMENT

The purpose of this study is to substantiate the implementation of torrefaction technology for the conversion of low-quality biomass into raw materials with high energy density and uniform physical and fuel characteristics. To achieve this purpose we set the following main tasks:

- to perform the qualitative and quantitative literature review of the torrefaction process;
- to define ways of using the torrefaction products;
- to assess the efficiency of the analyzed technologies.

## 3. TORREFACTION PROCESS

The high-temperature effect on the biomass results in the thermal degradation of its structure and is accompanied by mass loss (Mikhailov et al., 2017). The torrefaction process consists in heating the raw material under atmospheric conditions, in the absence of oxygen, to the temperature of 200–300$^{o}$C and keeping it at the temperature for the specified time (Fig. 2). During the torrefaction process, the initial biomass loses about 30% of its mass and only 10% of its energy due to the degassing of low-energy volatile compounds and moisture release. This leads to increasing energy density by around 20% (Bergman et al., 2005b).

The complex approach to the investigation of the torrefaction process was introduced at the beginning of the 21st century as part of the efforts aimed at improving the properties of raw materials for the production of bioreactive materials in particular with the application of thermochemical transformation technology (Medic, 2012). For better understanding, Bergman et al. (2005b) represented the torrefaction process as consisting of five stages (Fig. 3).

At the "initial heating" stage the heat is used only to increase the biomass temperature. This stage ends when moisture evaporates. At the second stage, called "drying," the temperature is increased a little bit, the free moisture constantly evaporates, and the biomass is compacted. Therefore, most of the chemical elements of biomass remain unchanged. After that at the third stage, called "reactive drying," the temperature is significantly increased again, which leads to the release of practically all physically bound moisture, structural deformation of biomass, and the beginning of phase transformation of solid components with the formation of gases.

The fourth stage is the basis of the process. It consists of heating up the processed material mass to the torrefaction temperature, keeping it at this temperature, and then cooling. The torrefaction stage is the highest level of the entire process and is responsible for the greatest loss of product mass. However, it should be taken into consideration, that when the temperature rises above 300$^{o}$C, the pyrolysis occurs and the biomass passes another process.

The torrefaction stage ends when the temperature again drops to 200$^{o}$C. The reaction time or the torrefaction time consists of the time when the material is heated

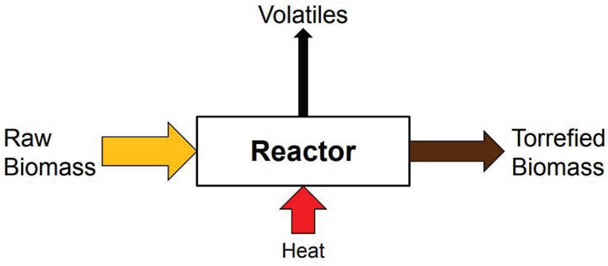

**FIG. 2:** The scheme of the biomass torrefaction process

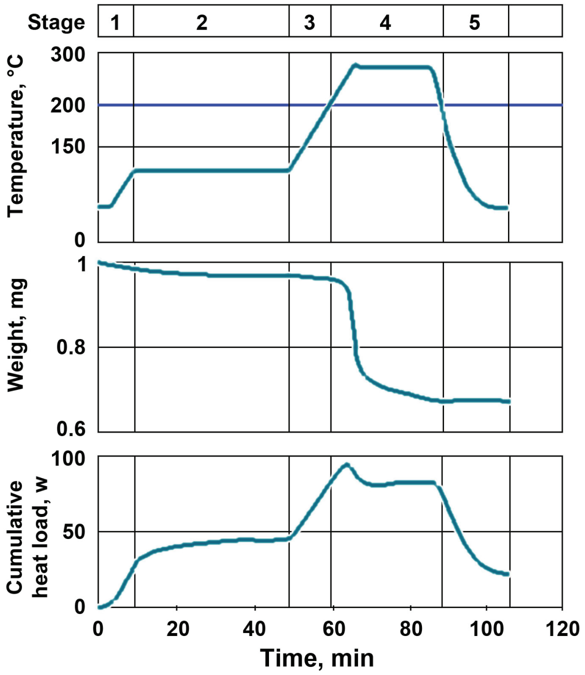

**FIG. 3:** Stages of the torrefaction process [based on the results of Bergman et al. (2005b)]

from 200$^{o}$C to the required temperature level (the torrefaction temperature) and the time of maintaining the constant torrefaction temperature. The cooling period of the product up to 200$^{o}$C is not taken into account during the reaction time, though, in this case, the drying process goes (Schorr et al., 2012).

At the fifth stage, the torrefied matter is cooled to the ambient temperature.

The peculiarity of the biomass thermal degradation is that its individual components are subjected to decomposition reactions with different intensities depending on the temperature (Fig. 4). That is why hemicellulose undergoes the most serious transformations at the torrefaction temperatures of 200–300$^{o}$C, and this process has a two-stage mechanism (Di Blasi and Lanzetta, 1997).

At the first stage, the sugar structure changes due to depolymerization while the second stage mainly consists of decomposition reactions and the generation of gases and volatile substances.

The first stage passes at the temperatures below 250$^{o}$C and with a fairly low mass loss, which increases significantly as the temperature rises, which initiates the second stage of the decomposition reaction.

However, according to the studies of Kaltschmitt et al. (2009), the certain mass loss can occur at the first stage when the solid materials of biofuel begin to slowly decompose at 150$^{o}$C and a significant pyrolytic decomposition begins at 200$^{o}$C with the formation of water, $CO_2$, CO, and methanol.

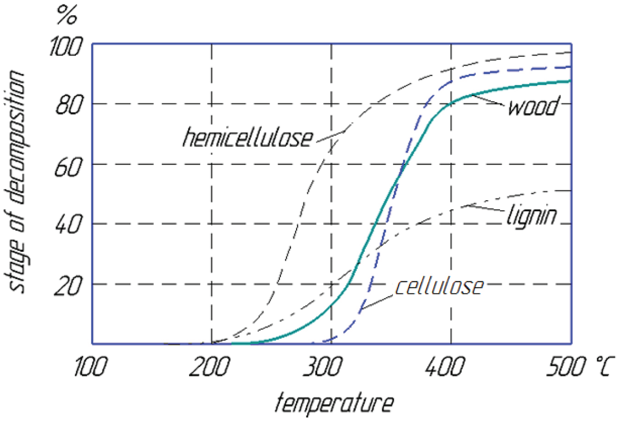

**FIG. 4:** Thermal decomposition of lignocellulose and wood fractions (Kaltschmitt et al., 2009)

The decomposition of cellulose and lignin at the temperature range, typical of torrefaction, is much slower and less intense than that of hemicellulose. Both substances have much more stable molecular structures, and the mass fraction of degraded hemicellulose at the temperature close to 300°C exceeds several times the sum of mass fractions of cellulose and lignin.

Compared to cellulose, the composition of lignin and the molecular structure of hemicellulose are different for deciduous and coniferous timber species which results in different kinetic parameters. According to the studies of Müller-Hagedorn et al. (2003), the coniferous lignin has higher thermal stability than the deciduous one, and the hemicellulose from deciduous wood is more reactive. However, cellulose, as a rule, is the most thermally stable component of wood.

## 4. TORREFACTION PRODUCTS

During heating of biomass, its thermal decomposition takes place, which results in the emergence of volatile substances and solid residue with high carbon content (Zakri et al., 2013). The composition of volatile products includes gases—$CO_2$, CO, $H_2$, $N_2$, and $C_nH_m$ ($CH_4$ is the main among gaseous hydrocarbons)—and the vapors of pyrogenic water, various acids, and resins, which under normal conditions form the liquid fraction.

This thermal conversion of biomass increases the calorific value, reduces the oxygen–carbon ratio, and reduces hygroscopicity. During the torrefaction process $H_2O$ and $CO_2$ are removed and the hydrogen–carbon ratio decreases.

The quantity and composition of volatile products of the refining depend on both the physical and chemical properties of the raw material and a number of technological parameters: the heating rate, temperature, the time of biomass residence in the reaction zone, the size of particles, etc.

The analysis of torrefaction products, carried out in Jakubiak and Kordylewski (2010) shows that gaseous and liquid torrefaction products can be up to 20% of the raw material mass.

It is known that during the torrefaction process, the combustible components, which make up the volatile substances, can be burned. The heat, released during this process, can be used to dry the processed raw materials (Bergman and Kiel, 2005). However, in this case, the combustion heat of the generated volatile products is small. A more effective way is thermal conversion of the volatiles into the synthesis gas—a mixture of hydrogen and carbon monoxide.

For this purpose, the technology described in Kosov et al. (2014) can be used: 1 kg of wood waste or peat allows nearly 1.4 $m^3$ of synthesis gas with the calorific value of 11.7 MJ/$m^3$ by means of thermal decomposition of the released gases and their subsequent filtration through a porous carbon medium. Dolomites and olivines may also be effectively used for gas treatment (Dayton, 2002). The resulting synthesis gas, in turn, can be used as fuel for the internal combustion engine which is part of the unit for torrefaction of various types of biomass.

According to the data given in Ovsianko (2015), specific power usage during the production of torrefied pellets is 95.46 kWh/t, therefore, the production of one kilogram of pellets requires 0.96 kWh or 0.36 MJ of electrical energy.

The specific output of synthesis gas obtained by thermal processing of volatile gases released during the torrefaction of 1 kg of wood waste pellets is about 0.3 $m^3$ (Zaichenko et al., 2012), which is equivalent to 3.57 MJ. Considering that the average efficiency of conversion for power generation units based on the gas reciprocating engine is 0.3, it is obvious that the obtained synthesis gas can be effectively used to ensure the functioning of the complex, converting wood waste into granular fuel with high thermal characteristics.

It should be mentioned that the issue of processing and efficient use of torrefaction gases is at the initial stage of the study. The resulting gases can be used to improve the efficiency of the torrefaction process itself as well as to obtain transport fuels.

Torrefaction causes a slight decrease in the energy component of biomass due to the partial evaporation of volatile substances, but the calorific value of the mass increases according to significant mass reduction. Therefore, the content of carbon, hydrogen, and oxygen determines the fuel combustion calorific value, and different types of fuels can be grouped based on the ratio of [O]/[C] and [H]/[C].

A visual representation of the elemental composition of different types of solid fuels is given by the Van Krevelen diagram (Bergman et al., 2005a), which is shown in Fig. 5. The diagram shows the data for untreated wood, torrefied wood, with the indication of the torrefaction temperature (in brackets), charcoal, fossil coal, and peat.

According to the Van Krevelen diagram, the torrefied biomass is close to solid fuels, which have high values of calorific value. This tendency persists with the increase of torrefaction temperature and holding time. It should be noted that the biomass type

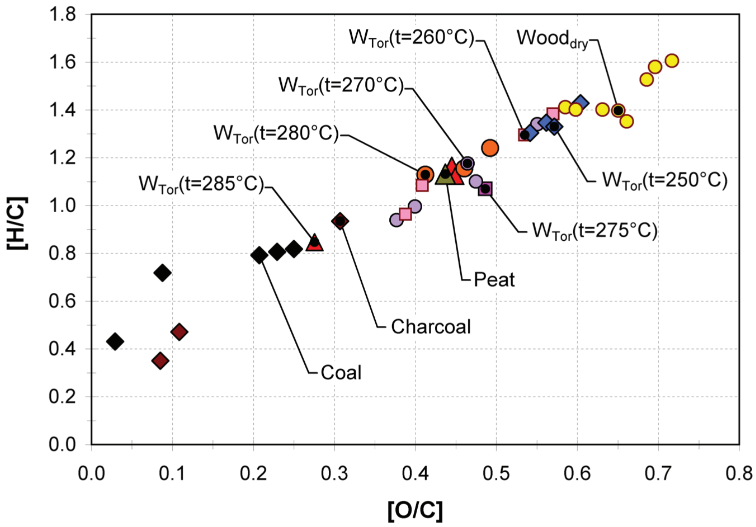

**FIG. 5:** Van Krevelen diagram [adapted from Bergman et al. (2005a)]

also influences mode parameters and properties of the final product of the torrefaction process. Thus, under identical conditions (with the torrefaction temperature of 290$^{o}$C and the torrefaction time of 30 min), mass losses of wheat straw (with the hemicellulose content of 30.8%) significantly exceed the mass loss of willow wood (with the hemicellulose content of 14.1%) (Kuzmina et al., 2016).

At the same time, among three organic biomass components, hemicellulose has the lowest calorific content and lignin has the largest one. Thus, it may be concluded that the biomass with the higher lignin content has a higher calorific value, and the torrefaction process has a smaller influence on the relative change in the calorific value of such biomass.

The latter conclusion is proved by the comparison of the literature data, represented in Trif-Tordai and Ionel (2011), which show the torrefaction effect on the calorific value of different types of wood and various types of agricultural wastes, in which the content of hemicellulose is usually higher and that of lignin is lower than in wood. The data given in Trif-Tordai and Ionel (2011) show that during torrefaction with the temperatures up to 300$^{o}$C and the holding time of up to 60 min, the energy output for different timber species ranges from 60% to 98% and for various types of agricultural wastes it is about 29–98%.

## 5. REACTORS FOR TORREFACTION

There are two main technological schemes for the torrefaction process—direct and indirect heating.

In the case of direct heating, the biomass directly contacts with the heating medium in the presence of an inert heat carrier, which can be heated torrefaction gases (Kaltschmitt et al., 2009).

Unlike the direct heating, in the scheme with the indirect heating the heat is transmitted through the reactor wall and all gas products of torrefaction are sent to the combustion chamber. Hot exhaust gases from combustions chamber go to the heat exchanger and heat up the intermediate heat-transfer agent (Pestaño and Jose, 2016).

The main types of reactors used for torrefaction are a screw, plate, fluidized bed reactor, and moving bed reactor.

In screw reactors (Fig. 6), the raw biomass is provided through the boot device 1 and is transferred by the screw conveyor 2 first to the torrefaction zone 3 and then to the cooling zone 4. The heat energy may be supplied to the torrefaction zone through the reactor wall and by means of a hot gaseous agent directly into the reactor (Junsatien et al., 2013).

The indirect heating allows the reactor space to be divided into different temperature zones. By varying the length of zones and the temperature of walls it is possible to create the reactor with the optimal temperature–time regime and combine in one unit the processes of drying and multi-stage pyrolysis with different temperatures.

Screw reactors are relatively simple and allow one to organize the continuous supply of biomass (Nhuchhen et al., 2014). However, they have a number of disadvantages:

- heat transfer intensity is small due to the lack of active mixing (hot gases do not penetrate into the volume of biomass which reduces the role of convective heat transfer);
- unequal thermal effects can lead to the possible heterogeneity of the final product properties; therefore, to improve the product quality it is necessary to use the schemes with several successive screw reactors, which significantly increases the cost of the units;

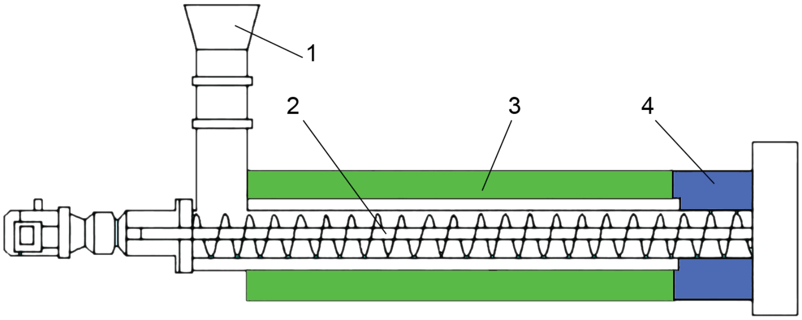

**FIG. 6:** Screw reactor [adapted from Eseyin et al. (2015)]: 1) loading device; 2) screw conveyor; 3) torrefaction zone; 4) cooling zone.

- in the case of direct heat supply, the screw creates a large gas-dynamic resistance, which requires the relatively high pressure of the heat carrier at the reactor inlet;
- the moving parts and components of the unit (the screw itself, bearings) operate in rather stressful conditions (mechanical and thermal loads), therefore, they are subject to severe wear and tear. Due to this, the reliability of the unit is relatively low and the period of maintenance-free operation is rather short.

The structures of plate reactors, also called "multilevel furnaces," have proved themselves to be good for drying the materials and therefore they can be used for torrefaction purposes. One of the variants of such a design is shown in Fig. 7 (Eseyin et al., 2015).

The raw material is supplied through the loading device 1 to the top of the reactor and enters plate 3, where it is heated and with the help of rotary mixers 2 connected to the drive mechanism 5 is mixed and transmitted through special openings 4 to the plate of the next level and so down to the bottom. The heat supply in these reactors can be either direct or indirect. In the first case, the heating is carried out by means of the hot gas flow with low oxygen content.

In the case of indirect heating, the heat can be supplied to the raw material either by means of heating elements or by means of the flow of gaseous or liquid heat carrier, supplied into the inner area of plates.

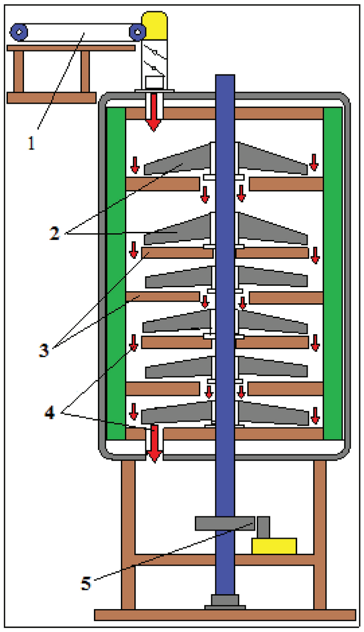

**FIG. 7:** Plate reactor [adapted from Eseyin et al. (2015)]: 1) loading device; 2) mixers; 3) plates; 4) special openings; 5) drive

The reactor of this type allows for a multistage process by means of regulating the temperature and holding time of biomass at each level. Besides, the design makes it easy to control the state of biomass and gas environment in the reactor at each level and opens up wide opportunities for optimizing the process. Despite obvious advantages, the plate type of reactors has not yet been widely used. First of all, this is because of the design complexity due to the rotating parts. Also in the case of indirect heating, the heat transfer efficiency decreases.

Moving bed reactor (Fig. 8) is a structurally simple unit since it does not have moving parts. The biomass is supplied through hopper 1 into the torrefaction column, then, under gravity, it gradually moves to the lower part of the reactor through the drying zone 2, preheating zone 3, and torrefaction zone 4. A hot gas flow, which rises towards it, is supplied through the branch pipe 5 and directly affects the biomass. Then, hot gas is withdrawn for cleaning and heating through pipeline 6 located in the upper part of the reactor (Tumuluru et al., 2010).

This type of reactor is characterized by very effective heat exchange and can be used for processing various types of raw materials with a wide range of granulometric composition. The disadvantages of the moving bed reactor may include the following:

- low gas permeability which leads to the increased aerodynamic resistance of the layer;

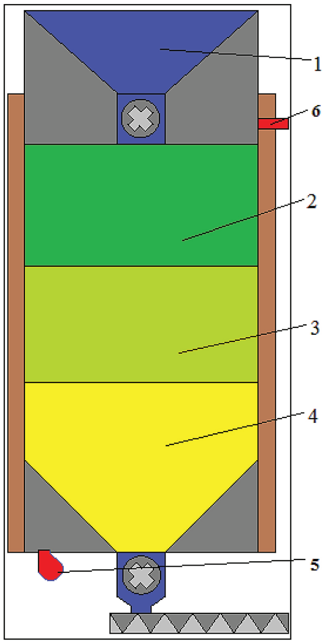

**FIG. 8:** Moving bed reactor [adapted from Tumuluru et al. (2010)]: 1) loading device; 2) drying zone; 3) preheating zone; 4) torrefaction zone; 5) hot gas supply; 6) gas outlet

- lack of mixing, which leads to the possible unequal heat processing and therefore heterogeneity of the final product properties (Koppejan et al., 2012).

In a fluidized bed reactor (Fig. 9), the gas flow, heated with burner 2, passes through biomass 1 from the bottom to the top. It is supplied with a certain pressure and velocity and passes through the stationary angular blades 3, resulting in complex toroidal twists, which provide sticking of biomass particles in the flow and their rapid heating (Koppejan et al., 2012; Sun et al., 2011). Visually there is the impression of boiling liquid. This state is characterized by very effective heat exchange between gas and biomass particles.

This technology provides for fairly small process duration of thermal effect on the biomass for 90–300 s at a temperature of 280$^{\text{o}}$C, after which the torrefied product is supplied through product pipeline 5 to the lower part of the reactor. The generated moisture is discharged from the unit through pipeline 6 and the waste gases 4 are reused.

It follows from the above brief review of structures that nowadays there is no single point of view on the design of reactor for torrefaction, each developer is guided by their own experience and relies on the available equipment and resources. However, increasing the intensity of heat and mass exchange helps to use the reactors of smaller sizes. These allow decreasing in the specific amount of metal materials while

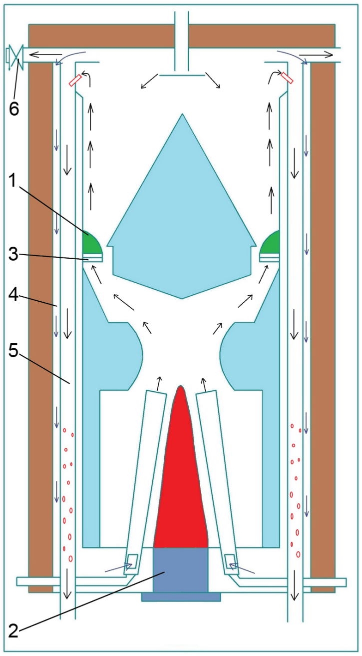

**FIG. 9:** Fluidized bed reactor [adapted from Sun et al. (2011)]: 1) biomass; 2) burner; 3) angular blades; 4) gas recirculation; 5) torrefied product; 6) water vapor pipeline

maintaining high productivity. Thus, the most efficient in terms of heat transfer coefficients are the moving bed and fluidized bed reactors.

Based on the above review, it is clear that it is prospective for Ukraine to use the technologies of fluidized bed reactors and moving bed reactors.

The fluidized bed reactors can be applied for the simultaneous processing of large quantities of raw materials and in locations with high concentrations of raw materials.

The moving bed reactors can be operated as parts of mobile units, which can work in stationary conditions as well as be moved to places with the volume of raw materials sufficient for processing. The use of mobile units minimizes the costs for biomass and enables to locate the torrefaction units in any region of Ukraine regardless of the existence of conventional energy facilities, utility, and transportation networks.

The production of torrefied pellets can provide the income and employment of the population at the regional level. The manufacturing of torrefaction units and their infrastructure with a gradual transition to local equipment will stimulate the Ukrainian economics.

## 6. USING THE TORREFACTION PRODUCTS

The torrefied biomass has a number of applications, the most promising of which are: combustion in pellet boilers, cofiring with coal in pulverized coal burners, gasification of torrefied biomass for fuel production, and production of composite wood-based materials.

The total number of pellets produced in Ukraine in 2015 was 1,319,465 tons (Geletukha et al., 2016). Therefore, the main features of the production are regional divergence and its relative incoherence as well as a large number of small-scale enterprises, working with traders.

From the economic point of view, it is quite promising for Ukraine to increase the production capacity by means of manufacturing the torrefied pellets, which have better operation characteristics such as calorific value, moisture, bulk density, and energy volumetric density (Table 1) (Kleinschmidt, 2011) and can be used in existing domestic and industrial pellet boilers.

It should be noted that there are rather significant logistic advantages of torrefied pellets during transportation and storage due to their greater bulk density as in this case more finished products can be placed in the same cargo space. According to the data given in Bergman (2005), the cost of the entire production chain—the cost and delivery of raw materials, production of pellets and their transportation over long distances—can be 30% lower for torrefied pellets than for conventional wood pellets.

The advantages of torrefied pellets are especially evident when they are cofired with coal in thermal power plants (Li et al., 2012). In recent decades, a number of studies have been carried out on cofiring of biomass and coal in electric power stations (Bergman et al., 2005a; Ionel et al., 2009). The results of the researches are

**TABLE 1:** Comparative analysis of different types of biofuels (Kleinschmidt, 2011)

| **Characteristics** | **Wood** | **Pellets** | **Torrefied Pellets** | **Charcoal** | **Fossil Coal** |
|---|---|---|---|---|---|
| Moisture, % | 30–45 | 8–10 | 2–5 | 1–5 | 10–20 |
| Lower calorific value, MJ/kg | 9–12 | 15–16 | 20–24 | 30–32 | 23–28 |
| Output of volatile substances, % db | 70–75 | 70–75 | 55–65 | 10–12 | 15–30 |
| Fixed carbon, % | 20–25 | 20–25 | 28–35 | 85–87 | 50–55 |
| Bulk density, kg/L | 0.2–0.25 | 0.55–0.75 | 0.75–0.85 | 0.2 | 0.8–0.95 |
| Energy volumetric density, GJ/$m^3$ | 2.0–3.0 | 7.5–10.4 | 15.0–18.7 | 6–6.4 | 18.4–23.8 |
| Ash content, % db | 0.7–1.2 | 0.9–1.4 | < 3 | < 3 | 10–40 |
| Dust content | Average | Allowable | Allowable | High | Allowable |
| Hygroscopicity | High | Reduced | Low | Low | Low |
| Biological degradation | High | Reduced | N/A | N/A | N/A |
| Grinding requirements | Increased | Increased | Ordinary | Ordinary | Ordinary |
| Storage requirements | High | Average | Low | Low | Low |
| Transportation cost | High | Moderate | Low | Low | Low |

quite encouraging—they show that the operation efficiency of boilers does not have significant losses. However, in the case of refurbishing of the existing coal boiler for combusting the biomass/coal mixture, the proportion of biomass depends on the properties of original components as well as on the design of boilers, and it should be defined for each specific case (Trif-Tordai and Ionel, 2011).

When the unprocessed raw biomass burns (with a significant amount of moisture, organic and mineral substances) there arise a number of negative technical and operational characteristics. Therefore, it is promising and economically feasible for the preprocessing of biomass to use the torrefaction process (Li et al., 2014). The torrefied biomass, according to the data in Table 1, has application properties close to those of fossil coal.

Table 2 shows comparative data for the electrical power station, with the capacity of 150 MW, which uses coal, torrefied and raw biomasses as fuels in various proportions, and Fig. 10 shows the total amount of energy, needed to obtain and prepare these types of fuels before they are supplied to the boiler (Boskovic, 2015). Rollinson and Williams (2016) obtained index (BWI) data, which represents the resistance of a material to crushing and amounts to 16 kWh/t for torrefied pellets and 413 kWh/t for conventional wood pellets. The work of Beets (2017) should also be mentioned, as it represents the technological chain, which includes the production of wood and torrefied pellets, their delivery, storage, and processing at electric power plants. At the same time, the economic effect in the case of using torrefied pellets is from 1–1.5 €/GJ.

It should be noted that using torrefied pellets for cofiring can significantly reduce $CO_2$ emissions in the near future and at the same time stimulate the creation of supply infrastructure that will reduce the costs within the biomass supply chain over the long-term and broaden the options for different uses of biomass (Nunes et al., 2014).

Coal industry is traditionally one of the key branches of the Ukrainian economics. It occupies an important place in terms of production output, raised capital and number of employees. For Ukraine, the level of domestic coal mining of anthracite group is still insufficient because of various reasons—technical, economic, and political. For

**TABLE 2:** Grinding energy requirement for cofired situations [adapted from Boskovic (2015)]

| — | Unit | Coal | Torrefied Biomass | Coal | Raw Biomass |
|---|---|---|---|---|---|
| Required amount, per cent | % | 70 | 30 | 70 | 30 |
| Required amount, mass | t/h | 18.5 | 7.94 | 19.7 | 8.44 |
| Grinding energy required | kWh/t | 25 | 45 | 25 | 245 |
| Grinding power required | kW | 463 | 357 | 492 | 2068 |

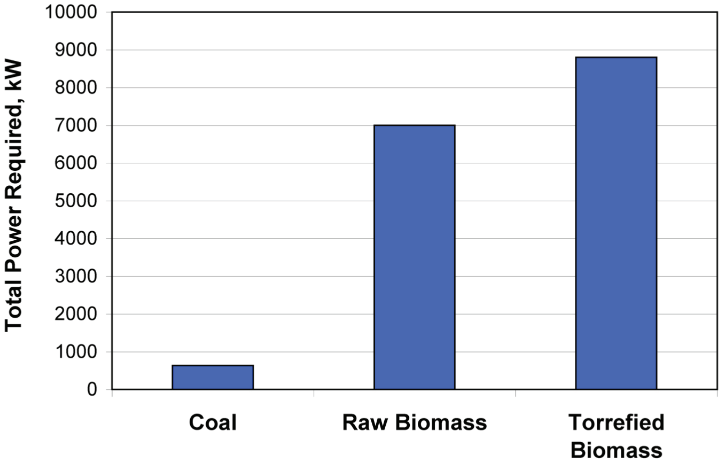

**FIG. 10:** Total power required, kW

example, in 2015, compared to 2013, the supply of anthracite coal to thermoelectric power stations decreased from 18 million tons to 8 million tons. At the same time, recently there has been the intensive growth of the biofuel market due to domestic and foreign investments (Dunaevskaya et al., 2017).

European consumers of biofuels can give a serious stimulus to the development of the Ukrainian bioenergy because of a significant amount of raw materials, proximity to state borders, and opportunities for the export of torrefied pellets. According to the data given in Bergman (2005), only electrical power stations in the Netherlands, using pulverized coal, can consume about six million tons of torrefied pellets per year. The markets of Poland, Germany, and the UK are also very promising. Therefore, in the near future, Ukrainian enterprises may supply the torrefied pellets to the Ukrainian market and for export.

In order to assess the economic efficiency of the use of torrefied biomass, it is necessary to compare the cost of fuel in terms of useful €/GJ. According to the data presented in Geletukha et al. (2016), the cost of coal of anthracite group and the cost of wood pellets are 150 €/ton and 85 €/ton, respectively. The cost of torrefied pellets can be determined by the formula (Ovsianko, 2015; Ovsianko and Yudkevich, 2015)

$$S = \frac{S_P Q_T}{Q_P}, \tag{1}$$

where $S_p$ is the cost of wood pellets; $Q_T$ is the lower calorific value of torrefied and wood pellets, MJ/kg, and $Q_P$ is the lower calorific value of wood pellets, MJ/kg. These calculations are shown in Fig. 11.

Table 3 shows the production costs of wood and torrefied pellets in terms of energy unit, which prove the results of calculations provided in Fig. 11. It should be men-

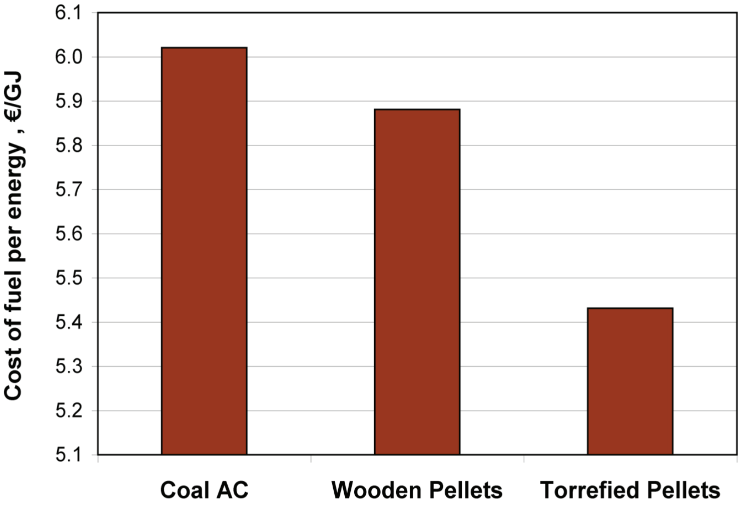

**FIG. 11:** Cost of fuel in terms of useful €/GJ

**TABLE 3:** Production costs of wood and torrefied pellets

| Parameters | Wood Pellets, €/GJ | Torrefied Pellets, €/GJ |
|---|---|---|
| Cost of raw material (Geletukha et al., 2016) | 2.3 | 3.0 |
| Production costs (Ovsianko, 2015) | 3.4 | 2.5 |
| Logistics | 1.33 | 0.89 |
| Total | 7.03 | 6.39 |

tioned that despite a significant number of research works, the actual production of torrefied pellets is currently at the level of pilot projects, and in Ukraine, it is absent altogether. The costs of the torrefaction process depend on the proposed technology, and the rational use of the products of the process, in particular, the synthesis gas.

The "Logistics" row in Table 3 shows the possibility of transporting the pellets produced in Western Ukraine (Lviv) to the Bełchatów power plant (Poland) operating on coal. The Bełchatów power plant is one of the largest power plants in Poland and the European Union, its capacity is 5354 MW. The distance from Lviv to Bełchatów is approximately 550 km. The lorry (22 t) is used for transportation. The cost of transportation is 0.85 €/km (the average rate). Increasing the distance will increase the delivery efficiency of torrefied pellets.

According to the data of Table 3, which correlate with the researches of Ovsianko and Yudkevich (2015), the cost of raw materials constitutes a major part of the total costs in the technological chain of production of torrefied pellets, including logistics costs. Figure 12 shows the diagram of the cost of raw wood in various countries, which are the potential exporters of torrefied pellets. According to provided data, the lowest feedstock cost is in Ukraine, which indicates the high competitiveness of the production of torrefied pellets in Ukraine.

Based on the analysis of the above calculations, it may be concluded that the use of biomass as a supplementary fuel for coal firing has significant prospects for Ukraine. At the same time, the efficient commercial realization of this direction requires further comprehensive scientific investigations.

The torrefied biomass has several advantages when used in gasification processes—it can be easily ground, it contains little moisture and has optimal proportions of the C, H, and O components (Ptasinski, 2008). It has been found out that moisture content and particle size are the key factors for the efficient operation of gas generator (Prins et al., 2006). In raw biomass, the high oxygen content leads to its overoxidation during the gasification process and increases thermodynamic losses. Due to the low moisture content and the oxygen content, the torrefied wood can reduce losses, raise the temperature of gasification and, as a result, increase the calorific value of the final product—the generator gas. The best results of the process are achieved when not only the torrefied biomass is put into the gas generator, but also the vapor–gas mixture, obtained during the torrefaction process (Prins et al., 2006). The torrefied mass has unique properties as well as raw materials for the production of wood-based products—chipboards and various composites (Wilén, 2014).

It is also perspective to use the torrefied mass for wood–polymer composites (WPC), which combine natural fiber and thermoplastics with various additives and

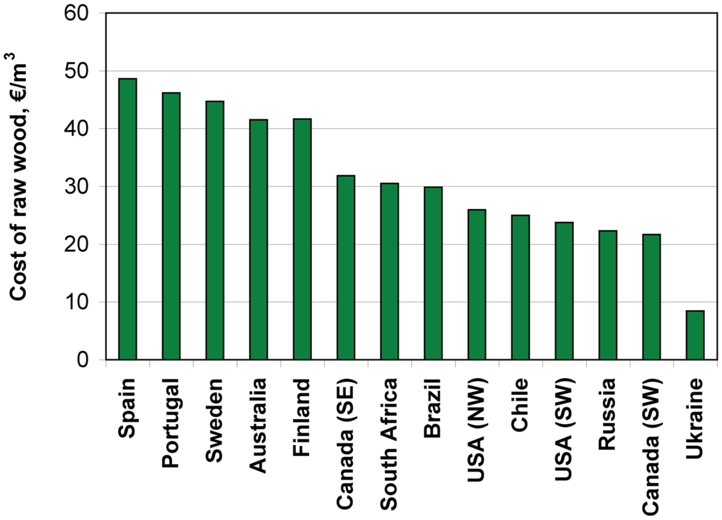

**FIG. 12:** Feedstock prices in selected countries, €/m$^3$ [based on the results of Gårdbro (2014), Geletukha et al. (2016), and Sipila (2013)]

are widely used as interior panels, floor coverings and protective pads for cars, work panels and furniture for offices, containers, etc.

That is why torrefied composites have higher performance properties and lower production costs, as the larger proportion of wood can be used compared to current products due to its better moisture resistance.

The peculiarity of using the torrefaction technologies is that they are not purely energy technologies but are the complex that provides the solutions to energy, environmental, agrochemical, forestry engineering, and social issues. This constitutes their profitability and competitiveness. By solving energy problems and stimulating heat and electric power production from torrefied pellets, the state can raise the level of environmental safety on the territory of Ukraine.

## 7. CONCLUSIONS

Nowadays, Ukraine has both a significant amount of plant biomass and powerful potential for its cultivation, suitable for energy use and without threatening the country's food security. In order to eliminate the defects of raw biomaterials and improve their properties, it is reasonable to use the torrefaction process—a new and viable technology that allows turning the original biomass into the highly efficient fuel.

The performed analysis has shown that there may be two technological approaches to the production of torrefied pellets in Ukraine. The first approach deals with the simultaneous processing of large quantities of raw materials. The second approach is based on using mobile units that can work in stationary conditions as well as be moved to places with the volume of raw materials sufficient for processing, which can minimize the costs. It is important to study the process of obtaining and efficient use of torrefaction gases in order to improve the process and for other purposes, in particular for the production of transport fuels.

The torrefied biomass has a number of applications, the most promising of which are: the combustion in pellet boilers, cofiring with coal in pulverized coal burners, biomass gasification for the production of various fuels, and production of composite wood-based materials.

The introduction of torrefaction technology can provide profit and employment of the population at the regional level and an increase in the level of environmental safety in Ukraine. The construction of torrefaction units and their infrastructure with the gradual transition to local equipment will further stimulate the Ukrainian economy.

Thus, we can conclude that the application of the biomass torrefaction process is a new direction in the Ukrainian bioenergy and is currently at the initial stage of development. At the same time, it is prospective to conduct scientific investigations to define the optimal torrefaction modes for various types of local raw materials, which will promote the extensive commercial use of the developed technologies.

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