

Torrefaction: Process Parameters and Reactor Design

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Abstract

Torrefaction is a thermochemical process, where biomass is obtained in temperature range from from 200 to 300 °C, in inert atmosphere with the aim to increase carbon content of biomass. In this paper, emphasis is on biomass feedstock types, different effects on torrefaction success, and torrefaction reactors.

Keywords

torrefaction, biomass biofuels, reactors, bio-charcoal

1 Introduction

The biomass energy is one of the most advanced and emerging renewable energies worldwide. Low energy and mass densities, large volume have undesirable effect on long-distance transportation. High moisture content and vaporization have influence on high costs of thermo-chemical conversion, and hydrophilic nature does not allow long-term storage. Fibrous nature of biomass intensifies energy usage for grinding, smoke generation during combustion. Heterogeneous nature of biomass complicates the process design and process control. All of these limitations make the application and usage of biomass directly as a fuel in the current gasification and combustion units difficult [1]. In order to overcome these drawbacks, biomass needs to undergo some pretreatment steps. One possibility is torrefaction, which became a prominent technology of biomass pretreatment.

The torrefaction goal is to intensify the energy density of the biomass by reinforcing its carbon content and reducing oxygen and hydrogen content [2]. Torrefaction is the initial reaction accompanied by pyrolysis and/or gasification [3].

During biomass torrefaction process, it comes to degradation of hemicellulose, and lignin and cellulose degrade to a small extent [4]. The feedstock is subjected to a thermochemical process, at temperatures between 200 and 300 °C, in inert atmosphere [5]. The main product is solid, which preserves 75 to 95% of original energy content [4]. Torrefaction product (solid fuel) can be applied

as a high quality solid biofuel for gasification and combustion [6]. Torrefaction improves biomass' properties, by improving its grindability, hydrophobicity, and energy density [4]. Also, produced bio-chars have lower atomic H/C and O/C ratios. CO₂ content and volatile matter emissions from burning the bio-chars are reduced. Because of the enhancement of biomass properties from torrefaction process, the upgraded biomass accomplishes an improved fuel quality. Due to its technological and economic feasibility, torrefaction could be a promising process used on the road of substituting coal from industrial applications [7].

2 Biomass feedstock types for torrefaction

About five percents of world wide's biomass can be used for energy creation. This energy amount could provide 26% of the global energy consumptions. Biomass is the third biggest primary energy source. Biomass is recognized as carbon neutral, because it can decrease net carbon emissions and undesirable environmental effects, if they replace fossil fuels. Biomass is classified in five categories [8]:

- virgin wood – biomass from forestry, arboriculture or wood from processing;
- energy crops – biomass from high-yield energy crops, cultivated especially for energy usage;
- agricultural residues – from agricultural harvesting or processing;

- food wastes – from food and drink production, preparation and processing and postconsumer waste;
- industrial waste and by-products – from manufacturing and industries.

Mostly, torrefaction was focused on the utilization of wood and agricultural by-products as feedstocks for torrefaction process [9]. Lignocellulosic biomass and energy crops are mostly used materials as torrefaction feedstocks [10]. Lignocellulosic biomass contains the non-starch and fibrous part of the plants that are composed of holocellulose (hemicellulose and cellulose) and lignin. On the other side, non-lignocellulosic biomass are organic substances used for nutritional purpose (sugars, protein, starch, fat contents of any crop) [8].

The principals of torrefaction can theoretically be applied to improve practically all wood and herbaceous biomass, and biomass containing mixed streams (wastes, plastics, etc.). The applied technology will bound the allowable variation in feedstock characteristics, from which size and shape are the most important. Contaminated streams like demolition wood, dry industrial wastes that contain synthetic polymers might affect the composition of torrefaction gas. When the torrefaction production plant is based on only one feedstock type, its design can be specific. But, when the plant needs to operate with different feedstock types, the torrefaction technology needs a multiple input, specific output approach, which means that special reactor must be flexible in processing different types of feedstocks concerning hydrodynamics, solids transportation and operating conditions [11]. Torrefaction process is more explained in detail in the previous work [12].

Hemicellulose degradation takes place within the same temperature range as torrefaction. In case when hardwood and softwood with comparable hemicellulose contents are torrefied under the same conditions each demonstrates different mass yields. Hardwood torrefaction provides lower mass yield than the softwood torrefaction, as xylan (the vigorous component of hemicellulose of hardwood) content is higher in hardwood 80–90%, than in the softwood, where it constitutes only 15–30%. So, the xylan is the most reactive constituent of hemicellulose in the torrefaction temperature range, and it breaks up faster than any other solid constituent of the biomass. Consequently, the mass loss is affected by the xylan amount in the biomass. During the process of torrefaction, hardwood gives up mostly acetic acid and water. Softwood releases mainly formic acid. Hardwood encounters greater mass loss on torrefaction

with no energy loss, it also gets a higher increase in energy density in comparison to that in softwood [2].

3 Torrefaction operating parameters

In this part of the work, effects of different torrefaction operating parameters are going to be discussed. Operating parameters: heating rate, residence time, catalysts, temperature, and particle size have the most effect on the torrefaction products and yields.

3.1 Effects of temperature and residence time on torrefaction process

Temperature is one of the most important torrefaction operating parameters that influence the biomass properties. Its effect is governed by the stability between exothermic and endothermic reactions, and it can be distinguished between three drying zones. Three drying zones are: non-reactive drying zone, reactive drying zone, and destructive drying zone, with five different temperature-time regimes. The zones are described on following way: first zone or the non-reactive zone (50–150 °C) is responsible for the disruption of the biomass cell structure and reduction of its porosity. Besides that, it comes to cellulose and hemicellulose drying and lignin softening and drying; in the second zone, reactive drying zone (150–200 °C) structural deformity of biomass, depolymerization of hemicellulose and decomposition of lignin take place. Second reactive drying zone also leads to the re-condensation of the shortened polymers and carbon and hydrogen bonds cleavage; third zone is the destructive drying zone (200–300 °C) where the torrefaction reaction occurs. The biomass cell structure is enduringly damaged, and it becomes fragile [13]. It can be emphasized that the change from one zone to another arises at slight temperature range for hemicellulose, whereas the changes for lignin and cellulose happen in a wider temperature range. From this it can be concluded that hemicellulose is the most reactive biomass component [14].

Depending on the range of operating temperature, it can be differentiated between three categories of torrefaction: light torrefaction (200–235 °C), mild torrefaction (235–270 °C), and severe torrefaction (275–300 °C). During light torrefaction, moisture and light volatiles are released. Hemicellulose, as the most reactive component of the lignocellulose material, is partly degraded during light torrefaction, while cellulose and lignin are only partly influenced. When it comes to mild torrefaction, hemicellulose is decomposed to the greater extent. Also, cellulose is more consumed during this stage of torrefaction. During

the severe torrefaction, hemicellulose is completely used and cellulose is also degraded to a greater degree. Lignin is hard for thermal degradation. Torrefaction is usually operated from several minutes to several hours. The calorific value of solid fuels is improved through torrefaction, and a longer residence time raises the carbon content and heating value in the biomass [10].

The temperature and residence time have influence on the characteristics of torrefied biomass. The fraction of mass yield drops with the temperature rise. Also, with the increasing retention time, the mass yield percentage decreases. The effect of temperature has more effect on the mass yield than the retention time has [2, 14]. Also, energy yield declines with the rise of temperature. With the increased temperature, it comes to decrease of mass and energy yields, but increase of energy density. Also, carbon content increases with the temperature rise, whereas hydrogen and oxygen contents decrease with torrefaction temperature rise. Biomass retention time in reactor is longer. This further affects the lowering of mass yield and increasing of energy density [2].

Temperature is the most significant parameter, which should be controlled during the torrefaction. In order to preserve the quality of the final products, there is a need of keeping the temperature constant. It is essential that emission of volatile compounds (non-condensable and condensable) takes place during the torrefaction. If this does not happen, especially when the removal of condensable products does not occur, the cooling process will boost the creation of tar and other hydrocarbon-based compounds which can be connected with the self-ignition of torrefied biomass. Condensable compounds arise from biomass with higher amounts of condensable materials [15].

Biomass tends to degrade thermally and change its physical structure; in case the temperature is very high. Temperature outlines the kinetics of the torrefaction reaction, and retention time affects torrefaction features, only for the duration of some temperature ranges [15].

Torrefaction of agricultural residues (wheat-barley straw pellets and wheat-rye chaff) was examined in the study of Jagodzińska et al. [16], with the emphasis on temperature and retention time effects on the properties of final products. With temperature increase from 210 to 260 °C, the content of biochar and condensable compounds expanded. With further temperature rise, the change was small. This minor alteration was caused by cracking and secondary reactions of condensable volatiles that followed in the origination of compounds characterized by lower

molecular weights. Some of them turned out to be part of noncondensable compounds. With temperature growth, it came to increase of a liquid yield which is an outcome of nonpolar or slightly polar compound development (e.g., benzene derivatives). Generally, with the time rise, the biochar content lowered for the sake of condensable and noncondensable compounds [16].

An interesting review study on different effects having an influence on palm oil torrefaction was done by Yaacob et al. [17]. Some of the important findings in this study are following: higher torrefaction temperatures lead to higher calorific values of the final products; as the torrefaction temperature increased, carbon content improved as well, while hydrogen and oxygen contents scaled down with the temperature rise; as torrefaction severity increased, the yields of mass and energy shrunk; and outcomes of torrefaction temperature were more important than that of retention time. Poudel et al. [18] have investigated the fuel properties of food waste at torrefaction temperatures from 150 to 600 °C, for torrefaction retention time varying from 0 to 50 minutes in a horizontal tubular reactor. This study also confirmed previous statements that torrefaction temperature has more influence on torrefaction than the retention time. Also, energy and mass yields reduced with a rise in temperature. Besides, the weight percentage of carbon increased with the temperature increase. At the same time the weight percentages of hydrogen and oxygen decreased. So, the O/C and H/C ratios declined with temperature rise.

3.2 Effects of particle size

The particle size is also one of the key parameters for biomass torrefaction. Biomass' conductivity is poor and the temperature gradient across the particle will determine the mechanism of biomass pyrolysis [10]. The mean particle size of ground torrefied biomass is lessening with higher torrefaction temperature. Generally, torrefaction of biomass not only reduces the specific energy required for grinding, but it also decreases the average particle size of ground biomass [19]. Basu [2] have discussed that the mass yield can be slightly increased when the volume mean diameter is increased or the length of a piece of constant diameter. Mass yield can be reduced when the diameter was increased, with the constant length. These results are outcome of heat transfer to inside the biomass and the temperature dependent reaction within it. Torrefaction includes convective heat transfer from the torrefaction reactor to the biomass exterior, conduction of the heat into

the biomass interior, and the reaction within the reactor. Relative extent of these three rates chooses which parameter will impact the whole torrefaction process. The Biot number is the proportion of the heat convection to the outside surface and conduction of the same into the inner part of the particle. Pyrolysis number is another parameter related to the outside surface heat transfer rate to the torrefaction reaction rate [2]. If Biot number is $\ll 0.1$, the resistance to conduction within the particle is much lower than the resistance to convection across the fluid boundary layer. So, the temperature within the particle is assumed to be uniform. The pyrolysis number is usually very larger than 1. This means that the external heat transfer rate is much quicker than the reaction rate inside the particle. So, the external heat transfer is capable of delivering enough heat energy to resist the torrefaction reaction, i.e., the endothermic reaction of torrefaction would not cause the particle surface temperature reduction. Biot and pyrolysis numbers show that the temperature gradient within the particle is minor during torrefaction [20].

So, in the case when the Biot number is small, (for fine particles), the thermal resistance inside is insignificant. In the case of high pyrolysis number, the reaction will be rate controlled. For the larger particles Biot number is higher and pyrolysis number is lower. So, the torrefaction will be measured by heat conduction into it, and it leads to a higher temperature in the biomass core [2].

Basu et al. [21] have investigated the aspect of size and shape of biomass on torrefaction. The research was conducted on different sizes of poplar and oak wood. Diameters of poplar were 13, 19, and 25 mm, and lengths were varying from 8 to 65 mm. Some of experiments were conducted on oak wood, with comparable shape and size as poplar wood. Experiments were performed primarily in directly heated convective reactors at 250 °C for an hour with only a few experiments conducted in fluidized bed reactors. With increasing particle length, mass and energy yield increased, but with increasing particle diameter, the opposite occurred. As wood sample size increased, the core temperature rose for a given temperature, according to Basu et al. [21]. Temperature rise in the core was minimally affected by changes in length. This can be attributed to the heat flow in small diameter long samples, which was mainly radial. Additionally, mass and energy yield decreased with increasing diameter despite no change in energy [21].

Another interesting study regarding the effect of particle size on torrefaction yield was conducted by Trubetskaya et al. [22]. Feedstock used for the torrefaction process

in the study was olive stones from Tunisia (high bulk density and abundance). Particle sizes of pulverized olive stones were ranging from 0.18 to 3 mm. During torrefaction, quartz tube reactor and condenser coolers were used, as well as a twin-neck receiving flask for collection of torrefaction liquids. The main outcome of the study was that olive stones smaller than 2 mm, processed at 270 °C for 30 minutes are the best material for coal briquetting, because they yield solid char, are less reactive, and have better thermal conductivity. Increased ash content was the result of olive stone size decrease. Also, the time-of-flight secondary ion mass spectrometry indicated that olive stones smaller than 0.425 mm had more cellulose than lignin on the particle surface than the material consisted of larger grains.

Wang et al. [23] studied the effects of temperature and particle size on biomass torrefaction in a slot-rectangular spouted bed reactor. Sawdust particles with different sizes (0.25–0.5, 0.5–1.0, and 1.0–2.00 mm) were torrefied in this study. Sawdust particles from this study are a mixture of spruce, pine, and fir wood species. Comparison of the different sizes of sawdust showed that the smallest (0.25–0.5 mm) sawdust had the lowest weight loss, because the smaller diameter particles were more readily entrained and had shorter residence times in the reactor. When larger particles were used more of the products stayed in the reactor, so that the energy yield decreased accordingly.

3.3 Effects of heating rate

Heating rate can change the properties of torrefied biomass, as the consequence of the change of its lignocellulosic polymer alignment. During the process of pyrolysis, a higher heating rate is desired, since it rises the degree of lignocellulosic polymer depolymerization and dehydration into volatiles, with minimal char yields. These conditions are not good for biomass torrefaction, because solid fuel is desired product. Torrefaction requires a low heating rate in order to produce more solid products [24]. The heating rate has only effect on torrefaction process during heating up stage [25].

Silveira et al. [26] have studied the effect of torrefaction on thermal behavior and fuel properties of *Eucalyptus grandis* macro-particulates. The feedstock samples were heated up at a linear heating rate of 5 °C min⁻¹ until following temperatures of 230, 250, 270 and 290 °C were reached. Afterwards they were torrefied for an hour. For temperatures of 250 and 270 °C treatment temperatures, a heating rate assessment was carried out, employing two more heating rates (3 and 7 °C min⁻¹). Experiments showed that

higher heating rates experience greater mass loss rate under the same temperature. With higher operating temperature and higher heating rates, the exothermic peak is more prominent. This happens because of the exothermic reactions within the wood sample. Similar thermodegradation kinetics was obtained for 5 and 7 °C min⁻¹, but there is a difference between 3 and 5 °C min⁻¹. This behavior can be explained by the earlier and higher internal heat release in exothermic reactions during the treatment with the higher heating rates which can lead to a different kinetics of mass loss following different reactions. This means that after a certain heating rate, there was no big difference for the studied sample size. Tran et al. [27] also confirmed that increased heating rate led to high mass losses.

Mamvura et al. [28] have investigated the consequences of diverse parameters on torrefaction of two South African biomass types, marula seeds and blue gum wood. The study concluded that the weight loss was more prominent when the heating rate was increased. Higher heating value, weight loss and energy density for each feedstock type improved with increase of a heating rate. Higher heating rates stimulate dehydration and decarboxylation reactions which further influences the faster removal of volatiles in a shorter period of time and thus densifying the biomass energy. This study determined that non-oxidative conditions with lower heating rates and shorter residence time accomplished the best torrefaction results.

3.4 Catalytic effects

Biochar yield and quality can be improved by using alkali and alkaline earth metals as catalysts. During torrefaction alkali and alkaline earth metals are released, resulting in products with high energy density, heating value, and grindability, as well as improved thermal degradation characteristics. Torrefaction usually produces greater amount of biochar when alkali and alkaline earth metals are used. Organically enclosed sodium, potassium, calcium, and manganese metals increase biomass's reactivity during torrefaction. Thermogravimetric analysis (TGA) can be used to study the effect of catalysts on solid yield. The reaction time is also reduced for pine and spruce biomass with K and Na [29]. Using TGA of Safar et al. [30] have studied the catalytic effects of K on the torrefaction of biomass (rubber wood). K almost has no effect at low temperatures, but its catalytic effect is more obvious at higher torrefaction temperatures (≥ 250 °C). Thermochemical reactions in biomass can be made possible by K impregnation. K's catalytic effects boost the productivity of biochar

formation and shorten torrefaction time while maintaining the same mass loss, resulting in time and energy savings. After removing the alkali and alkaline earth metals catalytic minerals from biomass, the mass loss occurred. Catalysts are removed by water, hydrochloric acid, and ammonium acetate. As a result of pretreatment and removal of alkali and alkaline earth metals, biomass turned out to be less sensitive to thermal degradation, resulting in increased mass and energy yield. Moreover, herbaceous biomass (*Miscanthus* and wheat straw) when pre-washed reduces the ash content of torrefied biomass. Also, when, hydrochloric acid and ammonium acetate were used for pre-washing of biomass, the ash content decreased further [31].

Zhang et al. [32] evaluated in the impact of K and Mg contained in rice husk during torrefaction. K increased the weight more rapidly, when compared to magnesium present in the rice husk. Both elements produced small molecule gas products from the catalytic conversion of the macromolecular liquid products. K was more catalytically active than magnesium. Mg had little influence on the elemental composition and higher heating value of solid product, but K showed an upturn of the carbon content and higher heating value. Chemical composition of the liquid and gas products can be controlled by impregnation by K or Mg. Only minor amount of K and Mg was discharged to the volatiles during the process, while the most of K and Mg remained in the solid product. Generally, torrefaction with the low potassium content improved biomass feedstock for the energy purposes, and the solid product from the process with high K impregnation is not appropriate as a fuel, due to the ash-related issues, but it can be used as a soil fertilizer. Another important characteristic of Mg-based additives is the strengthening of deoxygenation during torrefaction. Also, this additive serves as catalyst in further pyrolysis for producing of hydrogen and high-quality aromatic hydrocarbons [33]. An excellent study was conducted by Yek et al. [34], where authors have analyzed the biochar and catalytic effect of using microwave radiation and steam over a waste palm shell. Lower mass yield was accomplished with microwave wet torrefaction in comparison to the microwave torrefaction. Porous biochar was produced during this reaction, high heating rate and lower mass yield conversion were observed. Application of microwave radiation with steam purging led to more efficient torrefaction and prohibited the creation of the hot spot in the reactor, which would promote uneven heating and variable product yield.

4 Reactors for torrefaction process

Torrefaction plant typically involves several units like biomass handling, preparation, dryer, torrefaction reactor, and product cooler. Among these, torrefaction reactor is the most important one. Torrefaction reactors can be classified into two categories regarding the torrefaction process: heat transfer and solid contacting. Depending on the mode of heating, torrefaction reactors can be either directly heated or indirectly heated. It is also possible that reactors have a combination of heating modes. The heat transfer to biomass can take place on following ways: gas – particle convection, wall – particle conduction, electromagnetic heating of biomass, particle – particle heat transfer, and liquid – particle heat transfer [2].

There are three different scales of torrefaction reactors: pilot, commercial, and laboratory. Last type is the most important one, because these reactors serve for the development of process (testing of parameters, studies, etc.) that will be applied later on pilot and commercial scales [15]. The laboratory scale reactor's production capacity is less than 20 kg/h; however, the capacity of pilot scale reactors is between 20 and 600 kg/h, and the capacity of commercial scale reactors is more than 600 kg/h [35].

There are different categories of laboratory scale torrefaction reactors [15, 35]:

1. fixed bed torrefaction reactor,
2. microwave torrefaction reactor,
3. fluidized bed torrefaction reactor, and
4. rotary drum reactor.

The fixed bed torrefaction reactor is commonly used in laboratories for preliminary analyses. It has simple configuration and low costs. It is composed of a glass or stainless-steel cylinder, a furnace for heat supply, temperature measure devices, a cooling unit for condensation of gases. An inert atmosphere has to be provided during the process, and nitrogen is mostly used to achieve those conditions [10]. For microwave torrefaction the high frequency electromagnetic waves (microwaves) are needed. Microwaves vibrate the water molecules inside the biomass, which results in biomass temperature rise [35]. The microwave irradiation consists of electromagnetic waves from 300 MHz to 300 GHz. Typically, microwave reactors operate at 2.45 GHz. In this type of reactor biomass is heated internally, which means that each part of the biomass in microwave radiation range are heated at once [2]. In the fluidized bed torrefaction reactor, the raw biomass feedstock is positioned on a grate and the hot

inert gas comes from the lower part of the reactor through the raw biomass bed. At a right inert gas rate, the raw biomass lifts and behaves like a fluid. This spreads a uniform temperature through the raw biomass bed [15, 35]. Rotary drum reactors can be heated directly or indirectly [15].

Pilot scale torrefaction reactors are developed according to the laboratory reactor results [35]. The reactor types present in companies or scale-up laboratories involve [10]:

1. fixed-bed reactor,
2. rotary drum reactor,
3. screw reactor,
4. microwave reactor,
5. moving-bed reactor, and
6. other types of reactors, such as torbed reactor, belt drier, multiple hearth furnace, vibrating electrical elevator and reactor, rotating-packed bed reactor, and spouted-bed reactor.

Pilot scale fixed bed torrefaction reactor is comparable to laboratory scale fixed bed reactor apart from the heat source. The pilot scale fixed bed torrefaction reactor becomes a heat from raw biomass burning, while laboratory scale derives it from an electrical heater. This type of reactor cannot be operated continuously, no matter the process scale [35]. Nitrogen is mostly used as a carrier gas, for providing an inert condition during the process. Disadvantage of this type of reactor is difficult sampling, and low heat transfer and temperature regulation. This further influences the upsizing of reactor and its potential commercial application [10]. Rotary drum dryer can be applied as material heating and drying equipment. Rotary drum dryer is a sort of conveying equipment, and it is important for the expansion of a continuous torrefaction system. Parts of a continuous rotary drum reactor are [10]:

- a feeding unit with screw feeder,
- a rotary reactor unit with an external heating source,
- and a product collector unit.

Due to the continuous rotating of the reactor, the conductive heat shifts between wall and sample [10].

In a screw (Auger) reactor, biomass is pushed by a screw through the twisted screw of the reactor. This type of reactors ensures process continuity and is compactly designed. However, the issues of upscaling and low energy efficiencies limit the commercial use of screw reactor. A screw reactor employs one or more screws for transferring the biomass through the reactor. It is often heated directly. Mixing in this type of reactors is restricted, so the heat

transfer is poor. Large screw reactors are highly efficient because they mix biomass with hot medium with intense heat transfer [36]. Adeleke et al. [8] denoted following benefits of screw reactor:

- affordable prices,
- good flow of biomass,
- capability to take a broad range of biomass sizes,
- and it is an established technology.

Fig. 1 represents a simplified illustration of the screw reactor [36].

The microwave reactor differs from other types of reactors, which have direct heating. In this type of heating system, biomass is heated on the exterior, so that the heat from the heat carrier contacts the surface of particles and it is then conducted into their cores. On the other side, microwave heating takes place at the same time throughout the samples, and it is more efficient [10]. A lot of electricity is needed for generation of microwaves. But reactor can take biomass with large particle sizes. In this type of reactor torrefaction occurs very quickly, and temperature is easily controlled. However, the reactor needs to be equipped with traditional heater, if homogeneously heated particles are desired [36]. The main obstacle for its commercial application technology is electric power request [37].

Raw biomass is moved from the reactor's entrance to its outlet using mechanical mechanisms. This type of reactor can be classified into three categories: rotary kiln torrefaction reactor, screw conveyor torrefaction reactor, and multiple hearth torrefaction reactor [35]. Fig. 2. shows the illustration of moving bed reactor [37]. Rotary kiln reactors can process different materials, e.g., minerals, coke, cement, and waste. The movement of the particles inside the reactor depends on the operating parameters. Screw conveyor reactor has four sections: the biomass feeding section, the reactor section, where it comes to conversion of biomass into torrefied materials and combustible gas, the cooling section, and the combustor section, where

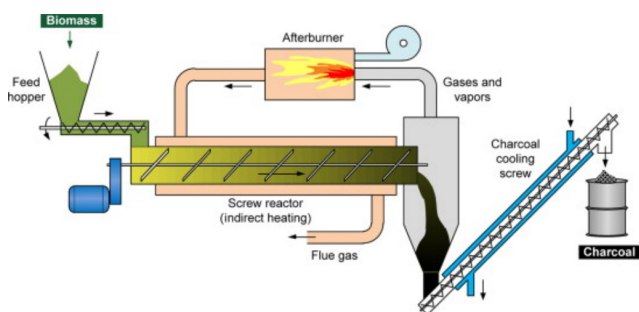


Fig. 1 Screw reactor – simplified illustration [36]

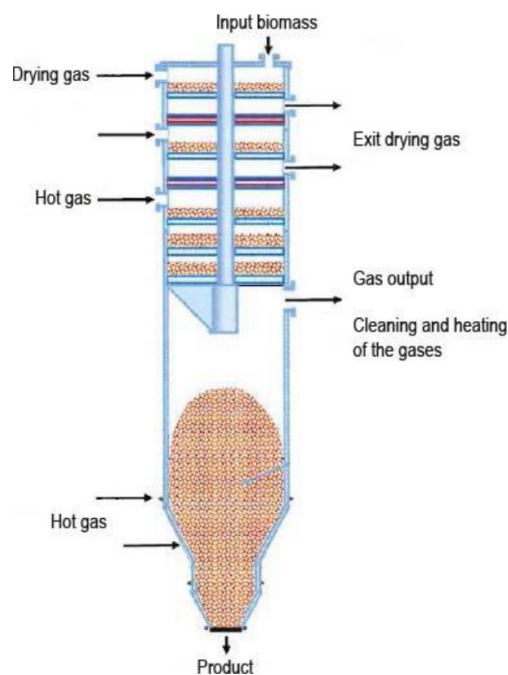


Fig. 2 Moving bed reactor [37]

produced gases and vapors are burned with an excess of oxygen in the combustor [38]. Screw conveyor reactors are indirectly heated reactors [39]. The required heat is provided by combustion of the gases that are released in the process. Gases are directed to a devoted combustion compartment. By forcing hot flue gas along the reactor's wall, biomass is indirectly heated. Limitations are [38]:

- upsizing is restricted,
- cleaning is challenging,
- and low mixing of the bed.

Multiple hearth furnace reactors are composed of several circular hearths or kilns and this type of the reactor allows use of high volume biomass particles. The biomass is provided from the upper side of the reactor. Biomass moves downwards inside the reactor, they are gradually mixed and heated as they pass from the upper side of the reactor to the first hearth, then to the second hearth and next hearth by rotating "rabble arms". As biomass particles move downwards within the reactor, they are gradually mixed and heated [37]. It is a continuous reactor that contains several layers. The temperature increases gradually from 220 to 300 °C. The biomass moves from the top of the reactor horizontally and it is mechanically pushed away, and then comes through another entrance, etc. This process is repetitive in many layers, arising in even mixing and gradual heating. Fig. 3 illustrates multiple hearth furnace reactor [36]. In multiple hearth furnace reactor,

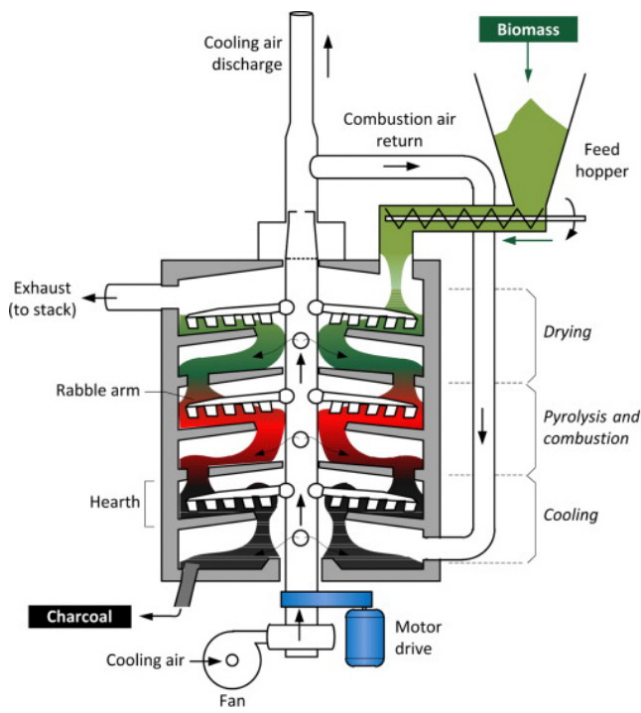


Fig. 3 Multiple hearth furnace reactor [36]

there is a good heat transfer, ability to obtain high volume of biomass particles, good regulation of temperature. The drawbacks are large reactor size, large consumption of gas for heating [37].

Torbed reactor uses transfer of heat by injection of high velocity gas from the bottom of the reactor through the stationary angled blade and as a result the gas lifts and moves the biomass bed vertically and horizontally making the particles warm. Due to the intensive heat transfer, reactor can operate under high temperatures [37]. Torbed reactor has low retention time and fast heat transfer that lead to great output. Temperature is very high, which influence the formation of tar and high loss of volatiles [8]. The graphic illustration of torbed reactor is given in Fig. 4 [37].

A modern solution would be REVE, adapted from the idea of roasting different food ingredients, like peanuts, barley, or soya. Another innovative concept of reactor design would be rotating packed bed (RPB) that proposes a better mass transfer of reactants. Chen et al. [10] showed different studies conducted with the application of this type of reactor. Piersa et al. [36] have provided a large overview of torrefaction facilities worldwide. Some of them are summarized in Table 1.

5 Conclusion

Biomass is an abundant resource worldwide, and when treated properly, it can be used as a solid fuel for gasification, combustion, densification, etc. Torrefaction is one

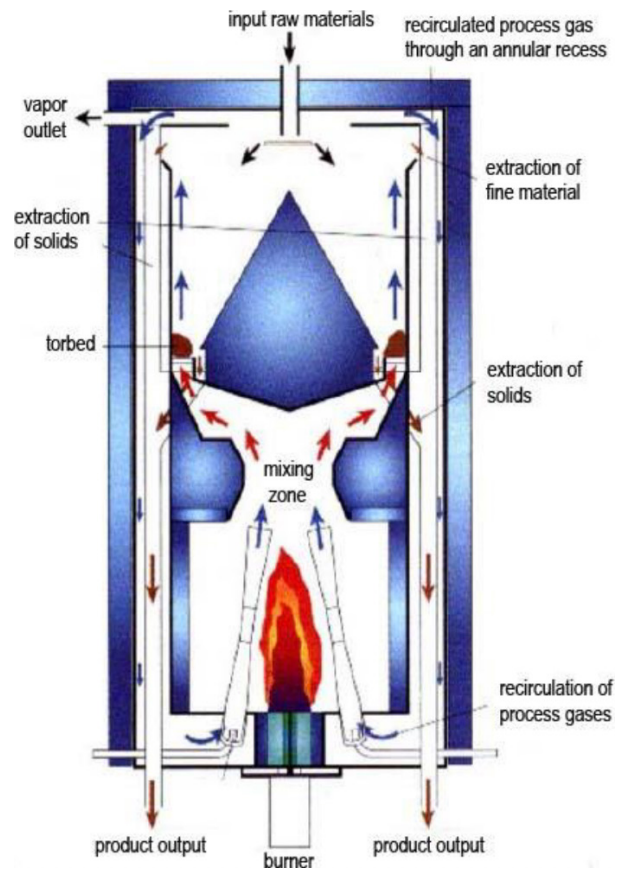


Fig. 4 Torbed reactor [37]

of the methods that can be used for biomass pretreatment. At the same time, torrefaction process improves biomass properties, like improving its grindability, hydrophobicity, energy density.

The main aim of this work was to show which types of biomass can be used for the process of torrefaction, to show what the most influential operation parameters are, and to summarize reactors of this process. Following feedstock types can be utilized in torrefaction process:

- virgin wood,
- energy crops,
- agricultural residues,
- food waster,
- and industrial waste and by-products.

Mostly, torrefaction was performed using wood and agricultural by-products. During torrefaction, in the lignocellulosic materials, hemicellulose degrades the most, while lignin and cellulose degrade to a certain degree.

In this paper, the following effects on torrefaction process were discussed: effects of temperature and residence time, effect of particle size, effect of heating rate, and catalytic effects. The temperature and residence time have effect on the properties of torrefied biomass. As the temper-

Table 1 Torrefaction technologies overview in regard to facility scale and process (adapted from [36])

Developer	Technology	Capacity (ton/year)	Country	Scale and status
Agri-Tech Producers LLC	Belt reactor	13 000	Columbia, S. Carolina, USA	Pilot operation
APS Ekoinnowacje	Conter-flow reactor	360	Lodz, Poland	Semi-pilot operation
Airex	Cyclonic bed	3 000	Canada	Planning, 10 000 – 30 000 ton/year, with SUEZ partnership, available
Bio Energy Development North AB	Dedicated screw reactor	16 000	Sweden	Demonstration scale, available
New Earth Renewable Energy Fuels, Inc.	Fixed bed	Unknown	Unknown	Out of business
Bioenergy Development and Production	Fluidized bed	Unknown	Nova Scotia, Canada	Pilot, unknown
Rotawave, Ltd.	Microwave	120 000	Chester, United Kingdom	Most probably not in the operation
ECN-Andritz	Moving bed	10 000	Stenderup, Denmark	Combine technology with Andritz
Thermya/Grupo Lantec	Moving bed	20 000	Urnieta, Spain	Early stage
Thermya/LMK Energy	Moving bed	20 000	Mazingarbe, France	Early stage
Torrec	Moving bed	10 000	Mikkeli, Finland	Demonstration scale, available
Grupo Lantec	Moving bed	20 000	Urnieta, Spain	Demonstration scale
Clean electricity generation	Oscillating bed	30 000	United Kingdom	Commercial scale, available
Torr-Coal B.V.	Rotary drum	35 000	Dilsen-Stokkem, Belgium	Commercial scale, available
FoxCoal	Screw conveyor	Unknown	Winschotel, Netherlands	Pilot, but under bankrupt
Topell Energy	Torbed, fluidized bed	60 000	Duiven, Netherlands	Commercial scale, available

ature increases, the percentage of mass yield decreases. By increasing the residence time, the percentage of mass yield decreases. The net effect of temperature rise has significant effect on the percentage of mass yield more than the residence time. Temperature is the most important parameter that has to be controlled during the process. So, there is a need of keeping temperature stable in order to provide high quality product afterwards.

When it comes to the effect of particle size, torrefaction output is depending on the size of the feedstock. When the particle length increases, it comes to mass and energy yields increase, but when the particle diameter increases,

the yields decrease. A low heating rate is desirable during the process of torrefaction, in order to produce solid products; higher heating rates are expected in pyrolysis, because they promote liquid product formation. For the biochar yield improvement, alkali and alkaline earth metals can be used. Mostly, applied are sodium, potassium, manganese, magnesium or calcium.

Torrefaction reactors can be divided in several categories depending on the heat transfer and solid contact. Also, torrefaction reactors can be divided according to the scale of the process into following categories: laboratory, pilot, and commercial.

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