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Torrefaction of Various Types of Biomass in Laboratory Scale, Batch-Wise Isothermal Rotary Reactor and Pilot Scale, Continuous Multi-Stage Tape Reactor

Toryfikacja różnych typów biomasy w reaktorze obrotowym w skali laboratoryjnej oraz wielostopniowym reaktorze taśmowym w skali pilotażowej

Torrefaction is a thermal pretreatment process that improves properties of biomass relevant to its use as a fuel. It increases a heating value of the biomass, bringing it closer to the one of coal. That prevents the loss of power due to a decrease in calorific value of the fuel when biomass is supposed to replace coal partially. Along with less hygroscopic nature, in comparison to raw biomass, it allows improving logistics of the fuel. It also enhances grindability of the fuel, which is important for boilers and gasifiers that use pulverized fuel. In this study, four types of biomass were torrefied under different temperature regimes. Tests were performed in two different torrefaction reactors: laboratory scale Isothermal Rotary Reactor and pilot scale Multi-stage Tape Reactor (output up 10 kg/h and 100÷÷500 kg/h respectively). The process was characterized using dry mass loss during torrefaction, known as the mass yield. Energy yield was also calculated. Raw materials have been compared to the corresponding torrefied products. The comparison was based on standard set of properties, that is mandatory to be tested for any solid fuel, e.g., results of the proximate and ultimate analysis, the calorific value of the fuel. Obtained results have shown a significant improvement, regarding grindability after torrefaction. Also, hydrophobic nature of raw and torrefied biomass was a subject of tests. The propensity towards the moisture absorption was determined, by long-term storage under constant relative humidity conditions. Decreased rate of moisture absorption was observed for torrefied biomasses when compared with corresponding raw materials.

Keywords: biomass, torrefaction, multistage tape reactor, grindability

Introduction

Biomass is considered a renewable energy source when the rate of growth is higher than the rate that biomass is consumed [1, 2], i.e., any biomass harvested either for energy or materials, such as construction wood or paper, shall be replanted. Good examples of such practices could be found in forestry sector [3] in

many countries. Use of biomass as a material without utilizing residues could lead to potential problems. For example, annual worldwide CO_2 emissions from forest fires can exceed 115 Mt/a for temperate and boreal forests altogether, while CO_2 emissions from fires of tropical forest can exceed 500 Mt/a [4]. This is more than an annual CO_2 emission of a mid-size industrialized country, such as Poland. On top of that residues become a subject of natural decomposition, thus producing other greenhouse gases, such as methane. In this context, it seems better to utilize residues rather than its energy, that will be released anyway, become wasted.

Torrefaction is a process of thermal valorization of solid fuel to enhance its fuel properties subsequently allowing low-grade fuels, such as biomass, to become a tradable commodity [5]. It is a process that is considered to improve the logistics of the upgraded fuel [6, 7] and make it more suitable for final use such as co-firing [8-10] or gasification [11-14]. Torrefaction is sometimes called slow pyrolysis and it typically takes place at temperatures between 250 and 300°C with residence times ranging between 10 and 60 min [5, 15-21]. Decomposition of hemicellulose starts below 200°C and decomposition of lignin is much slower, with a peak in temperatures higher than 300°C [16]. Therefore, it is possible to perform process outside of the conventional range. However, suitability should be assessed individually in each of the cases. During torrefaction part of the mass of the feedstock is removed. A part of volatile matter is being removed forming a by-product called torgas [19]. This by-product contains a portion of the chemical energy contained in the feedstock. Torgas can be used to supply the heat that is necessary for the torrefaction process [5].

Since wood has always been the most commonly used of all solid biofuels, its torrefaction has already been a subject of extensive research [5, 15-25]. Since its quite well known and abundant, it is also a good test piece for novel torrefaction reactors to assess its suitability for the case of the specific device. Nearly 60 million tons of palm oil is being produced around the world, with Malaysia and Indonesia being two mayor suppliers [26]. Palm oil fruit bunches are harvested from the trees that are between 10 and 20 years old [27]. Fruit bunches are being pretreated by sterilization under 145°C and 2,7 bar for 90 min, digested at 90 up to 100°C for 30 min and subsequently pressed [28]. Beside the woody residues from the palm trees pressing of the oil produces many residues such as palm kernel shells (PKS), empty fruit bunches (EFB) and palm mesocarp fiber (PMF) [27]. Palm oil industry produces approximately 4.6 million tons of dry mass of PKS per annum [27]. Due to its potential as an energy source torrefaction of PKS was a subject of studies. Sabil et al., studied torrefaction of PKS in temperatures ranging from 200 up to 300°C [29]. The research team conducted torrefaction in TGA using 2 mg portions of fuel. PKS was ground down to the particle size below 500 μm. Samples were torrefied for 120 minutes. Torgas was analysed by mass spectrometer coupled with TGA. CO was identified as the main species and CH_4 as the second most abundant, with much smaller amounts of CO_2 and H_2 present in the gas. In a follow-up study Sabil et al., conducted a fiber analysis and SEM analysis of the torrefied samples [27]. Okoroigwe and Saffron also analyzed PKS using TGA [30]. PKS was

obtained from Nigerian palm oil industry, but temperatures were slightly higher than in typical torrefaction. Within the scope of the study fiber analysis and SEM analysis was performed. The research team concluded that complete depolymerization of fibers in PKS could be achieved between 400 and 500°C [30]. Asadullah et al., went one step further by performing torrefaction of PKS in custom build lab scale setup [28]. Batch type reactor was used, although research team was able to avoid the problem of heating up of the biomass in temperatures lower than the target temperature, by feeding biomass to the hot reactor. Torrefaction experiments were performed at temperatures ranging from 200 up to 300°C and residence time varied between 10 and 60 min. A portion of approximately 100 g with "as received" particle size was used for tests. Torgas was condensed in a dry ice condenser and subsequently analysed by titration. Gaseous compounds were captured into bags and analysed in a gas chromatograph. Research team also conducted experiments with heating up of the PKS pellet with a diameter of 20 mm in the reactor with temperature of 300°C [28]. The team concluded that the surface of the pellet sitting inside of the reactor reached 300°C after more than 600 s the center of the pellet reached aforementioned temperature after more than 1050 s [28]. Determination of the specific grinding energy was also within the scope of the aforementioned study. Retsch SM 2000 with 1.5 mm screen was used to measure the specific grinding energy [28]. Ohm et al., also conducted experiments with torrefaction of PKS among other materials such as waste wood, logging residues and bagasse [31]. The feedstock was placed in a ceramic dish which in turn was put into the electric furnace. Gaseous compound was analysed. Ash fusibility of the torrefied samples was within the scope of this study and torrefied PKS achieved deformation temperature of 1,157°C [28]. Ueamura et al., studied torrefaction of PKS under both inert and oxidizing atmospheres [26]. Fibre and SEM analysis as well as the determination of reaction kinetics were within the scope of the study [26]. Obinna et al., torrefied Nigerian PKS at temperatures of 200 up to 300°C with residence times ranging from 40 to 120 min using ceramic boats and a tubular furnace reactor [32]. Poudel et al., performed a comparative study of torrefaction of PKS and EFB from oil palm grown in Malaysia [33]. After series of experiments in a tubular furnace, using particle size between 1 and 2 mm, it has been concluded that optimum torrefaction temperature for PKS is between 300 and 320°C. Rajnai et al., torrefied rapeseed straw along with other species such as wheat straw and black locust wood [34]. Torrefaction was performed at temperatures ranging from 200 up to 300°C in a tubular furnace, with nitrogen as an inerting agent. Fibre analysis was within the scope of the study. It confirmed that the content of Klason lignins increased, with increasing temperatures, at the expense of glucan, xylan, and arabinian [34]. Benavente and Fullana studied torrefaction of olive mill waste [35]. Torrefaction was performed in an oven under a wide range of temperatures, from 150 up to 300°C, with a residence time of 2 h. Tests performed between 150 and 200°C were performed in order to assess changes in a residual oil content, as the smoke point of the olive oil was 160°C [35]. Study demonstrated that the content of oleic acid had influence on the carbonisation pathway, when comparing tor-

refied olive waste with pathway for carbonisation of coal, which was shown at Van Krevelen's diagram [35]. Cellatoglu and Ilkan used a custom build, batch-wise operating torrefaction setup, to torrefy olive waste at the temperatures ranging between 210 and 280°C with residence times of 30 up to 120 min [36]. Study concluded that the optimum conditions for the torrefaction of olive waste would be temperature of 280°C and residence time of 30 min [36]. In another study Cellatoglu and Ilkan assessed torrefaction of olive waste in a novel type of reactor using solar energy, concentrated by a parabolic dish, to deliver the heat for the process [37]. The study demonstrated that solar energy can be stored in a solid fuel, by being used as a source of the process heat [37]. This would enable the use of torgas for other purposes such as biorefinery feedstock.

Performed literature study outlined differences between the process conditions used in a various studies. All proved the overall suitability of the torrefaction as a pre-treatment process for upgrading of the low-quality biomass of various types. All attempted to quantify the difference in the product quality with varying process conditions. However, none of the studies attempted to assess the influence of the type of the reactor on the quality of the obtained product. A lack of the published data from pilot scale units also made it difficult to put the obtained results into a perspective. Moreover, these differences might introduce a mayor problems, when data from one type of reactor is used for upscaling of another type of the unit. This study aims to fill the identified gaps. Two types of reactors, i.e., rotary with use of inert gas (nitrogen) and multi-stage tape without external gas, were used for the study of waste biomass. Therefore, the intensity of heat and mass transfer is different in both reactors and may affect the characteristics of the torgas and its calorific value varies considerably. Higher heating value has been chosen as a basis of the comparison, since in practice it determines the value of the fuel for the consumer. Comparison was performed only for a chosen types of feedstock, due to substantially higher quantities of the feedstock required for the pilot scale unit. Pre-selection was made, based on the results from the batch-wise reactor. The purpose of the pre-selection was to pick only feedstocks exhibiting significantly different conversion behavior, marked by the parameters of the respective product.

1. Materials and methods

Tests were carried out both at a laboratory and pilot scale. Materials used for tests were: PKS, residues from the production of olive (olive waste), wood chips that consisted of the mix of various wood species and rapeseed straw. Substrates, in particular, PKS, were selected for research as an example of waste biomass due to the high availability of the biomass market, imported into Poland as a biomass fuel by several distribution companies. PKS can be characterized as a residue with relatively uniform particle size, high combustion heat, with relatively high lignin content. However, the drawback is high hardness resulting in a drop in total mill output during the pulverization in a mill. The torrefaction process changes both the physi-

cal properties of the biomass and the extent to which it depends on the process conditions, which is the subject of the work. The particle size of PKS was greater than 12 mm. The particle size for olive waste was between 3 and 6 mm. Wood chips were fairly uniform with an approximate width of 20 mm and length of 40 mm. Rapeseed straw was pelletized to 8 mm diameter pellets.

Laboratory scale tests were performed using isothermal rotary reactor (Fig. 1). The core part of this test rig is a rotating pipe made of heat resistant steel and externally heated by the set of electric heaters. The test rig has its control system that can maintain the temperature set by the operator up to a maximum of 1000°C. Temperature is measured at the outside surface of the pipe by three thermocouples, one in the middle and two on both ends of the heated pipe. Samples of the torgas are taken by the sampling probe introduced to the inside of the rotating pipe (at the far end of the pipe, along the central axis; nr 9 at Fig. 1). All the solid products were collected at the bottom of the drop, out of the far end of the pipe (nr 8 at Fig. 1). Condensable gaseous compounds present in torgas were captured by the set of impinger bottles connected in series. Bottles were filled with water and cooled with ice-bath. Cold gas went through conditioning unit to get rid of any residual moisture and filter all the remaining particulate impurities. Gaseous (non-condensable) products of torrefaction were measured using FTIR analyzer Gasmet CX 4000.

a)   b)

Isothermal rotary reactor
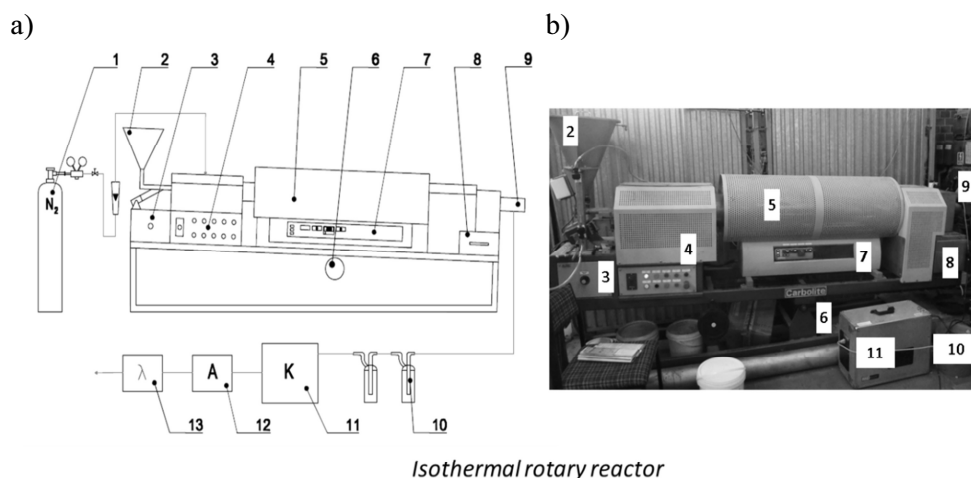
1 - nitrogen cylinder, 2 – feedstock hopper, 3 - motor, 4 - control panel, 5 – torrefaction reactor (rotary chamber), 6 – regulation of the tilt, 7 - temperature panel control, 8 -torrefied product container, 9 - gas sampling, 10 – impinger bottles, 11- gas conditioning system, 12 - gas analyser, 13 - oxygen analyser.

Fig. 1.   Isothermal rotary reactor setup - diagram (a) and picture (b)

The feedstock was torrefied at three temperatures: 250, 275 and 300°C with a residence time of 40 min in an inert atmosphere. Nitrogen was used to obtain inert conditions in the reactor, with a flow rate of 1500 dm^3/h. For each of the tests batch size of approximately 1 kg was used. Average residence time was obtained by series of pre-test, performed with the cold reactor. During these trials, the

sample was fed from the feedstock hopper with a specific tilt and rotational speed (rpm) being set. Time was measured since the start of the process. It was the time when the highest amount of material was flowing out of the pipe, that was considered an average residence time. In each of the cases, feedstock was weighted before the experiment. Solid products after torrefaction were also weighted. The mass yield was determined directly (dry basis) and energy yield was calculated using higher heating values.

Multistage tape reactor was used to perform tests at pilot scale (diagram is shown in Fig. 2). This is a patented technology [38] that performs torrefaction of biomass, continuously, using the indirect heating system. Biomass is heated externally using hollow shelves. Heat is delivered to the aforementioned shelves by hot flue gases. The reactor is equipped with three shelves and temperature was measured separately at each level, as depicted in Figure 2, and the average was considered to be the process temperature. The temperature of the shelves in the reactor was regulated by controlling the flue gas flow to the hollow shelves, using valves. On the other side of the hollow shelves, biomass is being moved by a set of scrapers. Inside of the reactor is isolated from the ambient by two airlocks at the inlet of the feedstock and one airlock at the outlet (Fig. 2). It can be assumed that reactions took place under anaerobic conditions as only air present in interstitial spaces, in between individual feedstock particles, was being delivered into the reactor (no inerting agent was used during performed experiments). Residence time was controlled by the velocity of the scrapers. Heat for the reactor was produced by burning of the gaseous by-product of the reaction, called torgas. Oil burner was used for the startup and for supplying the pilot flame in order to ensure stable combustion.

Moisture content and volatile matter content of feedstocks and products was performed using TGADT Pyris diamond from Perkin Elmer. Two-step program was set, i.e., the sample was heated in nitrogen up to 110°C with ramp of 20°C/min, with hold period of 15 min afterwards. During the second step sample was heated up to 900°C with the ramp of 200°C/min, with hold period of 15 minutes afterward. Ash content was determined using standard gravimetric method for coal, by ashing samples in 815°C for 3 h. The ultimate analysis was performed using Perkin Elmer 2400 analyzer, according to polish standard PKN-ISO/TS 12902:2007 (standard is compatible with ISO).

Higher heating value (HHV) was determined using IKA C2000 basic calorimeter, in compliance with ISO 1928. The isoperibolic method was used. The lower heating value was calculated using moisture content values obtained with TGA. The tendency towards moisture absorption was assessed by measuring mass increase due to water absorption during storage in a room with stable relative humidity of 40%, which is fairly similar to the typical storage conditions in hoppers in boiler rooms especially in case of large-scale units like power plants and CHP units. The energy requirement for grinding of feedstocks and obtained products was tested using cutting mill Retsch SM 100 with 500 μm screen. Same amount of sample (500 g) was fed to the mill for each of the cases and milling was always

performed for the same amount of time (20 minutes). Consumption of electricity was measured by a 3-phase electromechanical induction meter. Run with an empty grinder, performed for the same amount of time was used as a baseline. In case of wet feedstock, pre-drying was implemented, to avoid biased result, due to flowability issues with wet material. Without pre-drying wet particles of suitable size (smaller than the screen aperture) could have had problems with flowing through the aperture of the screen.
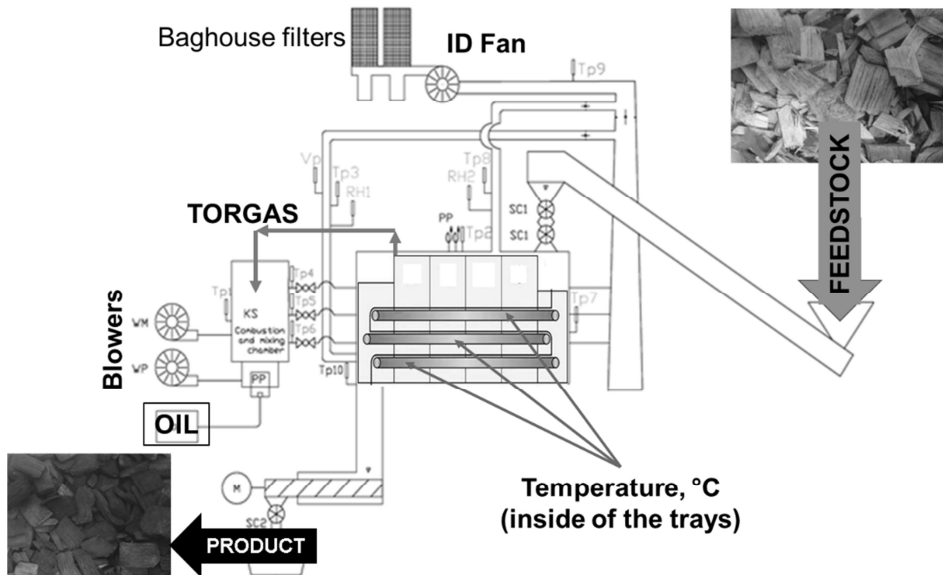
Fig. 2. Multistage tape reactor - diagram (SC - rotary valve; Tp - thermocouple; PP - pressure gauge; Vp - velocity probe)

2. Results and discussion

Tests performed at laboratory scale demonstrated some differences, regarding behavior during torrefaction, between each of tested feedstocks. Mass yield of torrefied PKS was a subject of steep decrease when the temperature of torrefaction increased from 250 to 275°C (as shown in Fig. 3). In this particular case further increase in temperature up to 300°C did not lead to a significant decrease in mass yield. Mass yield of torrefied Olive Waste decreased only slightly between torrefaction at 250 and 275°C, but dropped sharply for process temperature of 300°C. The more steady decrease was observed for the torrefaction experiments performed with wood chips (see Fig. 3). Regarding the energy yield, increasing torrefaction temperature of PKS from 275 to 300°C did not result in a decrease of the aforementioned parameter, which means that increased temperature comes at no penalty in terms of the energy balance of the process. This could be explained by increase in HHV combined with relatively similar mass yield.
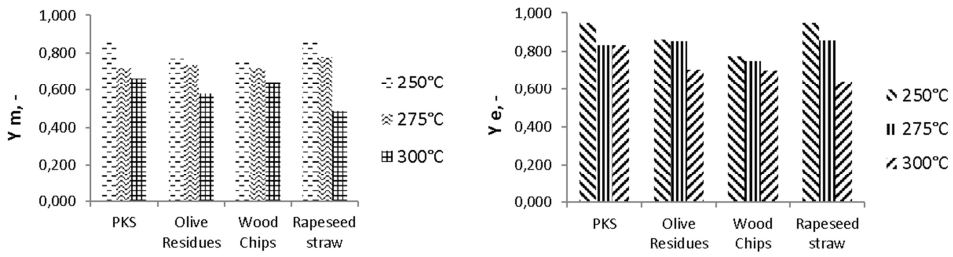
Fig. 3. Mass yields and energy yields obtained during torrefaction tests performed with wood chips, olive residues, rapeseed straw and palm kernel shells using isothermal rotary reactor

On top of that same amount of enthalpy in torgas in both of the cases, along with the higher amount of torgas is likely to suggest the decreased calorific value of torgas produced at 300°C. Energy yield during torrefaction of the olive waste followed the trend of the mass yield, i.e., there was little change in energy yield between torrefaction at 250 and 275°C with substantial drop of the discussed parameter for torrefaction of olive waste at 300°C. Energy yield observed for torrefaction of wood chips followed a similar trend as in the case of the corresponding mass yields.
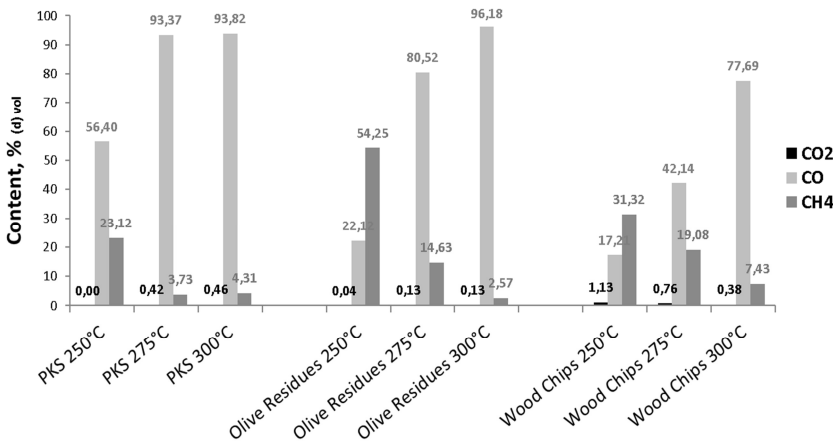

Fig. 4. Main gaseous compounds of torgas during performed torrefaction tests using rotary reactor

Substantial changes in torgas composition could be observed, depending on the temperature of the process. Results for torrefaction of PKS (Fig. 4) showed quite a similar trend as it was in the case of mass and energy yield, i.e., the content of mayor gaseous (non-condensable) compounds was quite similar for process temperatures of 275 and 300°C. For both of the cases, carbon monoxide was more than 93%$_{(vol)}$ of all the detected gaseous compounds produced, whereas for torrefaction at 250°C CO was only 56% of all of the detected gaseous compounds. It was also easy to notice that methane content dropped significantly for process temperatures

higher than 250°C. Increase of CO content along with a decrease in CH_4 content, with increasing temperature of the process, could also be observed for olive residues and wood chips (Fig. 4).

Comparing the results presented at Figure 4 with energy yields (Fig. 3) one might state that observed trends of changes in composition of various gaseous compounds have little effect on overall energy balance of the process, since heating value of CH_4 is higher than corresponding value for CO. However, it is well known that the majority of chemical energy of torgas is in its condensable compounds. On the other hand, increased CO content brings some health and safety implications due to the nature of CO.
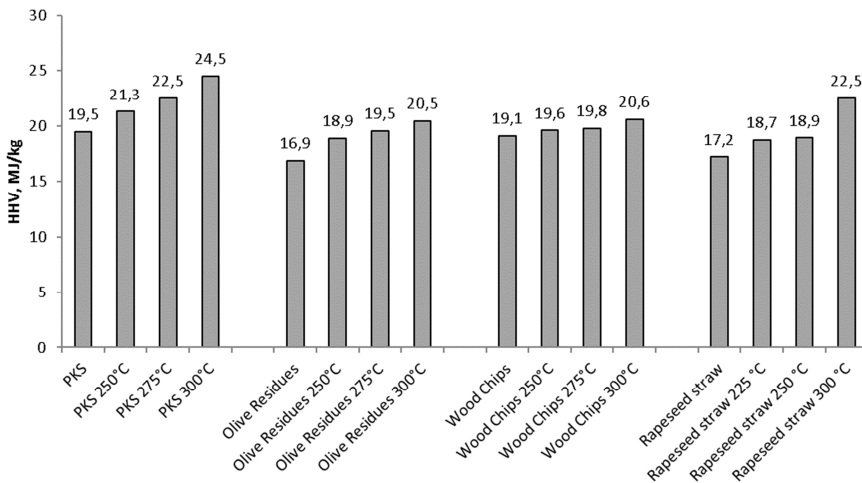

Fig. 5. Higher Heating Value of feedstocks and torrefied products

Results, presented at Figure 5, clearly demonstrated the capability of torrefaction to increase the higher heating value of the biomass in all of the cases, which is beneficial regarding thermal valorization of solid fuels. Higher heating value of the palm kernel shells was a subject of much more rapid increase in comparison with other feedstocks, whereas wood chips exhibited the least rapid increase of the respective parameter. Carbonization of the torrefied biomass has also been demonstrated (Fig. 6).

Carbon content increased in all of the analyzed cases. In all of the cases, increase in carbon content was mainly at the expense of the oxygen content, which is promising if torrefaction is used as a pretreatment technology for gasification or pyrolysis. It also explains quite well the aforementioned decrease in calorific value of torgas, as it would result in the higher content of oxygenated compounds. Proximate analysis has shown the loss of the volatiles in all of the cases (Fig. 7). The moisture content of the torrefied product decreased in all of the cases, with respect to the corresponding feedstock (Fig. 7). Ash content increased in all of the cases due to the loss of some of the organics (Fig. 7).
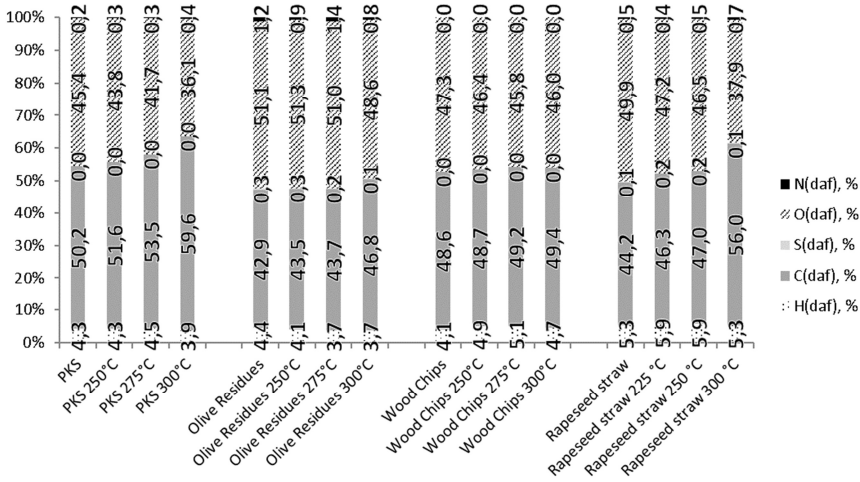
Fig. 6. Ultimate analysis of torrefied materials along with corresponding feedstocks
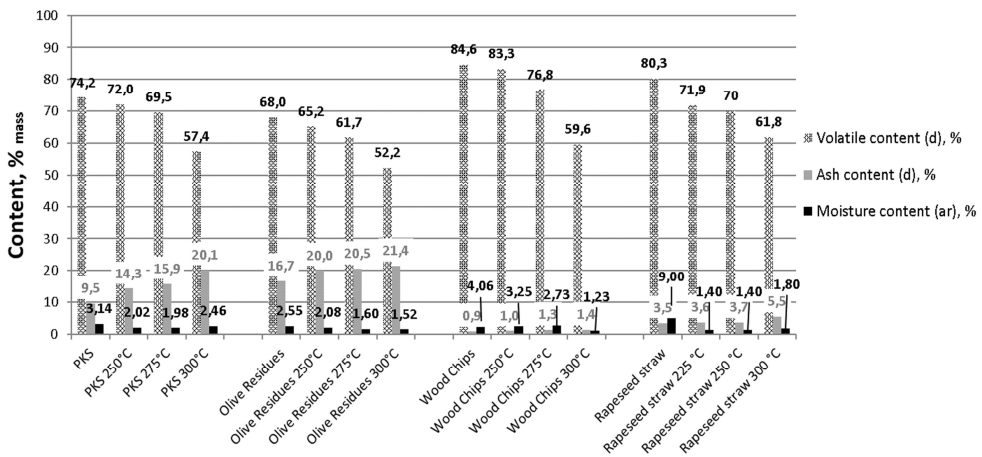

Fig. 7. Proximate analysis of tested samples

Storage of the samples in an environment with constant relative humidity delivered a proof that propensity of biomass towards moisture absorption has been reduced due to torrefaction. This is depicted at Figure 8. Time of 24 h is quite typical for fuel bunkers of industrial-scale boilers in industrial scale heating plants, CHP units and power plants. Storage conditions (temperature and relative humidity) resemble typical conditions of storage in fuel hopper in the boiler room, during the heating season. It can be seen that the rate at which the moisture is absorbed, varies in case of each of the tested fuels. Nonetheless, it is quite clear that the increase in the torrefaction temperature sub-sequentially leads to lower rates of the moisture absorption, leading to lower equilibrium.
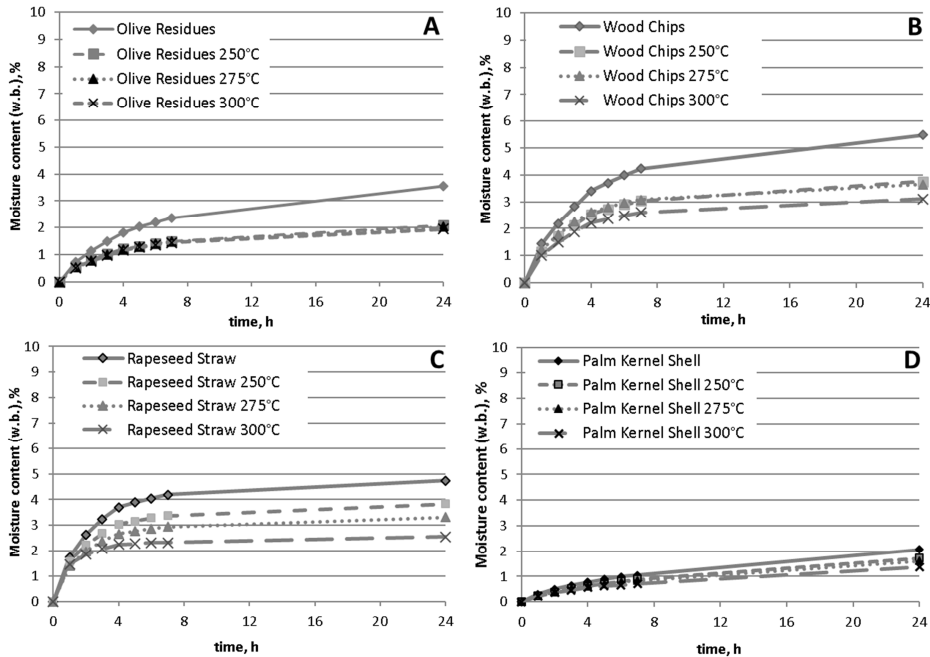
Fig. 8.   Moisture absorption during storage of feedstock and torrefied samples: olive residues (A), wood chips (B), rapeseed straw (C) and palm kernel shells (D)

Due to significant differences in the higher heating value palm kernel shells were pre-selected for further trials with the pilot scale unit. Wood chips were also selected due to the most modest increase in its higher heating value, during the laboratory torrefaction tests. Tests performed at the pilot scale confirmed some of the findings from the laboratory scale tests. As demonstrated by Figure 9, HHV of torrefied materials was a subject of increase, both in the case of PKS and wood chips. Slightly different HHV values of feedstock obtained from the bomb experiments, using feedstock samples from the rotary reactor and pilot scale reactor can be attributed to the natural variability of biomass, especially taking into the account the fact that wood chips consisted of the variety of mixed species. It is clear that temperatures are not directly comparable, as there was no possibility to measure the temperature inside of the bed of torrefied material. Also, implications of the heat transfer mechanism should be taken into account. This general observation is quite consistent with the results range of results observed in the literature. Especially experiments with temperature gradient within a PKS pellet give us some valuable insight [28]. Residence time and particle size also have an important influence on the overall outcome of experiments. With the existence of a thermal gradient within the particle itself, it is certain that the gradient within the bed is higher. In this context, it seems reasonable that results obtained on the pilot reactor with PKS are in better agreement regarding the HHV with tests performed at 300°C by Asadullah et al., in comparison with HHV obtained by the same team for 350°C.

It is also in good agreement with tests performed within this study in the rotary reactor (lab scale).

This brings the conclusion, that transition of the results from one type of the reactor to another is not straightforward, especially when differences in terms of the scale of the device are taken into account. Tests from one reactor can be used to make some general predictions regarding the suitability of the feedstock in another unit. However, a suite of tests shall always be performed, using a pilot unit, to confirm the expected outcome.
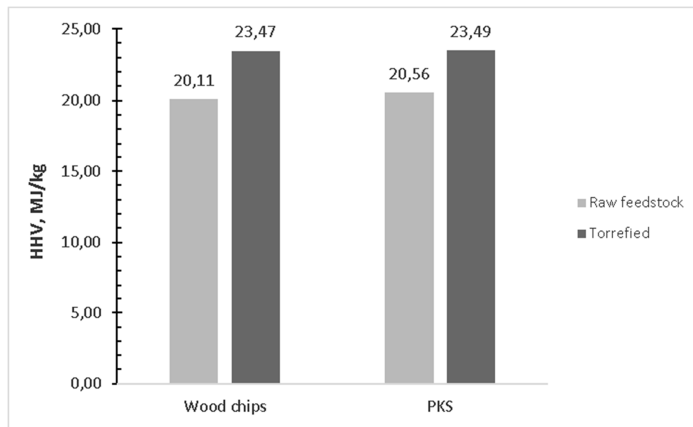

Fig. 9. Higher Heating Value of raw and torrefied wood chips and palm kernel shells - results from the pilot-scale multistage tape reactor

Interesting results were obtained from a suite of grindability tests, performed with wood chips and PKS torrefied in the pilot scale unit (Fig.10). Performed tests confirmed improvement in the grindability of torrefied material, by demonstrating the decreased energy consumption, with respect to the corresponding feedstocks.

Raw, wet wood chips were pre-dried, before performing a grindability test, which was deemed insignificant in terms of the specific energy consumption results. It is worth an acknowledgment that drying can potentially weaken the structure of wood. However, in any final use that would require pulverization, wood would have been dried before its final application (for example combustion).

It is interesting to notice that wet wood chips (moisture content of 48% $_{wet\ basis}$), torrefied at 370°C with residence time of 45 min needed higher amount of the energy for grinding in comparison with air-dried wood chips (moisture content of 20% $_{wet\ basis}$), torrefied at 350°C for 35 min (Fig. 10). This shows that the moisture content of feedstock has a profound effect on the overall quality of the product. This is a direct consequence of the time and amount of heat required for drying. It is reasonable to suspect that due to the highly endothermic nature of the drying process it took much longer for all the wet particles to reach the temperature within the torrefaction range.
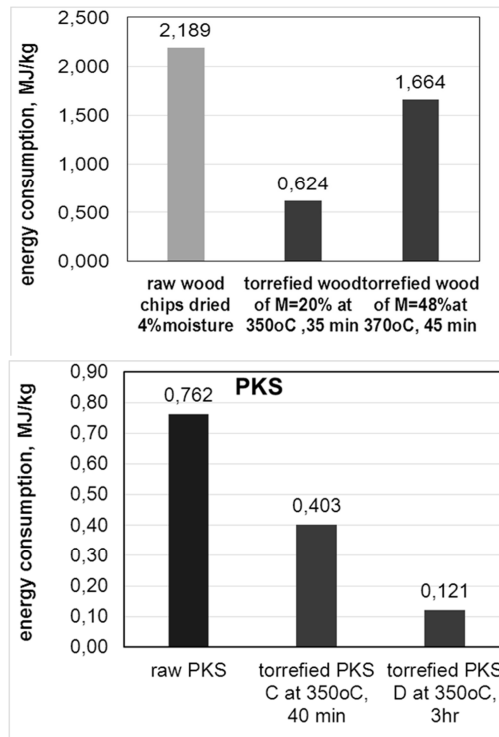
Fig. 10. Specific energy consumption for comminution of raw feedstock and product torrefied in pilot multi-stage tape reactor: wood chips (left), palm kernel shell (right)

Grindability tests of PKS showed the profound effect of the residence time on the specific energy consumption during grinding (Fig. 10). Specific grinding energy results obtained for PKS showed some differences in comparison with the literature results. It could be attributed to the different aperture of the screen in the mill (500 μm) in comparison to other studies (1.5 mm used by Asadullah et al.). Overall the suite of performed tests proved without any doubt that torrefaction is a viable way to decrease the specific energy requirement for comminution of different types of biomass, such as wood chips or PKS.

Conclusions

Performed tests confirmed that benefits of torrefaction as a pretreatment process for solid biofuels are available for many different types of feedstock. The ability to increase Calorific Value of the fuel, increase the carbon content was demonstrated at both laboratory scale and pilot scale. Obtained results confirmed benefits of torrefaction as a process capable of curtailing the hydrophilic nature of the raw biomass. The suite of performed tests proved without any doubt that torrefaction is a viable way to decrease the specific energy requirement for grinding of different types of biomass. Performed work also demonstrated the profound influence of the

moisture content of the feedstock on the overall quality of the product. Residence time was also identified as an important parameter, which is partially connected with the aforementioned moisture content and the time required for drying of the feedstock.

Results obtained using pilot scale unit revealed that transition of the results from one type of the reactor to another is by no means straightforward. Differences in terms of the different scale of the device could play an important role amplifying any changes introduced by differences between the batch and continuously working reactor. Apart from the different scale of the installations also heat transfer to the particle was different, implying different heating rates. On top of that inert agent was used in case of the rotary reactor. Differences in the installation's design cause differences in the process parameters, if the goal is to achieve similar degree parameters of the product using two distinctly different reactors. However, in case of both reactors, fuel properties (such as HHV) improved qualitatively up to the similar extent.

Results obtained using a pilot reactor may be treated as a proof-of-concept and a case study that could be used in practice during projects developed in the future. In the long term, it seems to be important to develop a coherent theoretical model, that would take into the account differences in working principals of different reactors. This would allow the more appropriate choice of the process condition to obtain the required product quality, based on the set of laboratory tests. At the moment results of such tests can only be used as a useful indication of the expected gains.

Acknowledgements

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Streszczenie

Toryfikacja jest procesem obróbki termicznej, który poprawia własności biomasy pod kątem jej zastosowania jako paliwa. Proces zwiększa wartość opałową waloryzowanej biomasy, czyniąc ją bliższą do tej, jaką ma węgiel. Pozwala to zapobiegać obniżeniu mocy w przypadku częściowego zastąpienia węgla tak przetworzoną biomasą. W połączeniu z mniej higroskopijną naturą, w porównaniu do nieprzetworzonej biomasy, pozwala to na poprawę logistyki paliwowej. Proces poprawia też przemiałowość biomasy, co jest niezwykle istotne w przypadku kotłów i zgazowarek wykorzystujących paliwo stałe w postaci pyłu. W zakres niniejszej pracy wchodziło przeprowadzenie toryfikacji biomasy w różnych reżimach temperaturowych. Testy zostały przeprowadzone na dwóch różnych reaktorach: izotermicznym reaktorze obrotowym (w skali półtechnicznej) i wielopoziomowym reaktorze taśmowym (w skali pilotażowej). Proces został scharakteryzowany pod względem utraty suchej masy w procesie toryfikacji (zwanym powszechnie uzyskiem masy) oraz pod względem uzysku energii. Dokonano także porównania biomasy nieprzetworzonej z jej toryfikowanym odpowiednikiem pod względem uzyskanych wyników analizy technicznej, elementarnej oraz kaloryczności. Testy wykonane na młynie laboratoryjnym potwierdziły wzrost podatności na przemiał biomasy poddanej procesowi toryfikacji. Oszacowany został także wpływ toryfikacji na jej długoterminowe przechowywanie poprzez ocenę jej hydrofobowości. Ocena ta została dokonana na podstawie obserwacji zmiany wilgotności próbek przechowywanych w warunkach stałej wilgotności. W porównaniu z nieprzetworzoną biomasą toryfikaty wykazały mniej hydrofobową naturę.

Słowa kluczowe: biomasa, toryfikacja, wielopoziomowy reaktor taśmowy, podatność na przemiał