ENERGY BALANCE OF BRIQUETTE PRODUCTION FROM VARIOUS WASTE BIOMASS*

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Production of briquette bio-fuel is related to several aspects of densification process. The present paper deals with the relation between briquette volume density ρ (kg·m^{-3}) and required deformation energy E_d (J). Wood, energy crop and cardboard feedstocks were compressed by a laboratory briquetting press of two diameters (40 and 65 mm); in this way six kinds of briquette samples (W_{40}, W_{65}, E_{40}, E_{65}, C_{40}, C_{65}) were produced. The values of compressing force F (N) and briquette volume density ρ were measured directly during feedstock densification; the deformation energy E_d was calculated subsequently. The amount of deformation energy E_d consumed within the achievement of specific briquette volume density ρ levels differed in case of all samples, the same as the maximum achieved briquette volume density ρ levels. Best results, i.e. efficiency of briquette production (the highest ρ, the lowest E_d), were achieved by cardboard samples, followed by wood and finally by energy crop samples. An overall evaluation indicated a higher production efficiency of briquette samples 40 mm in diameter and the disadvantage of the production of briquette samples with briquette volume density ρ > 1000 kg·m^{-3}; above such level, the amount of consumed deformation energy E_d increased disproportionately sharply.

solid biofuel, deformation energy, volume density, energy demand, briquetting

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INTRODUCTION

The process of briquette bio-fuel production is subjected to a set of regulations, all related to specific steps of this process (biomass densification). Such regulations determine proper feedstock material selection and preparation, technical specifications of densification process (pressing technology, compressive pressure), briquette size and shape, and the demands on the level of briquette quality indicators. Some of these regulations are based on mandatory instructions for precise form of the procedures (EN 15234-1, 2011; EN ISO 17225-1, 2015); some are represented by recommendations arising from previous researches (Grover, Mishra, 1996; Kaliyan, Morey, 2009; Mitchual et al., 2013; Tumuluru et al., 2015). The official form of the mentioned regulations is represented by mandatory technical standards defining all mentioned aspects of briquette production. Such standards must be strictly adhered during the whole briquette production process in an effort to achieve the required level of briquette quality indicators (chemical and physico-chemical), thus, to produce high quality briquette bio-fuel for commercial purposes.

Final briquette quality is influenced by various factors, specifically by pre-production, production, and post-production factors (Kaliyan, Morey, 2009; Mitchual et al., 2013). Pre-production factors are related mainly to feedstock material properties such as particle size or moisture content (Saptoadi, 2008; Eissa et al., 2013); post-production factors are related to briquette storage, transportation, and handling conditions (Brozek, 2013; Brunerova et al., 2016). In contrast, production factors are directly related to the aspects of densification process

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(briquetting) and used equipment. By combining such specific aspects it is possible to influence the indicators of briquette physico-mechanical quality, e.g. the briquette volume density ρ ($kg \cdot m^{-3}$) (Birwatkar et al., 2014) which expresses the efficiency of densification process, the suitability of specific feedstock materials for briquette production, and the ability of briquette bio-fuel burning. A higher level of ρ provides longer time of briquette burning and a greater amount of produced heat which is highly required. The level of ρ is directly influenced by technology of the pressing machine and its operating conditions, besides minor factors (Obernberger, Thek, 2004).

Kaliyan, Morey (2009), Wakchaure, Mani (2009), and Obi, Okongwu (2016) proved that volume density ρ of high quality briquette bio-fuel ranges from 1000 to 1200 $kg \cdot m^{-3}$ (depending on used feedstock material). If the commonly used technical mandatory standards are considered, according to ÖNORM M 7135 (2000) the briquette volume density ρ must be > 1000 $kg \cdot m^{-3}$, the German standard DIN 51731 (1996) requires ρ > 1120 $kg \cdot m^{-3}$ (Stolarski et al., 2013). The European standard EN ISO 13061-2 (2014) requires ρ of wood briquettes > 1000 $kg \cdot m^{-3}$, the same as the American mandatory technical standards ASAE S269.4 (1996).

Previous researches indicated that the briquette physico-mechanical quality goes up in relation with the briquette volume density ρ increase (Lindley, Vossoughi, 1989; Karunanithy et al., 2012; Tumuluru et al., 2015). Based on the mentioned facts, ρ = 1000 $kg \cdot m^{-3}$ can be considered sufficient for high quality briquette bio-fuel production.

The relation between the ρ and the compression force F (used for compressing feedstock material in bulk form) was investigated in previous researches (Bossel, 1984; Kaliyan, Morey, 2009; Tumuluru et al., 2015) which proved a close relationship between those two parameters – increasing of the compression force F causes increasing of the briquette volume density ρ. Moreover, F is also related to the required deformation energy E_d consumed during the densification process. Thus, the amount of required E_d increases in relation to F increasing. During the production of high quality briquette bio-fuel (ρ ≥ 1000 $kg \cdot m^{-3}$), a specific amount of E_d must be consumed, therefore, a specific amount of financial costs must be invested. Thus, E_d also represents one of the financial inputs of briquette production (Niedziolka, Szpryngiel, 2014). In general, ρ increasing causes the increase of consumed deformation energy E_d, thus, increasing of financial costs, too. Consequently, it is important to monitor the relation between ρ and related E_d (financial costs) of briquette during the densification process and assess its highest profitability and efficiency. The amount of consumed E_d also expresses the energy demands of specific investigated briquette kind production; such energy demands differ in relation to the variability of used feedstock materials (biomass kind) and their chemical and mechanical properties (Niedziolka, Szpryngiel, 2014).

Therefore, the present paper attempts to determine the energy demands of briquette production from various biomass kinds, namely wood biomass, herbaceous biomass, and waste paper. To achieve the main objective, the relation between consumed deformation energy E_d and briquette volume density ρ was monitored and evaluated with the aim to optimize briquette production and prevent energy and financial losses during high quality briquettes production. Up to date, the problem has received scant attention in scientific studies.

MATERIAL AND METHODS

Despite the fact that briquette samples investigated in the present research were produced by a special laboratory press (not by the commonly used high pressure briquetting press machine), the whole process of feedstock selection and preparation, briquette production, and qualitative testing was performed in accordance to appropriate mandatory technical standards which correspond to commercial briquette production, namely the technical standards EN 14918 (2010), EN 15234-1 (2011), EN 643 (2014), EN ISO 16559 (2014), EN ISO 17225-1 (2015), EN ISO 17831-2 (2015), EN ISO 18122 (2015), and EN ISO 18134-2 (2015).

Samples preparation

Three different kinds of feedstock materials were used for the experimental part of investigation, namely ash tree (*Fraxinus excelsior*) wood chips, energy crop (*Miscanthus x giganteus*) cuttings, and multilayer cardboard stripes. The mentioned feedstock materials were specifically chosen to represent frequently used biomass kinds suitable for briquette production. Primarily, the raw feedstock materials were processed to meet the demands of the briquetting process according to mandatory technical standards EN 643 (2014) and EN ISO 17225-1 (2015). It included preparation of feedstock materials to match proper particle size and proper moisture content. Suitable feedstock materials moisture content should be equal to 10% in maximum, while suitable particle size depends on the feedstock materials kind. In the case of investigated cardboard feedstock material the particle size corresponded to dimensions adjustment of paper shredder which was used for the material processing. Subsequently, the processed feedstock materials were subjected to determination of their chemical and mechanical parameters. Specifically, moisture content, ash content, particle size, and gross calorific value

Table 1. Basic parameters of investigated feedstock materials in average

	M_c (%)	A_c (%)	GCV (MJ·kg^{-1})	PS (mm)
Wood	7.7	0.6	19.4	12.0
Energy crop	8.1	2.7	18.1	8.0
Cardboard	6.2	13.9	15.5	4.0 × 39.0

M_c = moisture content, A_c = ash content, GCV = gross calorific value, PS = particle size

were determined in accordance with the mandatory technical standards EN 14918 (2010), EN ISO 18122 (2015), and EN 18134-2 (2015). Resulting values of investigated feedstock materials parameters are in Table 1.

The prepared feedstock materials were used for densification into cylindrically shaped briquette samples by a hand-crafted laboratory briquetting press (utility model CZ 222269 U1, inventors M. Brozek and A. Novakova, Czech University of Life Sciences Prague, Czech Republic) with pressing chambers of two different diameters – 40 and 65 mm (Fig. 1). Both pressing chambers were 120 mm high with the underlay of 9 mm placed inside. The pressing chambers were not filled to the edge, therefore the initial feedstock materials height was 108 mm before pressing.

A hydraulic universal tensile compression testing machine (ZDM 50; VEB, Dresden, Germany) served as an energy source for feedstock materials densification into the briquette shape; maximal used compressing force was equal to 500 kN and compressing speed was 1 mm·s^{-1} in average.

Within the densification process, six different kinds of briquette samples were produced. Namely, wood briquette samples with diameters 40 mm (identified as W_{40}) and 65 mm (W_{65}), energy crop briquette samples with diameters 40 mm (E_{40}) and 65 mm (E_{65}), and cardboard briquette samples with diameters 40 mm (C_{40}) and 65 mm (C_{65}). Constant laboratory conditions with air temperature 22.5°C and relative air humidity 40% (mean values) were ensured during the experimental measurements.

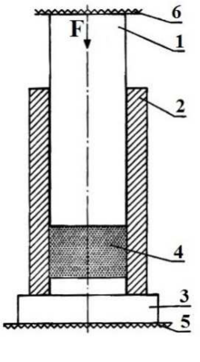

Fig. 1. Scheme of used laboratory briquetting press

F = compressing force, 1 = piston, 2 = pressing chamber, 3 = underlay, 4 = material, 5 = bottom pressure plate, 6 = upper pressure plate

Experimental measurement

The relation between compressing force F (N) and piston movement s (m) (deformation of feedstock material) was monitored at the beginning of experimental measurements; resulting values of the investigation were measured directly during the densification of feedstock materials. Displacement of the piston inside the pressing chamber (filled with the investigated feedstock material) caused deformation of the feedstock materials (feedstocks height reduction) resulting in the increase of volume density ρ (kg·m^{-3}) of the just created briquette sample. The values measured during the piston displacement reflected the precise process of briquette volume density ρ increasing simultaneously with increasing related compression force F. The measurements provided basic input data for subsequent calculation and expression of deformation energy E_d (J) consumed during the densification process.

The specific values of material compression were expressed using a specific tangent curve function (Eq. 1). The present tangent curve was chosen and verified as the most suitable regression curve in accordance with previous studies (Herak et al., 2012; Sigalingging et al., 2014):

$$F(x) = C_0 \tan(C_1 x)^{C_2} \quad (1)$$

where:
C_0 = force coefficient (N)
C_1 = deformation coefficient (m^{-1})
C_2 = exponent of fitted function

The observed data were analyzed in MathCAD 14 software (PTC, Needham, USA) using the tangent curve function (Eq. 1) and the 'genefit' function, and coefficients of the tangent curve model for all briquette samples variants were determined (Table 2).

In the following step, the deformation energy E_d (J) consumed during the production of specific investigated briquette samples was determined using integral (Eq. 2) of the mentioned tangent curve function and was expressed as an area located under that curve.

$$E_d(s) = \int_0^s F(x)dx \quad (2)$$

Table 2. Coefficients of tangent curve model determined for investigated briquette samples

	W_{40}	W_{65}	E_{40}	E_{65}	C_{40}	C_{65}
C_0	6 915	14 130	2 306	4 561	2 796	1 921
C_1	18.421	13.968	18.359	12.885	18.446	11.686
C_2	1.639	1.825	2.272	2.408	2.492	4.004

C_0 = force coefficient (N), C_1 = deformation coefficient (m^{-1}), C_2 = exponent of fitted function (–); W_{40}, W_{65} = wood briquette samples with diameters 40 and 65 mm; E_{40}, E_{65} = energy crop briquette samples with diameters 40 and 65 mm; C_{40}, C_{65} = cardboard briquette samples with diameters 40 and 65 mm

Table 3. Deformation energies E_d (J) consumed during achievement of specific volume density ρ ($kg \cdot m^{-3}$) levels

ρ ($kg \cdot m^{-3}$)	E_d (J)					
	W_{40}	W_{65}	E_{40}	E_{65}	C_{40}	C_{65}
800	709.7	2190.0	449.2	2469.6	204.9	558.2
900	1022.4	3228.8	794.2	–	317.8	897.3
1000	1482.3	–	1456.7	–	483.5	1405.3
1100	2197.3	–	–	–	713.9	2133.7
1200	–	–	–	–	1057.4	3123.0

W_{40}, W_{65} = wood briquette samples with diameters 40 and 65 mm; E_{40}, E_{65} = energy crop briquette samples with diameters 40 and 65 mm; C_{40}, C_{65} = cardboard briquette samples with diameters 40 and 65 mm

The investigated materials occurred in bulk form at the beginning of the experimental measurements, thus their bulk density could be determined according to the standard EN ISO 17828 (2015). The volume density ρ levels of the investigated samples were measured from the beginning of compression force F loading (deformation of feedstock material) until the maximal achieved volume density ρ (differing in each briquette kind). Nevertheless, the low levels of volume density ρ measured at the onset of compressing were not considered because of unimportance for the present research. In attempt to meet the mechanical quality requirements of briquette production for commercial purposes (for production of high quality bio-fuel), the level of briquette volume density ρ was monitored and evaluated from the level 800 $kg \cdot m^{-3}$ up to 1200 $kg \cdot m^{-3}$ with step 100 $kg \cdot m^{-3}$. Thus, the resulting values of deformation energy E_d were assigned to the corresponding volume density ρ levels in the range 800–1200 $kg \cdot m^{-3}$ and subsequently compared with each other in consequence of different briquette samples diameters and different feedstock materials kinds (biomass kinds).

RESULTS

The measured values obtained during the densification process primarily reflect the ability of the investigated feedstock materials (ash tree *Fraxinus excelsior* wood chips, energy crop *Miscanthus x giganteus* cuttings, and multilayer cardboard stripes) to be densified, i.e. their suitability for briquette production purposes. Primarily, all the investigated briquette kinds ($n = 6$) achieved different levels of maximal volume density ρ (higher level was required), therefore they consumed different amounts of deformation energy E_d (lower level was required) during their production. Such parameters of the briquette production process (resulting values are presented in Table 3) were the main objective of the present investigation.

In the cases when the investigated feedstock material could not be densified into the briquette samples with specific volume density ρ, the deformation energy E_d values are missing (–) in Table 3. The level of maximum achieved volume density ρ and the amount of consumed deformation energy E_d varied in relation to the materials variation (biomass kinds). Best results were achieved by the briquette samples produced from cardboard material, followed by wood briquette samples, and the worst results (the highest energy consumption, the lowest maximal achieved volume density ρ) were achieved by the energy plant briquette samples. A comparison of the individual investigated materials at specific monitored volume density levels is presented in Figs. 2 and 3.

Briquette samples of smaller diameter (40 mm) yielded better results, i.e. lower level of deformation energy E_d was consumed for achieving identical levels of volume density ρ in compare with briquette samples of larger diameter (65 mm).

In accordance with mandatory technical standards and previously published observations (described in Introduction section), the volume density ρ equal to 1000 $kg \cdot m^{-3}$ was stated as sufficient for high quality briquette production. Figs. 2 and 3 show that all investigated levels of volume density ρ (800–1200 $kg \cdot m^{-3}$) were achieved only by the cardboard briquette samples; the other investigated briquette samples achieved lower levels. Wood and energy crop briquette samples, both with 65 mm in diameter, did not achieve the required volume density ρ level ($\rho \geq 1000$ $kg \cdot m^{-3}$) at all.

In general, the observed results indicated that the briquette samples with larger diameter 65 mm (W_{65} and E_{65}) did not achieve the briquette quality level required for commercial production, moreover, their production consumed several times more deformation energy E_d, i.e. represented higher financial costs. In respect to such observations it can be concluded that the production of briquette samples with smaller diameters (< 65 mm) is more efficacious as concerns the briquette mechanical quality and production costs. The whole process of such briquette production seems to be more preferable.

The relation between the volume density ρ and deformation energy E_d (parameters of briquetting process) increasing was evaluated in detail for each investigated briquette sample kind (*n* = 6). Comparisons of the mentioned parameters increasing during the densification process are given in Figs. 4–9. The number of data points in each chart expressed the number of volume density ρ levels achieved by the specific investigated feedstock materials (monitored levels from 800 to 1200 $kg \cdot m^{-3}$); a higher number of data points indicated the achievement of a higher level of volume density ρ, thus the higher suitability for briquette production.

If the increasing of the two curves (deformation energy E_d, volume density ρ) presented in the diagrams is compared, we can see that after achieving the specific volume density ρ level (different in each sample) the deformation energy E_d (financial costs) started to increase very sharply in compare with volume density ρ which increased almost constantly. In most cases, maximal profitable volume density ρ level was equal to 1000 $kg \cdot m^{-3}$; such results were observed for briquette samples W_{40}, C_{40}, and C_{65}. The remaining briquette samples exhibited different results, namely, for briquette samples W_{65} and E_{40} the maximal profitable volume density ρ level was stated at 900 $kg \cdot m^{-3}$; the briquette sample E_{65} achieved only the level of volume density ρ equal to 800 $kg \cdot m^{-3}$.

The mentioned trend supports previous observations which indicated that after achieving the volume density ρ equal to 1000 $kg \cdot m^{-3}$ the energy consumption increases disproportionally faster, bringing about higher financial demands of the briquetting process. Therefore we may speculate if the production of briquettes with volume density $\rho > 1000$ $kg \cdot m^{-3}$ is still advantageous and profitable. Moreover, such intentional increase of briquette volume density ρ is not necessary for commercial briquette production according to mandatory technical standards.

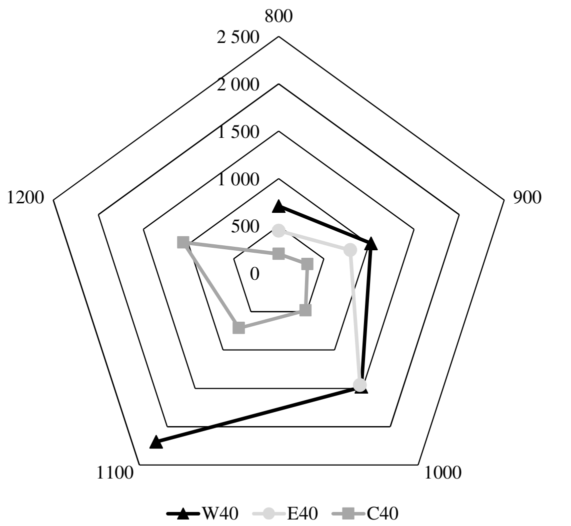

Fig. 2. Energy demands of investigated briquette samples 40 mm in diameter

W40 = wood briquette samples 40 mm in diameter, E40 = energy crop briquette samples 40 mm in diameter, C40 = cardboard briquette samples 40 mm in diameter

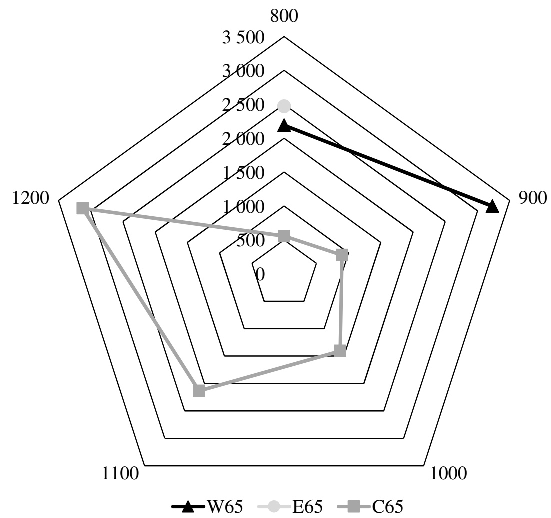

Fig. 3. Energy demands of investigated briquette samples 65 mm in diameter

W65 = wood briquette samples 65 mm in diameter, E65 = energy crop briquette samples 65 mm in diameter, C65 = cardboard briquette samples 65 mm in diameter

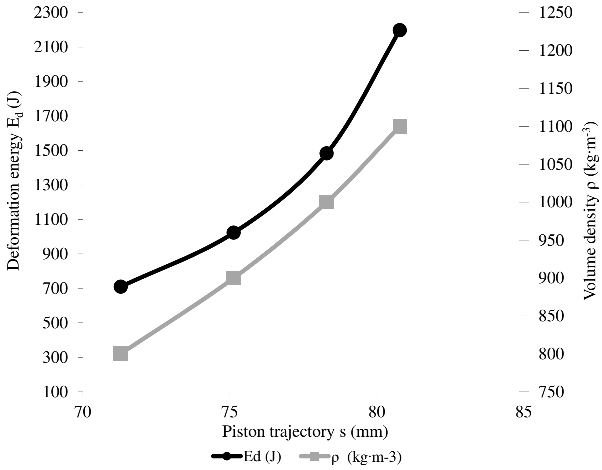

Fig. 4. Relation between briquette volume density ρ and related deformation energy Ed – wood samples 40 mm in diameter

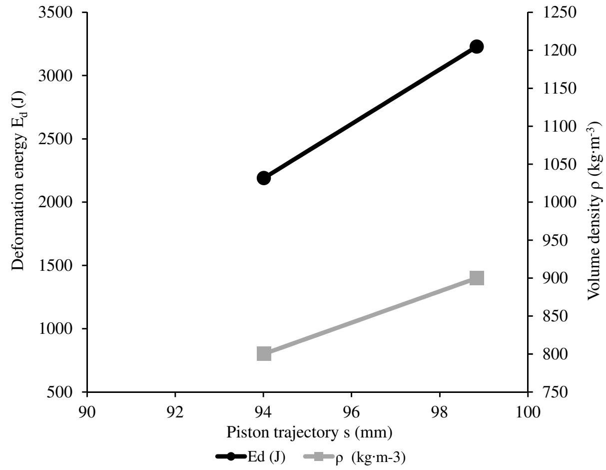

Fig. 5. Relation between briquette volume density ρ and related deformation energy Ed – wood samples 65 mm in diameter

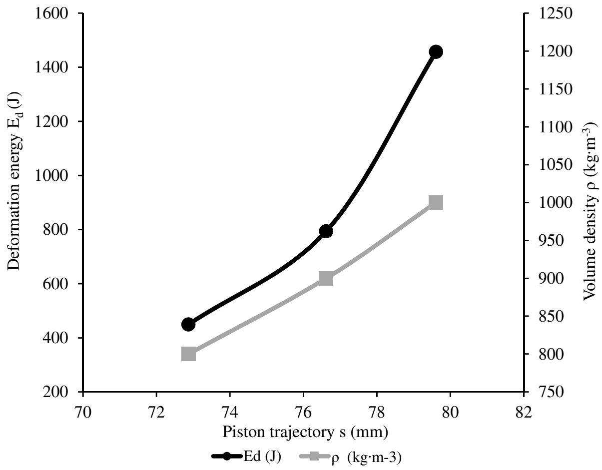

Fig. 6. Relation between briquette volume density ρ and related deformation energy Ed – energy crop samples 40 mm in diameter

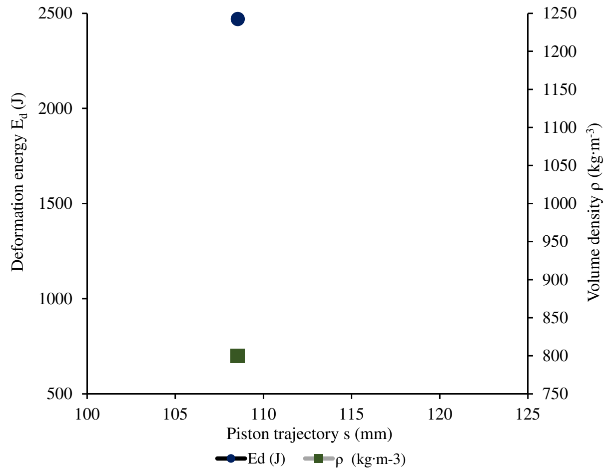

Fig. 7. Relation between briquette volume density ρ and related deformation energy Ed – energy crop samples 65 mm in diameter

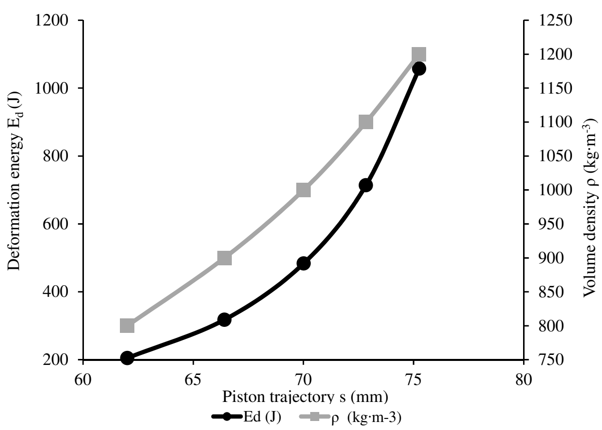

Fig. 8. Relation between briquette volume density ρ and related deformation energy Ed – cardboard samples 40 mm in diameter

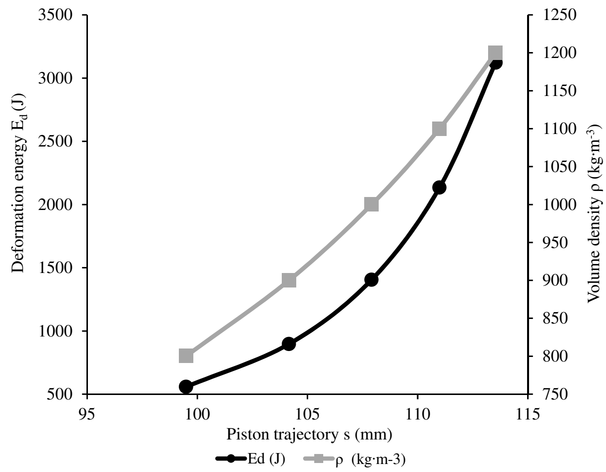

Fig. 9. Relation between briquette volume density ρ and related deformation energy Ed – cardboard samples 65 mm in diameter

DISCUSSION

W a k c h a u r e , M a n i (2009) investigated energy demands of production of briquettes with different diameters produced from milled solid residues derived from olive oil pressing. The highest level of mechanical quality was proved for briquette samples with volume density ρ equal to 747.5 kg·m^{-3} (on average) which was not the highest observed level of volume density ρ. The other investigated briquette samples exhibited a higher level of volume density ρ, thus it was proved that the highest level of briquette volume density ρ was not always in line with the highest briquette mechanical quality. The effort to produce briquette bio-fuel with the highest possible volume density ρ need not always guarantee the best briquettes quality. L e q u e u x et al. (1990) indicated that briquette samples with volume density ρ higher than 1000 kg·m^{-3} did not exhibit a distinctly higher level of quality than briquette samples with volume density ρ lower than 1000 kg·m^{-3}. However, as proved by the present research outcomes, production of briquette samples with higher volume density ρ always indicated higher energy consumption, thus, higher financial costs.

Previous published studies on the energy consumption of briquette production were mainly focused on energy demands of the overall operation of briquetting press or the whole briquette manufacturing process. In contrast, the aim of the present experiment was to determine the energy consumed purely during the production of each individual briquette sample, no other consumed energies were considered.

G e n t i l , V a l e (2015) dealt with the overall evaluation of energy consumption (electric, human, chemical, and thermic energy) of briquette plant operation. Their research indicated that production of 1 t of sawdust briquettes consumed 101.66 kWh·t^{-1} in total. Electrical energy for all production processes (briquetting, drying, sieving, etc.) represented 65.12 kWh·t^{-1} of the total resulting value (101.66 kWh·t^{-1}), nevertheless, pure briquetting process (operation of briquetting press) consumed 49.73 kWh·t^{-1} of the total resulting value. The number of briquettes produced per 1 t was not given, so the energy demand on production of one briquette sample cannot be enumerated, which makes the comparison with our results unfeasible. According to M e w e s (1959), of the overall energy used for specific briquette sample production, approx. 40% were constituted by the energy consumed for feedstock material compressing and remaining 60% represented the energy consumed for overcoming friction. Identical limitation was observed in the study by N i e d z i o l k a , S z p r y n g i e l (2014) focused on the energy consumption of briquette production from agricultural herbaceous biomass (wheat, rye, rape straw, meadow hay); the energy intake of briquetting press was 139.0 kWh·t^{-1}, however a detailed description of produced briquette samples was missing, too. Based on the mentioned observations as well as on the present results it can be stated that the production of briquette bio-fuel from herbaceous biomass is more energy demanding than that from wood biomass.

CONCLUSION

The present data evaluation enabled us to detect the specific moment in the briquette production process when the relation between the briquette volume density ρ and the deformation energy E_d changed and production became unprofitable. This moment differed for each investigated sample but in most cases it was observed after achieving the level of volume density ρ equal to 1000 kg·m^{-3} (for samples W_{40}, C_{40}, and C_{65}); in the case of other briquette samples this moment was observed even at lower levels of volume density ρ (800–900 kg·m^{-3}). Comparison of the maximal achieved volume density ρ levels and the lowest amount of consumed deformation energy E_d revealed the difference between the individual feedstock materials investigated. Best results were achieved by cardboard briquette samples (C_{40}, C_{65}), followed by wood samples (W_{40}, W_{65}), and finally by energy crop briquette samples (E_{40}, E_{65}).

In general, it is important to note that the results in this study proved that the production of briquette samples with volume density ρ higher than 1000 kg·m^{-3} (which is not necessary for commercial purposes) is not advantageous and profitable in terms of energy demands. Moreover, with the briquette samples W_{65}, E_{40}, and E_{65} such level of volume density ρ could not be achieved.

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