TEKA Kom. Mot. Energ. Roln. – OL PAN, 2010, 10, 454–463

ESTIMATION AND ANALYSIS OF CHOSEN FACTORS OF THE INFLUENCE ON QUALITY AND ENERGY CONSUMPTION AT THE PROCESSING OF PLANT MATERIALS FOR ENERGY PURPOSES

Mariusz Szymanek*, Magdalena Kachel-Jakubowska**

* Department of Agricultural Machines Science
** Department of Machine Exploitation and Management in Agricultural Engineering

Summary: In the paper the influence of chosen factors on the process of disintegration and densification was presented. The quality and energy consumption of the final product (briquettes, pellets) was evaluated. A selected theory of this process was showed.

Key words: biomass, disintegration, densification, energy consumption, physical properties

INTRODUCTION

In the industrialized countries energy produced from biomass amounts to about 30%. However, about 50% of people population who mainly come from the developing countries uses about 35% of energy from biomass. The share of biomass energy in the whole world reaches about 14% [Ramage and Scurlock, 1996].

Biomass is defined as all plant materials, including wood, grass and by-products which are produced at their harvesting and processing [Grover and Mishra, 1996]. As to its chemical constitution, biomass consists of three main elements: cellulose, hemicellulose and wood-wool. The operations for biomass adaptation to energy purposes are size reduction and densification [Opielak and Komsta, 2000]. The physical structure of biomass and its durability play a significanct part in the processing of biomass. The purposes of densification of biomass is reducing the volume and increasing its density. Such a shape of biomass makes its transport and logistics economically intensive. During the processing of biomass its heat value is not basically changed. However, loss of water and partial change in structure of inflammable compounds can affect the reduction of heat value [Antal et al., 1990]. Energetic value defined as calorimetric value depends on the percentage content of carbon and hydrogen [Demirbas, 2001].

Biomass can be used in a direct way through its burning and indirectly through the processing for liquid fuel (e.g. alcohol) or gas fuel (e.g. biogas) [Mashchenko et al., 2005]. The nett value of energy obtained from biomass ranged from 8 $MJ \cdot kg^{-1}$ (fresh biomass) to 27 $MJ \cdot kg^{-1}$ (dry biomass) [Demirbas, 1998].

The objective of this work was an estimation and analysis of the influence of selected factors energy consumption during the processing of biomass for energy purposes.

Size reduction of plant materials

Cutting the material into little parts of small dimensions is aimed at its size reduction [Zawiślak, 2006; Dziki, 2008]. Reduction in size can be achieved either by using cutting tools or size reduction by crushing. Size reduction by cutting tools can be classified as the cutting process. The common example of a cutting process is chopping. The aim of chopping is the division of the material into little parts of small dimensions and irregular but small shape. The diagram of the chopping process is illustrated in Fig. 1

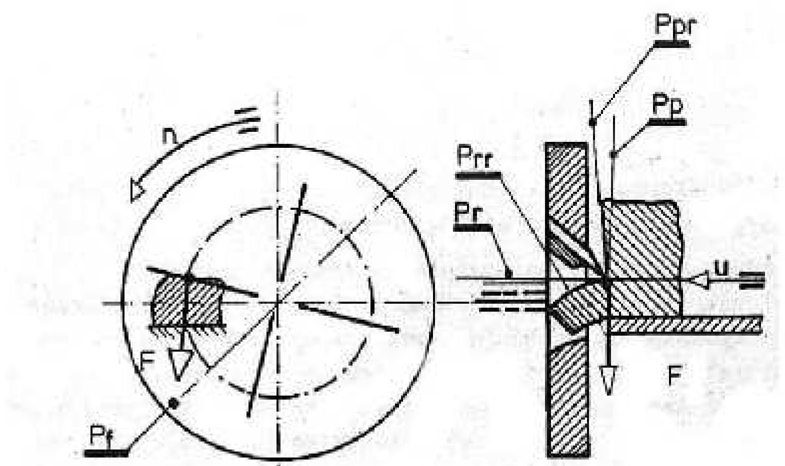


Fig. 1. The chopping process: P_r – base plane (front), P_f – working plane, P_p – back plane, P_{pr} – working back plane, P_{rr} – base working plane, v_k – longitudinal cutting speed, u – speed of movement, n – rotational speed [Czyżyk et al. 1982].

The resistance of materials during its cutting to compression, bending and cutting as well as its density are highly significant. These properties depend on the varieties, their stage of maturity, moisture content and cell texture as well as place and way (direction) of cutting and knife edge geometry. Igathinathane et al. [2006] reported that during the cutting process the materials undergo a large defomation and compression before the very cutting occurs. So the materials of a higher moisture need a higher energy expenditure for the reduction of their size [Hakkila, 1989]. For instance, Person [1987] reported that the energy needed to cut plant materials increases with an increase of age and stage of plant maturity.

During the crushing there is no contact with tools which have a cutting edge. In this case differently shaped blunt working elements act on the processed material.

Walker et al. [1937] and Earle [1983] reported that energy consumption during the grinding can be expressed by the formula:

$$dE \quad K \cdot \frac{dL}{L^n}, \qquad (2)$$

where:
L - size of material particle,
K and n - constants.

The *n* value is described by three grinding theories: Rettinger, Kick and Bond.

The Rettinger's theory found that the working during the grinding process is directly proportional to the rise of a new surface of the product. On the basis of this theory it is possible to count the surface of the product. This theory found that the whole input energy is being transfered to the surface of the ground material. If n = 2 then formula (2) is:

$$\Delta E = K_R\left(\frac{1}{L_p} - \frac{1}{L_f}\right), \qquad (3)$$

where:
K_r – Rettinger's constant,
L_p – initial size of particle,
L_f – final size of particle.

A lot of studies have shown that this theory is overly simplified. In reality, not all the input energy of grinding is being transfered to the material. It depends on the kind of grinding device and the grinding conditions.

The Kick's theory found that the input energy of material grinding is directly proportional to the size of particle at dimension dl/L [Bond, 1961]. It means that n = 1. This energy can be expressed by the formula:

$$\Delta E = K_K \ln\frac{L_f}{L_p}, \qquad (4)$$

where:
K_s – Kick's constant.

Kick's theory is based on the force – strain figures which are created by compressing tests [Bond, 1961].

The Bond's theory defines grinding energy as the mass unit of substance from the dimension of endless length to 100 μm. This energy is expressed by the formula:

$$W = \frac{10W_i}{\sqrt{d}} - \frac{10Wi}{\sqrt{D}}, \qquad (5)$$

where:
W_i – index of working, determinant of the material's resistance to grinding,
d – linear dimension of a particle before grinding,
D – linear dimension of a particle after grinding.

DENSIFICATION OF PLANT MATERIALS

The process of densification of plant materials includes the three basic stages:

- grinding of product,
- elastic deformation of product,
- mechanical joining of the ground particles.

This process depends on the grinding technology and kind of material and can involve such actions as moistening, cooling and screening (Fig. 2).

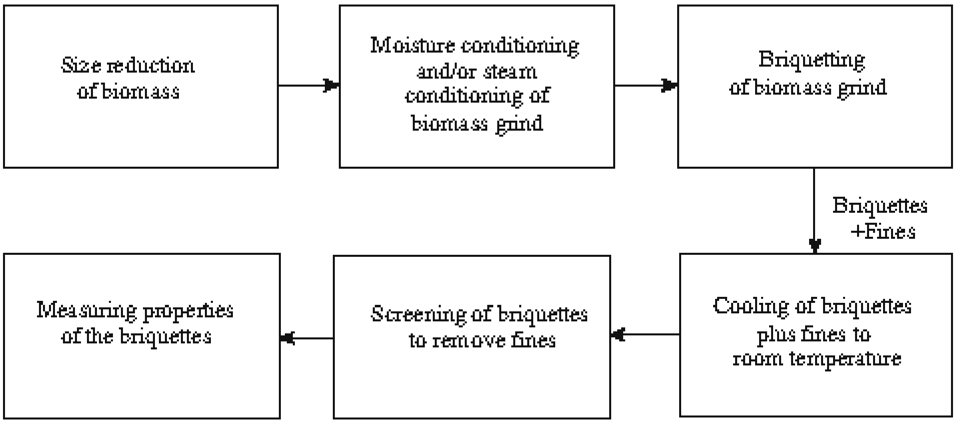
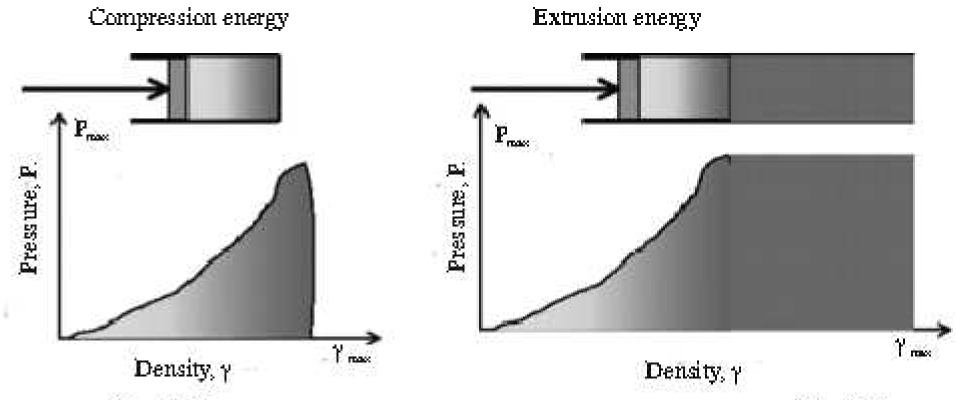


Fig. 2. Technology of briquette production [Nalladurai and Morey, 2007]

Depending on the degree of grinding the final products are [Sudhagar, Tabil, Sokhansanj 2006a]:

a) bales – 150-400 kg·m^{-3},
b) briquettes – 650-750 kg·m^{-3},
c) pellets – 600-1000 kg·m^{-3},
d) cubes – 500-800 kg·m^{-3}.

The total unitary energy of densification is the sum of energy needs to densification of loose material and energy needs to extrusion of compacted materials (Fig. 3).



$$E_c \int_{\gamma_0}^{\gamma_{max}} P \cdot \left(\frac{1}{\gamma}\right)$$

$$E_E \int_{\gamma_0}^{\gamma_{max}} P \left(\frac{1}{\gamma}\right) + \frac{P_{max}}{\gamma_{max}}$$

Fig. 3. Unitary energy of densification and extrusion of biomass [Sudhagar, Tabil, Sokhansanj 2006]

FACTORS INFLUENCING THE PROCESS AND ENERGY AT BIOMASS DENSIFICATION

The factors influencing the process and energy at biomass densification are [Łysiak and Laskowski, 1999; Obidziński, 2005; Laskowski and Skonecki, 2005; Sudhagar, Tabil, Sokhansanj 2006b]:

a) physical properties of materials (moisture, bulk density),
b) value of compression force,
c) temperature and time of densification process,
d) densifications methods.

The moisture of plant biomass product ranged from 5% to 80% and it depended on the variety, stage of maturity, part of plant and weather condition. At harvest the straw of plant such as wheat or barley has a lower moisture than e.g. maize. In plant materials there are significant differences among the parts of a plant. It is especially evident in maize straw. Figure 4 presents percentage share of straw maize fraction (without grain) [Pordesimo et al., 2004; Niedziółka I., Szymanek M., Zuchniarz A. 2007].

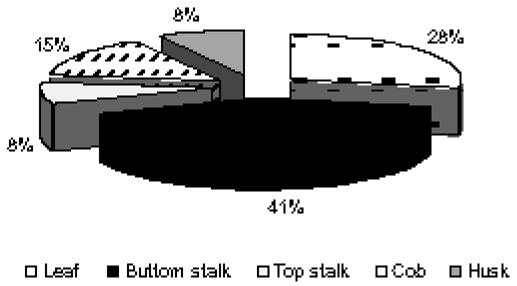


Fig. 4. Fractions of maize straw and cobs

The moisture of biomass and value of compression force in the densification process affect the final product. These parameters decide on the density and mechanical strength [Sitkei 1986; Sudhagar, Tabil, Sokhansanj 2004b].

The changes of energy consumption at densification in dependence of pressure and moisture are given in Figure 5.

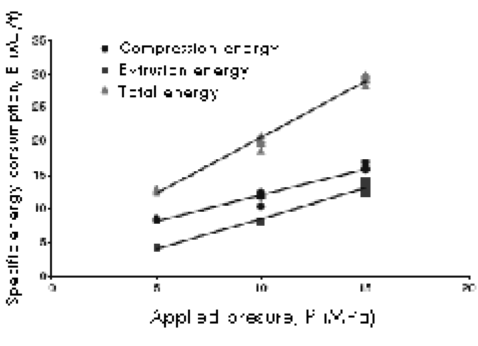


Fig. 5. Specific energy consumption at densification of maize straw [Sudhagar, Tabil, Sokhansanj 2006a].

At the lowest pressure (5 MPa) the extrusion energy was smaller then densification energy for all the moisture levels. However, at the highest pressure (10 and 15 MPa) the extrusion energy was nearly equal to densification energy. The authors Sudhagar, Tabil, Sokhansanj [2006a] expressed the influence of pressure and moisture on energy consumption during densification of briquettes by the formula:

$$E = 1.55 + 1.80P + 0.13M; \ R^2 = 0.96, \qquad (6)$$

where:
E – specific energy consumption ($MJ \cdot t^{-1}$),
P – pressure (MPa),
M – moisture (% wb).

Authors Sudhagar, Tabil, Sokhansanj [2006] proved that the maximum density of about 950 $kg \cdot m^{-3}$ was achieved at moisture ranging from 5% to 10%. Densification at the moisture of 15% and the pressure of 15 MPa negatively influenced the density of briquettes. At higher moisture the surface of briquettes was cracked and showed an axial distention. Similar effects were observed by Smith et al. [1977] during the densification of wheat straw. Gustafson and Kjelgaard [1963] reported that during the densification of hay in moisture range from 28% to 44%, the density of briquettes was decreasing with an increase of moisture. Andrejko and Grochowicz [2006] showed a decrease of energy by about 54% during the densification of crumbled grain lupine in range from 9.5% to 15%. A similar effect was observed by Al-Widyan et al. [2002] during the densification of oil cake. Wamukonya and Jenkins [1995] reported that a relatively high quality of briquettes from agricultural and wood residues was obtained at the moisture range of 12-20%. However, Sudhagar, Tabil, Sokhansanj [2006] claimed that the highest quality of briquettes were obtained at the moisture range of 8-10%. At this moisture the briquettes are durable and do not crack.

Table 1 shows regression equation for energy consumption at grinding of different plants straw in dependence of sieve diameter and moisture [Sudhagar, Tabil, Sokhansanj 2004a].

Table 1. Regression equation for energy consumption (E) in $kWh \cdot t^{-1}$ in dependence of sieve diameter (S) and moisture.

Straw	**Moisture, %**	
	8%	12%
Barley	$E = -16.45S + 76.52$ ($r^2 = 0.99$)	$E = -9.16S^2 + 24.22S + 43.12$ ($r^2 = 0.99$)
Wheat	$E = -16.30S + 65.08$ ($r^2 = 0.97$)	$E = -4.07S^2 + 7.48S + 41.95$ ($r^2 = 0.98$)
Maize	$E = -16.78S + 64.38$ ($r^2 = 0.96$)	$E = 45.31S^2 - 30.86S + 55,45$ ($r^2 = 0.96$)

The authors showed the changes of energy grinding using linear function at the moisture of 8% and square function at the moisture of 12%.

The pellets or briquettes production demands application of crumbled materials. However, grinding into little particles is very expensive and, as a rule, it is needed only at production of pellets. According to Samsona et al. [2005] production of briquettes demands the length of chaff in range of 6-8 mm. Kaliyan and Morey [2006] reported that the decrease of geometrical dimension of straw maize particle from 0.80 to 0.66 mm results in the increase of density of briquettes by about 5-10% and their durability by about 50-58% at densification pressure of 100 MPa and by about 62-75% at pressure of 150 MPa, and moisture of 10%. These changes influence the increases of energy consumption from 0.8 to 1.3 MJ/t for maize straw and from 2.5 to 4.3 $MJ \cdot t^{-1}$ for switchgrass.

The friction between materials and matrix during densification process involves resistance which causes the densification [Sudhagar, Tabil, Sokhansanj 2004a]. Abd-Elrahim et al. [1981] reported that about 40% of input energy at the densification of maize straw and hay is used for the densification process and 60% for overcoming the friction resistance. A similar conclusion was put forward by O'Dogherty and Wheeler [1984] at the densification of cotton and barley straw. Hann and Harrison [1976] reported that the friction energy is increasing with an increase of densification pressure. This energy can be reduced by the initial heating of matrix, so then the time of extrusion is shorter [Reed, 1980]. Sitkei [1986] reported that the heating of matrix during the process of densification might influence the crumbling of briquette surface. Sudhagar, Tabil, Sokhansanj [2006a] claimed that the moistening, conditioning, addition of chemicals and physical action before the densification process significantly influences the reduction of consumption energy. According to Austina et al. [1964] the value of friction energy is closely related with the kind of the used densification materials.

Fig. 6. shows the changes of briquette strength in dependence on the densification pressure and biomass moisture.

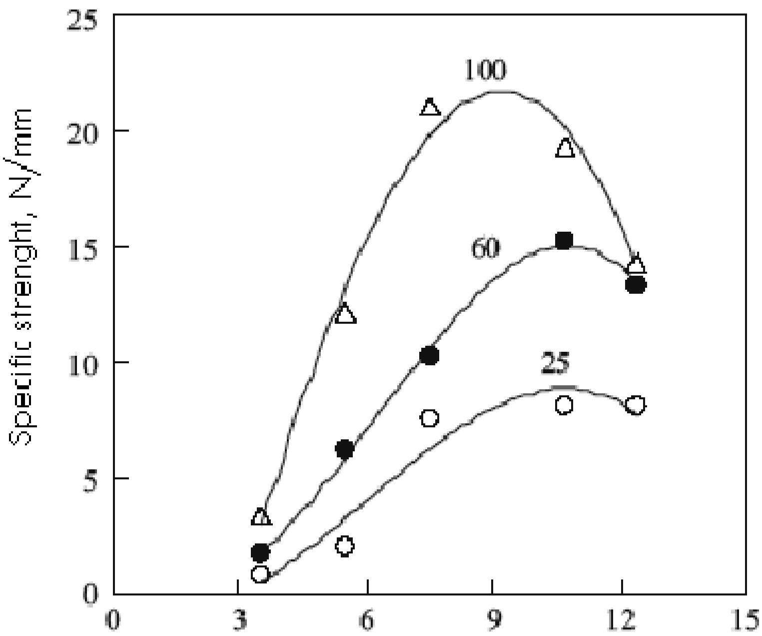


Fig. 6. Dependence of specific strength of briquettes on moisture content and compaction pressure

Data in Fg. 5 confirm that since the maximum strength of artificial structures with a change in compaction pressure is reached with a moisture content, then the strength of briquettes with an increase in compaction pressure may only be produced with a reduction in moisture content: with an increase in the value of pressure there is a reduction in briquette porosity, and the value of maximum molecular moisture capacity also decreases.

CONCLUSIONS

The carried out evaluation and analysis of the grinding and densification processes of plant biomass on the basis of literature review have shown that the quality of the final product (briquette or pellet) as well as energy consumption at its production depends on numerous factors such as: composition of granulates, physical and chemical properties of plant materials and technology, methods and conditions of production as well as the construction and working parameters of the used devices. During the organization of the process of grinding and densification it should be taken into consideration that the quality of the processed product is influenced not only by individual parameters but also by their combination (interaction).

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OCENA I ANALIZA WYBRANYCH CZYNNIKÓW WPŁYWAJĄCYCH NA JAKOŚĆ ORAZ ENERGOCHŁONNOŚĆ PRZETWARZANIA MATERIAŁÓW ROŚLINNYCH NA CELE ENERGETYCZNE

Streszczenie. W pracy przedyskutowano wpływ wybranych czynników wpływających na proces rozdrabniania i zagęszczania biomasy roślinnej w aspekcie jakości pozyskiwanego produktu finalnego (brykietu, peletu) oraz ponoszonych nakładów energetycznych. Przedstawiono także wybrane teoretyczne podstawy dotyczące rozdrabniania i zagęszczania.

Słowa kluczowe: biomasa, rozdrabnianie, zagęszczania, energochłonność, właściwości fizyczne