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FACULTY OF TROPICAL AGRISCIENCES

Department of Sustainable Technologies

Diploma Thesis

Analysis of briquettes' production process from different biomass materials

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DIPLOMA THESIS ASSIGNMENT

Bc. Radek Novotný

Sustainable Rural Development in the Tropics and Subtropics

Thesis title

Analysis of briquettes' production process from different biomass materials

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Objectives of thesis

The main objective of this Thesis is to analyse influence of initial raw material properties on energy consumption within briquettes' production process. In order to obtain the main aim the following specific objectives are set:

- Collection of biomass with different structure and its processing into form of briquettes.
- Grinding and briquetting process throughput analysis.
- Assessment of grinding process and analysis of energy consumption during the grinding.
- Assessment of briquetting process and analysis of energy consumption during the briquetting.
- Evaluation of briquettes' quality.

Methodology

Materials:

Biomass from energy crops and bio-waste will be used for briquettes production.

- Energy crops collected from experimental fields of CULS: two varieties of miscanthus (Miscanthus sinensis and Miscanthus x giganteus) and technical hemp (Canabis sativa L)

- Bio-waste to be used: apple wood residues from trees trimming

Methodology in sequence of steps:

1) Study of relevant references – scientific articles on biomass densification, solid biofuel production, energy consumption, briquetting technologies, crusher and piston press throughput, briquettes properties, etc.

2) Preparation of selected biomass (determination of moisture content and biomass crushing into several fractions).

3) Measurement of energy consumption and calculation of throughput during crushing process.

4) Production of briquettes by piston press Brikstar 30-12 – measurements of energy consumption and throughput.

5) Determination of briquettes' mechanical properties (mechanical durability, density).

6) Data processing and analysis.

The proposed extent of the thesis

50-60 pp.

Keywords

piston press, briquettes, input material, energy consumption, throughput

Recommended information sources

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Prague on 13. 04. 2017

Declaration

I hereby declare that the present Bachelor Thesis "Analysis of briquettes' production process from different biomass materials" is my own work and effort. Where all the information sources and literature derived from the published and unpublished references of other authors has been acknowledged in the text and a list of references given.

Prague April 27th 2017 ....

Radek Novotný

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Abstract

Biomass is a significant source of energy and it is abundant with high potential. Fossil fuels participate on energy production in largest percentage. Fossil fuels are non-renewable energy source and therefore it is necessary to use renewable energy sources as biomass solid fuels.

The Diploma thesis deals with the study of grinding and briquetting processes. For the experiment were used various types of materials such as Hemp, *Miscanthus sinensis*, *Miscanthus x gigantheus* and Apple wood. These materials were dried, grinded and pressed by piston press with diameter of 65 mm. Materials were grinded into three fractions (4 mm, 8 mm and 12 mm). Material throughput ($kg.h^{-1}$) and energy consumption ($kWh.t^{-1}$) were determined in the present research.

The research showed that the highest throughput was detected for apple wood material, in both cases grinding as well as briquetting; however, energy consumption during production of briquettes from apple wood is relatively high. The worst results concerning throughput and energy consumption (especially within briquetting) were found for hemp material. Both *Mis. sinensis* and *Mis. X gigantheus* species have very similar requirements. Herbaceous biomass like *Mis. sinensis* and *Mis. x gigantheus* had quite good total relation between throughput and energy consumption for selected types of used machines. The most quality briquettes due to mechanical durability are briquettes made of hemp, probably thanks to fibre biomass character.

Keywords: piston press, briquettes, input material, energy consumption, throughput

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List of Abbreviations

°C	Degree Celsius
kWh	Kilowatt hour
$kWh.t^{-1}$	Kilowatt hour per tonne
kg	Kilogram
kg.m−3	Kilogram per cubic metre
$kg.h^{-1}$	Kilograms per hour
$MJ.kg^{-1}$	Megajoule per kilogram
mm	Millimetre
min	Minutes
MPa	Megapascal

1 Introduction

In the present world there is a problem with fossil fuels. It is a global problem and this problem depends on various factors such as world population growth, decrease of fossil fuels reserves and other. Fossil fuels could not be restored in short period. Renewable energy can be one of the solutions.

Renewable energy has different forms (solar energy, water energy, wind energy, energy from biomass and several others). In recent years, the interest at the global level in the use of biomass increase (Wang, et al., 2017). Biomass energy is generally obtained by direct combustion. Biomass can be used in various forms such as chips, briquettes, pellets or raw form. Biomass can be divided into waste biomass, agriculture waste and deliberately cultivated biomass. Biomass cycle can help to reduce CO_2 concentration (Havrland, el al., 2013). Biomass is the only renewable source that can be directly converted into solid, liquid and gas forms (Kambo and Dutta, 2014).

Briquettes are produced by pressing equipment (piston press, screw press etc.). Briquetting increases energy density and significantly reduces volume of raw material (Muntean, et al., 2012). The briquetting process is pressing loose raw material into briquettes with a particular shape. Briquettes are reducing transportation and storage costs (Wang, et al., 2017).

For briquetting is most important to use material with specific moisture content. Moisture content is reduced by drying. Drying processes and their operation are expensive. Modern methods are improving the drying technologies and efficiency of the dryers (Havrland, et al., 2010; Ivanova, 2012).

This Diploma Thesis is focused on studies of briquetting process and crushing process analysis. Energy consumption and material throughput are the main parameters which are measured and calculated on examples of different biomass materials during both briquettes’ production processes.

2 Literature review

2.1 Biomass

Biomass is organic matter from plants, bacteria, algae, fungi and also animals. Biomass can be used as source of energy. Biomass is the third largest energy source in the world, after coal and oil. Half of the world is using biomass energy as primary energy source (Chen, et al., 2009). Biomass for energy purposes can be agricultural or industry waste, biodegradable waste from houses and purposely grown biomass. Energy from biomass is environmental friendly. **Figure 1** show the dendromass cycle. This cycle is explaining why the CO2 is neutral. The importance of biochemical process in the formation of biomass is that during the growth of biomass, CO2 is consumed and replaced by O2. The biomass energy has a form of thermal energy. It can be used for heating or production of electric energy.

One of the alternative ways of replacing fossil fuels is the use of biomass. Biomass is all organic matter in the natural form, which is produced by photosynthesis and transformation of solar energy in plants such as trees, herbs, grasses, algae and seaweed (Andert, et al., 2006) .

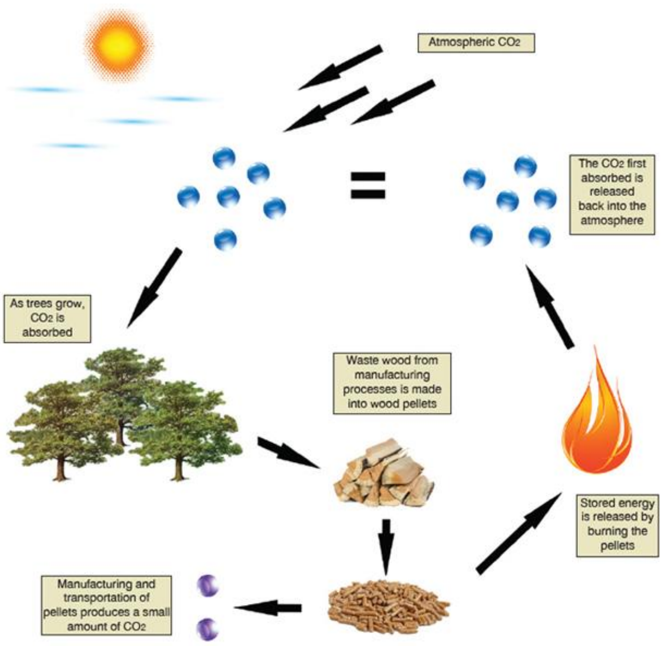

Figure 1 The cycle of dendromass

Source: Perďochová, (2010)

2.1.1 Distribution of biomass

According to Bechník (2009), biomass could be classified into several categories

- **Phytomass** –mass from plants
- **Dendromass** – wood biomass
- **Purposely grown biomass** – fast growing trees or grass
- **Waste biomass**
    - From plant production – straw, residues from cleaning grains, etc.
    - From livestock production – manure, etc.
    - From extraction and processing of wood – sawdust, shaving, wood chips, etc.
- **Biodegradable waste**
    - Municipal waste – food scraps, paper packaging
    - Industrial waste - waste from the paper manufacture, sugar, flour, etc.
    - Sewage from the sewer (Bechník, 2009)

2.1.2 Biomass processing

According to Motlík (2002), the biomass processing could be classified into several categories:

- **Mechanical processes**
    - Cutting
    - Crushing
    - Chipping
    - Compression for briquettes or pellets
    - Oil production
- **Thermal processes**
    - Combustion
    - Gasification
- **Chemical processes**
    - Esterification – reaction of alcohol with an acid in order to obtain ester and water
- **Microbiological processes**
    - Alcoholic fermentation – bioethanol production
    - Anaerobic digestion – biogas production
    - Composting – from composting is possible to use thermal energy

2.2 Solid biofuels

It is possible to categorize solid biofuels into several forms: raw fuel (wooden logs), chips (wooden chips, crushed dry material) and pressed fuels (briquettes and pellets). Energy from solid biofuels is obtained by combustion. Main product from combustion is heat energy which is possible to transform into electric energy. Solid biofuels are produced by following processes:

- **grinding, chipping, cutting** (wooden chips, logs)
- **pressing** (briquettes and pellets)
- **pyrolysis** (charcoal, liquid fuel and gas)
- **torrefaction** (torrefied fuels) (Guan, et al., 2015; Stupavský, 2010)

2.2.1 Pellets

Pellets are mostly manufactured with diameter about 6 mm and length between 5 to 40 mm (Stupavský, 2010). Pellets are made from wood, industry or agricultural waste and purposely grown biomass.

Pellets are produced by pressing raw dry material without binders. The process of pellets production is called pelletizing. Pellets have high energy density, heat value and excellent transporting and handling properties (Guan, et al., 2015).

Calorific value: 16 – 18 $MJ.kg^{-1}$

Density: up to 850 $kg.m^{3}$

Moisture content: maximal 10% (Stupavský, 2010)

2.2.2 Briquettes

Briquettes can be made from various materials (wood, industry or agricultural waste and purposely grown biomass). Briquettes are produced in press machine by pressing raw dry materials. Briquettes are high pressure solid fuels with quality ranking between brown and black coal. Briquettes have excellent properties in term of handling and transporting. From briquettes can be obtained heat energy the same as from brown or black coal (Stupavský and Holý, 2010).

Briquettes advantages and disadvantages (Hrázný, et al., 1999):

- Briquettes have slower and more uniform combustion.
- The functional parts in briquetting press have lower wear and tear.
- Briquetting is cheaper than pelletizing and less demanding on the input material.
- Lower investment demands and energy input.
- Calorific value of briquettes is almost similar to brown coal.
- Ash content is insignificant, nontoxic and without heavy metals.

Disadvantages (Hrázný, et al., 1999):

- The main disadvantage is price. Briquetting process is expensive. Costs of purchasing briquetting lines and energy inputs are high.
- Briquetting process needs a new material whole year.
- The quality of source material.

2.3 Briquettes characteristics

2.3.1 Particle size

According to Grover, et al. (1996) the optimum particle size is 6-8 mm with 10-20% powdery component (powdery component means the size less than 4 mm). Larges particles (more than 12 mm) are not suitable for briquettes production, because final briquettes will not be compacted. Particle size is important for densification. Optimum for input material is a random distribution of particle size. Material mixture has to contain small particle and also larger particles. The presence of different particles can improve packing and handling dynamics and it also contributes to better mechanical properties (Oladeji, et al., 2012).

2.3.2 Moisture content

Moisture content is necessary for briquettes production and final product properties. Briquettes with high moisture content have worse combustion properties. Combustion of these briquettes with high level moisture content leads to releasing of large amount of water vapour. Water vapour can cool and damage the heater (Jevič, et al., 2008).

Moisture content is also necessary for briquettes production. According to Briklis company the moisture content of input material have to be in a range between 10 - 15% for piston presses. The moisture content is varying for different types of briquetting presses. Screw press has to have moisture content about 8-9% (Ander, et al., 2006). High level of moisture content leads to problems with briquette compaction and handling properties.

2.3.3 Particle density

Particle density and mechanical strength are main properties of standardized biofuels. These parameters depend on used material, structure, water content and compacting pressure (Aivars, et al., 2010). The standard for the briquettes density determination is EN 15150:2011. Particle density means the ratio of the sample mass and its volume including pore volume (Temmermana, et al., 2006). Briquettes density is important for handling and water resistance. Density depends on pressure. When the pressure is increasing, briquettes density increases as well.

2.3.4 Mechanical properties

Mechanical properties are necessary for storage and handling processes. This parameter is important for pellets, which are used in automatic heaters, but also for briquettes (Kotláková, 2009). Mechanical durability is measured by rotary drum with cylindrical shape and with a volume of 160 l (Ivanova, et al., 2014). Mechanical strength depends on moisture content, particle size, input material and compaction pressure (Plíštil, et al., 2005).

2.3.5 Calorific value

Calorific value is an indicator of combustion properties. Calorific value is defined as the amount of heat released in combustion (burned quantity unit of fuel). Calorific value is necessary for fuel utilization in combustion process. Calorific value is determined by calorimeter (Kers, et al., 2010).

2.3.6 Ash content

Ash content enables to determine residues after combustion. According to the ash character, it is possible to show formation of sediments in combustion chamber. It is possible to determine content of elements in ash after the dissolution of ash. Ash can contain metals and other elements (As, B, CL, Cr, Cu, Fe, P, Zn) and also can contain heavy metals (Cd, Pb, Ti) (Kotlánová, 2009).

2.4 Briquetting technologies

The briquetting technologies can convert agricultural residues into high density solid biofuels. Briquetting process is working without added binders. Briquetting and pelletizing are widely spread technologies of material densification. Presses are used for briquettes production. These presses are possible to divide into two groups: Hydraulic presses and screw presses. Hydraulic presses are represented by piston press. In piston press the biomass is pressed by piston. In a screw press the biomass is extruded continuously by screw. Both technologies are trying to achieve uniform and efficient combustion properties.

2.4.1 Screw press

In a screw press the biomass is extruded continuously through screw. Screw press die is externally heated for friction reduction. The outer surface of briquettes obtained through this technology is carbonised and has a hole in the centre (Tripathi, et al., 1998). Optimum moisture content is 8-9%. Approximate energy consumption is 60 $kWh.t^{-1}$. Screw press can carbonize part of briquette which increases combustion performance.

Screw press advantages and disadvantages (Grover, et al., 1996):

- The output is continuous
- The part of surface is carbonized
- Concentric hole helps in combustion
- The machine is lighter compared with piston press

Disadvantages:

- The energy requirements are high compared to piston press
- Mechanical parts are quickly worn out

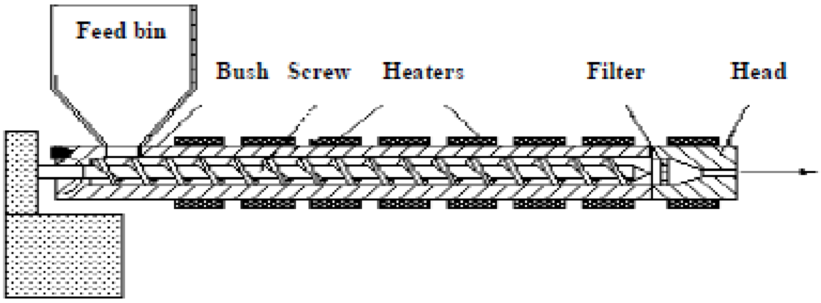

Figure 2 Diagram of screw press

Source: Havrland, et al. (2011)

Screw press on **Fig.2** consists of heaters - heater control temperature, working body - screw, loading hopper. Pressure is created by turning pressing screw in conical chamber (Havrland, et al., 2011).

2.4.2 Piston presses

Piston press can be hydraulic or mechanical. They can be used for pressing raw material as agriculture waste, sawdust etc. or industry waste as paper. The piston presses works with lower pressure than screw presses. **Table 1** show differences between piston and screw press (Grover, et al., 1996).

Mechanical piston press operates with the highest pressure in briquetting chamber. Mechanical piston press works on principle of crank mechanism. The shape of briquettes is usually cylindrical. Briquettes have an inner hole (Andert, et al., 2006; Havrland, et al., 2011). The performance of this type of presses is about one tone per hour. Briquettes have cylindrical or hexagonal shape (Andert, et al., 2006).

Hydraulic piston press works with lower pressure than mechanical piston press. Briquettes are produced in open briquetting chamber. The biomass is pressed into the infinity briquette (Matúš et al., 2009). The performance of these presses is between 0.05

and 0.5 ton per hour. Hydraulic presses are suitable for pressing herbs, sawdust or mixtures. Briquettes from this type of presses have lower cohesion (Andert, et al., 2006).

Table1 Comparison between screw and piston presses

	Piston press	Screw extruder
Optimum moisture content of raw material	10-15%	8-9%
Output from the machine	in strokes	continuous
Density of briquette	1 000 – 1 200 kg/m^3	1 000 – 1 400 kg/m^3
Combustion performance of briquettes	not so good	very good
Homogeneity of briquettes	non-homogeneous	homogeneous

Source: Andert, et al., (2006)

2.5 Briquettes production process

Briquetting process has three parts: drying, crushing and briquetting. Drying and crushing are necessary for briquettes production. Without these processes is impossible to create a briquette. One of the problems is costs. Drying and crushing are the most expensive (Grover, et al., 1996). Briquetting process is developed in **Fig. 3**.

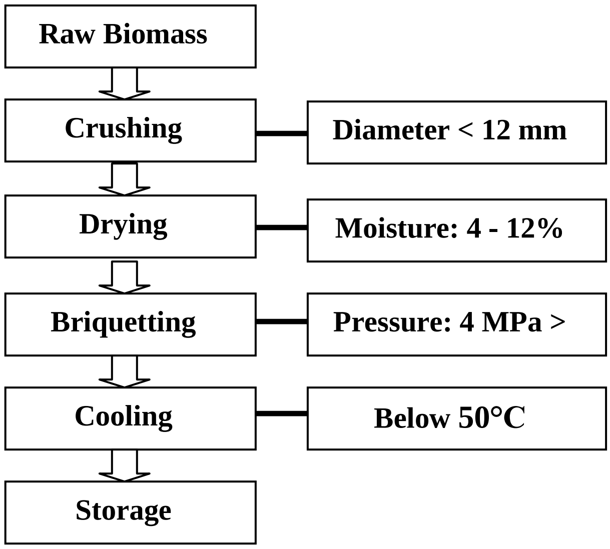

Figure 3 Briquetting process

Source: Novotný (2015)

2.5.1 Drying process

Drying is a process of evaporation of liquids from wet materials with supply of heat. Drying can be understood as material dehydration. The drying of biomass could be performed in various types of dryers. Different types of dryers have their own merits and demerits (Verma, et al., 2017). During the drying, heat is transported by convection from surroundings to the boundary of the drying object and then diffused into the material conduction (Celma, et al., 2007).

The moisture content has effect on briquettes production and on the calorific value reached at the burning process. Optimal moisture content is between 8-15% (Briklis, 2011). The briquette with moisture content higher than 20% will not be compressed and the briquette will crumble (Plíštil, et al., 2005).

The types of dryer employed for biomass materials are packed moving bed dryer, rotary dryer, pneumatic or flash dryer, disk dryer, conveyor belt dryer, fluidized bed dryer and helio-collectors dryers (Verma, et al., 2017; Ivanova, et al., 2012).

2.5.2 Material grinding

Particle size of biomass materials is important for energy conversion. Size reduction is also crucial to the densification process. For material grinding, the hammer mill is widely used. Hammer mills are relatively cheap, easy to operate and produce wide range of particle sizes (Lopo, 2002). Hammer mill can affect particle geometric. Geometric means diameter and particle size distribution of the ground product. Hammer mill is using sieves with different sizes. The size of sieves decides of the particle size.

Energy consumption of hammer mill depends on moisture content, target particle size, material properties, feed rate of the material and machine variables (Mani et al., 2004). Grinding is an energy expensive process. In briquettes production, grinding and drying are the most expensive processes. Hammer mill energy consumption depends on electric motor power intake. Mani et al. (2004), reported the relation of energy consumption and moisture content. The higher the moisture content is the higher is energy consumption.

2.6 Briquetting operating parameters

In order to produce good quality briquettes, briquetting press parameters are very important. These parameters are influencing the quality of final briquette (Grover, et al., 1996).

2.6.1 Operating temperature

The temperature has importance in compaction pressure and material slippage. Demirbas (1999) shows in his work the relevance between briquetting temperature and briquettes density. He said that the briquettes density is increasing with increasing temperature. When the temperature is higher it is possible to use lower pressure for briquetting. Chen et al., (2009), provided a research about temperature influences. Research showed that the briquettes made with temperature more than 90 °C have higher density then briquettes with room temperature (Chen, et al., 2009).

Pressing temperature is significant for lignin excretion from cellular structure (Križan, et al., 2009).When the temperature rise to 80 °C lignin is secreted from the structure of the cellulose skeleton and intercellular space (Muntean, et al., 2012). Tripathi, et al., (1998) indicated that lignin present in the biomass is fluidized and acts as binder when the temperature increases. The heat between 85-105 °C would result in much stronger briquettes. Brikstar 30-12 has operation temperature 60°C (Briklis, 2011).

2.6.2 Compacting pressure

Compacting pressure has influence on the strength of final briquettes. The quality of briquettes is increasing with increasing pressure in briquetting chamber (Križan, et al., 2009). Compacting pressure depends on type of briquetting press. Compacting pressure can be higher, which is related to higher energy consumption.

Compacting pressure can be lower, but the pressing temperature has to be higher. That means, when the temperature is higher, final briquettes will have similar quality as high compressed briquettes (Kers, et al., 2010).

2.6.3 Holding time

Holding time is connected with compacting pressure. Li (2000) made a research about effect of pressure and holding time. In his study was used hydraulic press with maximal pressure 138 MPa and different holding times ranging between 0 to 60 sec. Experiment showed that holding pressure was more effected at lower pressure than at higher pressure. It follows from this study that compacting pressure is more necessary than holding time. Holding time at high pressure is negligible. (Li, 2000)

2.6.4 Energy consumption

Energy consumption is an economic factor. Mechanical, hydraulic and screw presses have different energy consumption. Energy consumption is defined as the energy used to unit mass of briquette per time. **Fig. 4** shows the specific energy consumption in briquetting process. There are differences between process A and B, where A is without briquetting process. That means the process A is energetically suitable, but briquettes production is necessary for easy transportation (Sakkampang and Wongwuttanasatian, 2014).

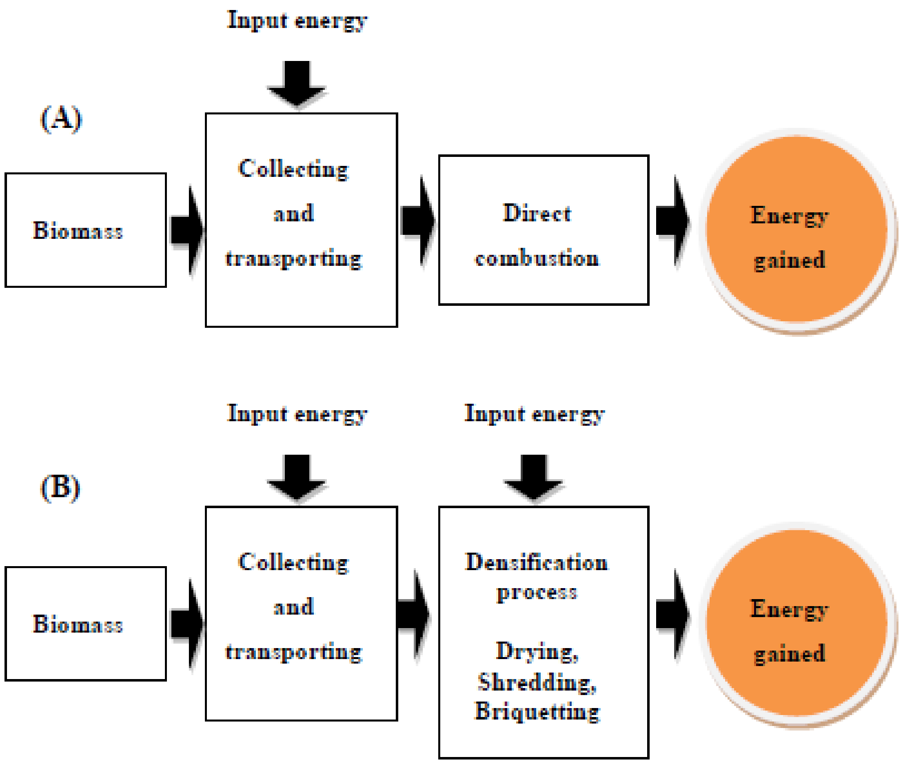

Figure 4 Conversion of biomass to energy diagram.

Source: Sakkampang, et al., (2014)

2.6.5 Material throughput

Material throughput is dependent on particle size of the material, density and type of input material. Material throughput is characterized as weight of input material per one hour. Particle size and shape have important effect on flow characteristics. The granular (preferably 6–8 mm in size) homogeneous materials which can flow easily in conveyors, bunkers and storage silos, are suitable for briquetting (Chen, et al., 2009).

2.7 Structural parameters of briquetting press

Briquetting presses have different structural parameters. The successful pressing of high quality briquettes have to fulfil all briquetting parameters. Better quality of briquettes is possible to increase by changing of some structural parameters. Major structural parameters are (Križan, et al., 2010):

- diameter of pressing chamber
- length of pressing chamber
- conicalness of pressing chamber
- friction coefficient between chamber and pressing tool
- length of cooling canal

Briquetting chamber geometry is an important factor for briquettes compaction. For successful pressing of high-quality briquettes, all the parameters have to be in synergy. The diameter of pressing chamber has a significant effect on the properties of stamping and wear of working parts (Križan, et al., 2010).

2.7.1 Pressing chamber

Geometry of pressing chamber is very important during compacting. Briquetting chamber is shown in **Fig. 5.** Maximal compacting pressure $p_{k,}$ which is rising by pressing process, depends on pressing chamber length and shape, and also on friction relations between compacted material and wall of the chamber (Križan, et al., 2010).

The main structural parameters of pressing chamber are: the diameter of the pressing chamber, the length of the pressing chamber, the conical shape of the pressing chamber, the length of the cooling channel and the effect of counter pressure in pressing chamber (Křižan, et al., 2012).

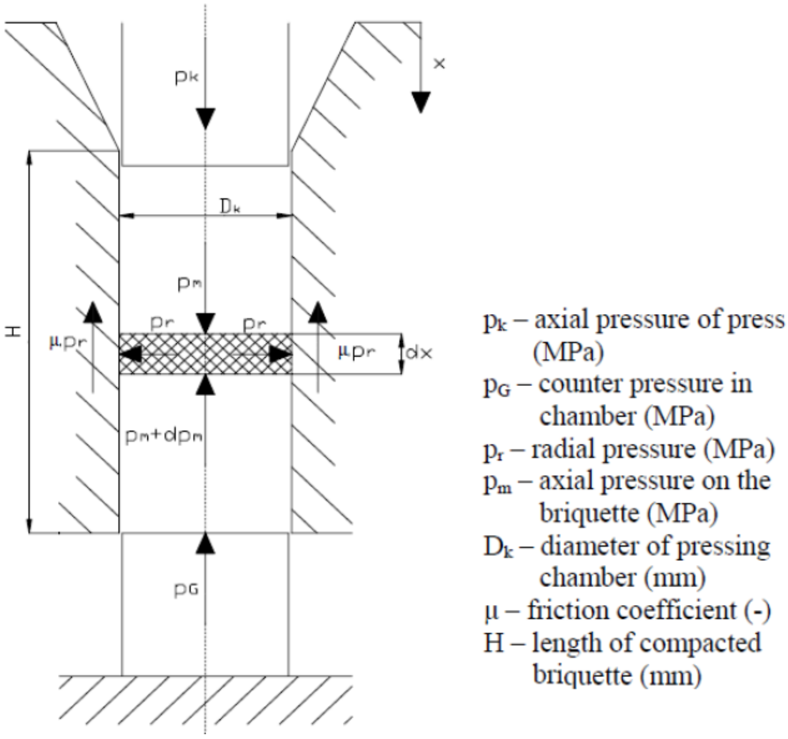

Figure 5 Pressing condition in closed pressing chamber

Source: Križan, et al., (2010)

2.7.2 Conicalness of the pressing chamber

Conicalness of the pressing chamber improves the quality of the final briquettes. Křižan et al. (2012) said that the conicalness of the pressing chamber has a significant effect on the final briquette quality and on the construction of briquetting machines. The conicalness of the pressing chamber is shown on **fig. 6.**

Pressure in pressing chamber is distributed by conicalness of briquetting chamber. **Fig. 6** shows the material flow in pressing chamber with conical part. The first part has cylindrical shape. The conical part has positive pressure properties in briquetting chamber (Křižan, et al., 2012).

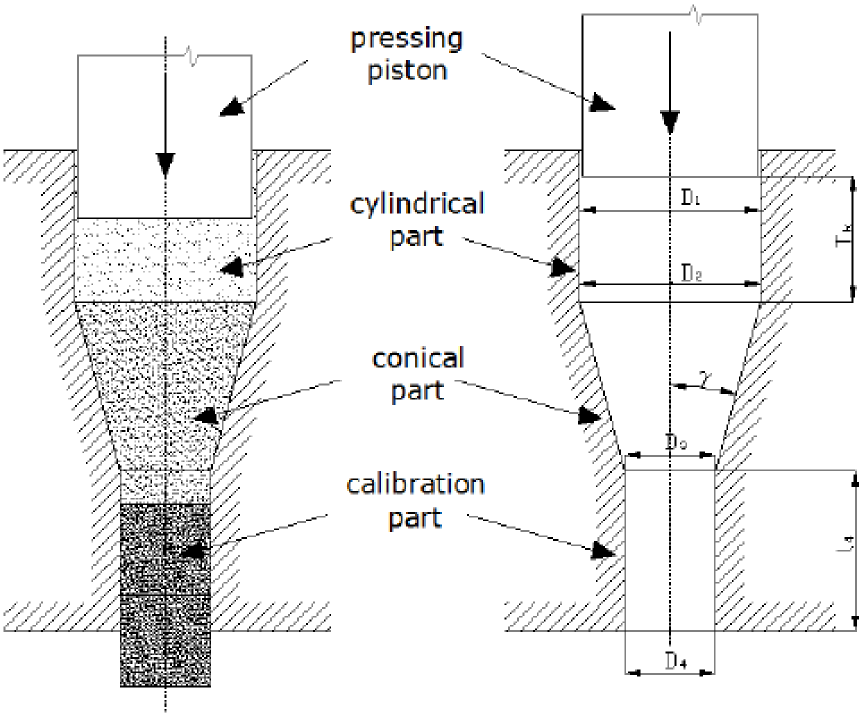

Figure 6 Briquetting chamber diagram

Source: Křižan, et al., (2012).

3 Objectives and hypothesis

3.1 Objectives

The main objective of this Thesis was to analyse influence of initial raw material properties on energy consumption within briquettes' production process. In order to obtain the main aim the following specific objectives were set:

- Collection of biomass with different structure and its processing into form of briquettes.
- Grinding and briquetting process throughput analysis.
- Assessment of grinding process and analysis of energy consumption during the grinding.
- Assessment of briquetting process and analysis of energy consumption during the briquetting.
- Evaluation of briquettes' mechanical quality.

3.2 Hypothesis

1) Hammer mill and piston press throughput and energy consumption differs depending of initial material.
2) The particle size has influence on briquetting press throughput and energy consumption.
3) The grinding process is more energy intensive than briquetting process.

4 Material and Methods

4.1 Methodology of literature review

The main background for elaboration of literature review was articles from scientific databases ScienceDirect and Scopus regarding to briquetting. Articles were searched by the key words: briquetting presses, briquettes, power consumption, input material and biomass. Scientific articles from Czech and international sources were used in the Thesis. Bibliography is listed at the end of the Thesis in the References. Literature review contains information about biomass, briquettes and briquetting parameters.

4.2 Material

Experimental materials were provided by Faculty of Tropical AgriSciencesand Research institute of Agricultural Engineering.

Totally five different biomass materials were used for briquettes production. The energy crops were used - Miscanthus (*Mischanthus x giganteus*), (*Mischanthus sinensis*) and industrial hemp (*Cannabis sativa* L.) and woody materials - sawdust and apple wood residues. Sawdust was represented by a mixture of pine and spruce wood.

Miscanthus (*Mischanthus x giganteus*), (*Mischanthus sinensis*) have different raw structure than industrial hemp (*Cannabis sativa* L.). Industrial hemp is more fibrous because Industrial hemp is textile hemp. Miscanthus has rough structure similar to wood (Murphy, et al., 2013).

Apple wood is a bio-waste from apple cultivation process. Every year it is necessary to prune trees and this waste is possible to use for briquetting production.

4.3 Grinding process

Material for briquettes productions has to be dried and crushed before production. These processes are most important and expensive. Dryers have expensive operation service but the material is dry in short time period. Material drying is difficult without dryers (Verma, et al., 2017). Material was dried on the ground without energy input in Research institute of Agricultural Engineering. Drying process is shown in **Fig. 7**. Material disintegration is made by biomass crushers. These crushers have different constructions (hammer mill, knife mill).

For material disintegration was used the hammer mill ŠV-15 **(Fig. 8)** with energy input 15 kW (Stoza, 2016). Materials were crushed in three fractions (4 mm, 8 mm, 12 mm - screens' holes diameter).

Figure 8 Hammer mill ŠV- 15

Source: Author (2017)

Figure 7 Biomass material drying

Source: Author (2017)

4.3.1 Determination of hammer mill throughput

Hammer mill throughput was determined by weight of used material and total grinding time. Throughput was calculated by following equation:

$$TP = (\frac{m}{t_m}) \cdot t_{60} [kg.h^{-1}] \quad \textbf{(2)}$$

TP- material throughput ($kg.h^{-1}$)

m- material weight (kg)

t_m- measured time (min)

t_{60}- time (60 min)

4.3.2 Determination of hammer mill energy consumption

Energy consumption was determined by Prowat-3 (16A, 380V) **(Fig.9)**. Research was done in Research institute of Agricultural Engineering. Prowat-3 can measure three phases and it is more accurate than normal electric meter.

Figure 9 Prowatt - 3

Source: Author (2017)

Power consumption was deducted from Prowat-3 (in Wh). Measurement was made in different times (depending on weight of input material), but every 10 minutes readings were made. The time is necessary for calculation, but also is the weight of material. Two equations were used. The first formula is used to calculate the energy consumption per 60 minutes:

$$E_{60} = \left(\frac{E_1}{t_m}\right) \cdot t_{60} [kWh] \qquad \textbf{(3)}$$

E_{60}- energy consumption (kWh)

E_1- measured specific energy consumption (kWh)

t_m- measured time (min)

t_{60}- time (60 min)

Second formula is used to calculate the energy consumption needed for production of one tonne of material:

$$E_{ton} = \left(\frac{E_1}{m_m}\right) \cdot m_t [kWh.t^{-1}] \qquad \textbf{(4)}$$

E_{ton}- energy consumption per one tonne ($kWh.t^{-1}$)

E_1- measured energy consumption (kWh)

m_m- measured weight (kg)

m_t- weight of one tonne (1000 kg)

4.1 Determination of biomass moisture content

Determination of moisture content was processed according to the applicable standard CSN EN 14774-1: method of drying in labour drier. The Drier UFE 500 - MEMMERT was used for measurement. Materials were divided into two samples of wet material and were weighed in beakers with different masses. Samples were dried for twenty four hours at a temperature of 105 ° C. After drying, samples were removed and weighed again. The moisture content in percentage was defined by using equation:

$$\omega = \frac{(m_w - m_d)}{m_w} \times 100\ [\%] \quad \textbf{(1)}$$

$\boldsymbol{\omega}$ − moisture content (%)

$\boldsymbol{m_w}$ − wet material weight (g)

$\boldsymbol{m_d}$− dry material weight (g)

4.2 Briquetting process analysis

Briquetting was accomplished by briquetting piston press Brikstar 30-12 (Briklis, Malešice, Czech Republic) with working pressure 18 MPa (180 bar). Briquettes were produced without any additional binders. Briquettes were prepared from four different materials and three different fractions for each material. Briquettes were produced with length of 30 - 50 mm and diameters of 65 mm. Measurements were done in Research institute in Ruzyně.

Table 2 Brikstar 30-12 parameters

Press type	Brikstar 30 - 12
Throughput of material	20 - 40 kg/h
Diameter	65 mm
Power intake	4.4 kW
Material moisture	8-15 hm%
Briquettes density	900 – 1100 kg/m3
Operation pressure	18MPa (180 bar)
Operation temperature	60 °C
Control voltage	400 V

Source: Briklis, (2011)

Figure 10 Briquetting press - Brikstar 30-12

Source: Author (2017)

4.2.1 Determination of briquetting process throughput

Briquetting press throughput was determined by weight of used material and total grinding time. Throughput was calculated by **formula 2.** Materials were weighted before briquetting.

4.2.2 Determination of briquetting press energy consumption

Energy consumption was measured by Prowatt - 3 (16A, 380V). Measurement of electric energy was performed in order to determine energy consumption. Measurements were conducted on Brikstar 30 - 12 (pressing chamber diameter 65 mm).

The measurement was made with the time 60 minutes. This time was divided into ten-minute sections. Values were deducted every 10 minutes by Prowatt - 3. Energy consumption was determined by **formula 3.**

Energy consumption was also determined for one tonne of input material. The calculation for one tonne of material is more useful for next research. The energy consumption was calculated by **formula 4**. Calculation of hammer mill energy consumption is similar to calculation of briquetting energy consumption.

4.3 Determination of mechanical durability of produced briquettes

Mechanical durability determination of produced briquettes was done according to standard ČSN EN 15210-2: Determination of mechanical durability of briquettes, by briquette durability tester in the Laboratory of Technical Faculty in CULTS, Prague. The drum has cylindrical shape with volume of 160 l.

Before the measurements in the drum, it was necessary to prepare briquettes samples. The sample of each group of briquettes was about 2 kg. The sample was inserted into the drum to determine the mechanical durability. The sample portion was rotated at 21 ± 0.1 revs. min^{-1} for 5 min. The mechanical durability was calculated by following formula:

$$DU = \left(\frac{m_a}{m_e}\right) \cdot 100[\%] \quad \textbf{(5)}$$

DU- mechanical durability (%)

m_a- weight of input briquettes (kg)

m_e- weight of output briquettes (kg)

5 Results and Discussion

Briquettes were produced from various materials and differences between materials were visible, as shows the research results. The research has evaluated energy consumption and throughput of crusher and briquetting press and the results are presented in this chapter.

5.1 Analysis of material preparation process

5.1.1 Hammer mill throughput

The test estimated the material consumption of hammer mill. **Fig. 11** shows each material, fraction (mm) and throughput (kg.h^{-1}). Material was divided into three fractions (4, 8 and 12 mm). Material is grinded by hammers. Screens perforation determines final particle size.

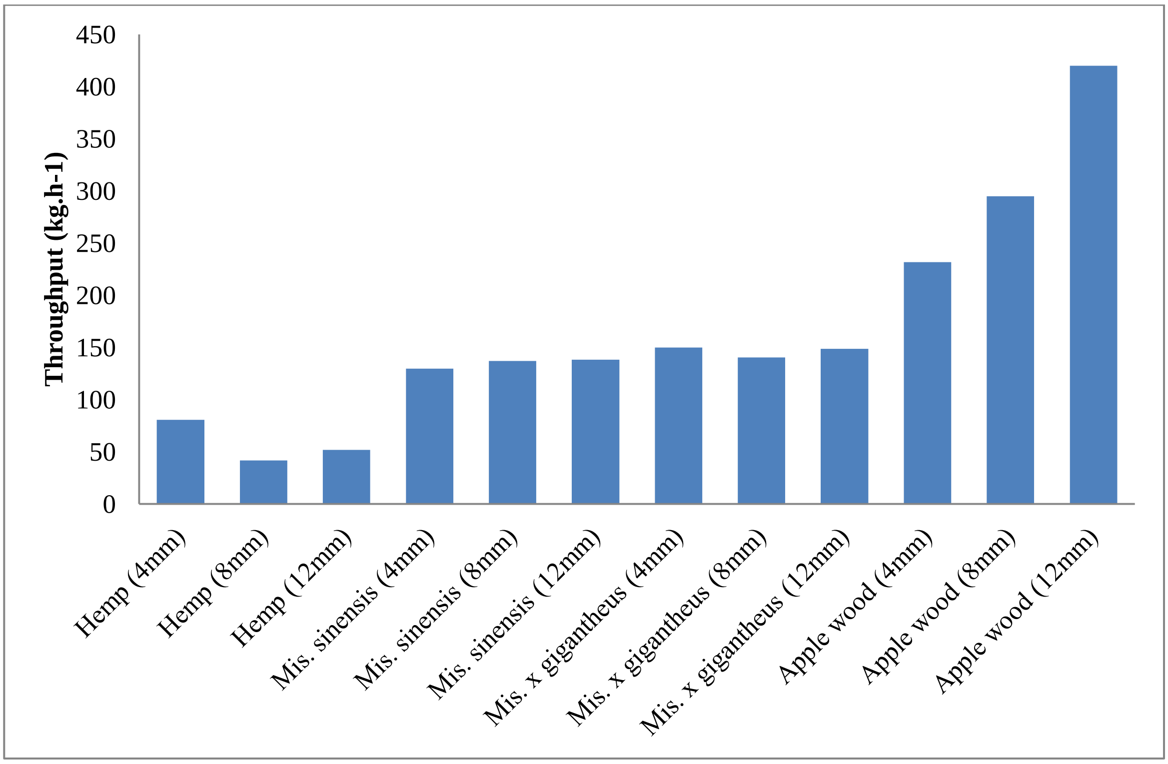

Figure 11 Hammer mill throughput with different fractions

Source: Author (2017)

From the **Fig. 11** is evident that the apple wood had the highest (the best) throughput (231.50, 294.67.420.00 kg.h^{-1}). From the result of apple wood is evident that the fraction 12 mm has higher throughput than others fractions, followed by 8 mm and then 4 mm. Hammer mill throughput was rising with screen size during grinding of this wood material. *Mis. x gigantheus* (149.65, 140.29 and 148.64 kg.h^{-1}) and *Mis. sinensis* (129.48, 136.00 and 149.65 kg.h^{-1}) have almost similar throughput. During the grinding of these straw materials were not found differences between fractions. Hemp have different (very low) values (80.40, 41.50 and 51.71 kg.h^{-1}) comparing to other materials. During the measurements were observed complications with grinding of hemp due to the rolling of hemp fibres on hammers of the grinding machine.

Fig. 11 shows differences between apple wood and others materials. For hammer mill is better to grind harder materials such as apple wood. According to the company Stoza s.r.o the material flow is 2.2 - 3.2 t.h^{-1}. The maximum material flow measured in this research was420 kg.h^{-1}. Apple wood has the best results for each fraction. Materials *Mis. x gigantheus* and *Mis. sinensis* have very similar material throughput. Bitra et al. (2009), determined material throughput for switchgrass, wheat straw and corn stover. The throughput was similar for each material and the value was150 kg.h^{-1}. Hu et al., (2014), used chopping machine in his research. Corn stalk was used. The particle size of the corn stalk from the chopping machine was 4 mm. He recognized that the chopping capacity of the chopping machine ranges from 300 to 500 kg.t^{-1}. The corn stalk has structure similar to *Mis. x gigantheus*. In this research Mis. gigantheus with fraction of 4 mm had throughput for hammer mill at least two times smaller.

5.1.2 Hammer mill energy consumption

Fig. 12 lists the average energy consumption for grinding of selected biomass using the hammer mill with three different screen sizes. Energy consumption to reduce hemp to particle sizes 4, 8 and 12 mm was 65.97, 117.47, 66.85 kWh.t^{-1}, respectively. Hemp has different (medium) energy consumption than other materials. From the **Fig. 12** is evident that the *Mis. sinensis* and *Mis. x gigantheus* had the lowest energy consumption.

The **Fig. 12** shows differences between each fraction. From the **Fig. 12** is evident that apple wood has the highest energy consumption (**141.25, 135.29** and **129.52 kWh.t^{-1}**) than other materials. Apple wood is hard material for grinding. **Fig. 12** shows differences between fractions 4 and 8 mm. Fraction 8 mm had less electric energy consumption than fraction of 4 mm. Mani et al. (2004), made an experiment with energy consumption of hammer mill. They used Switchgrass, which was grinded to fractions 0.8, 1.6 and 3.2 mm. It seemed that switchgrass have similar structure as *Mis. sinensis.* Results show the difference between fractions. Fraction 0.8 mm had energy consumption of 62.55 kWh.t^{-1}, 1.6 mm - 51.76 kWh.t^{-1} and 3.2 mm - 23.84 kWh.t^{-1}. It is evident that the energy consumption is rising with smaller fraction.

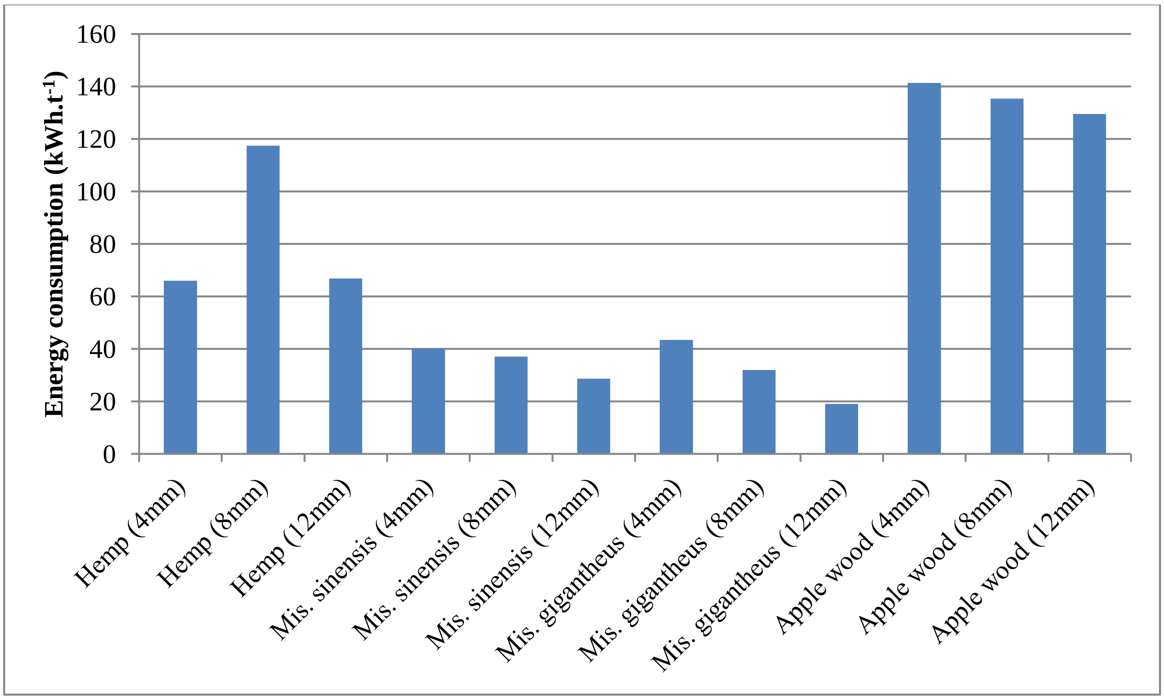

Figure 12 Hammer mill energy consumption of different biomass materials and different fractions

Source: Author (2017)

The energy consumption of hammer mill was comparable with the work of Cadoche and López (1989). Screen size has effect on energy consumption. That means bigger screens have lower energy consumption. Hu et al. (2014) used chopping machine for chopping of corn stalk (fraction 4 mm). The energy consumption was

20 kWh.t^{-1}. The hammer mill has higher energy consumption. Only *Mis. x gigantheus* has energy consumption 19.08 kWh.h^{-1}.

Materials *Mis. sinensis, Mis. x gigantheus* and apple wood had the same trend in energy consumption. Fractions 4 mm had the highest energy consumption, while fractions 12 mm had lower energy consumption. This trend was not evident in case of Hemp.

5.2 Evaluation of moisture content of experimental raw materials

Moisture content was determined with use of the oven (UFE 500 - MEMMERT) drying method. Values of moisture content are in **Fig. 13**.

From **Fig. 13** is evident that the moisture content is not more than 15%. This value is a maximum border for briquettes production by Brikstar 30-12 (Briklis, 2011). According to Briklis (2011) the lowest moisture content of input material is 8%, but in this thesis is material with moisture content less than 8% were tested as well. Briquettes with moisture content of 7.37% (*Mis. x gigantheus*, 12 mm), 7.60% (Hemp, 8 mm), 7.29% (*Mis. x gigantheus*, 4 mm), 7.65% and 7.69% (Apple wood, 4 mm) were compacted.

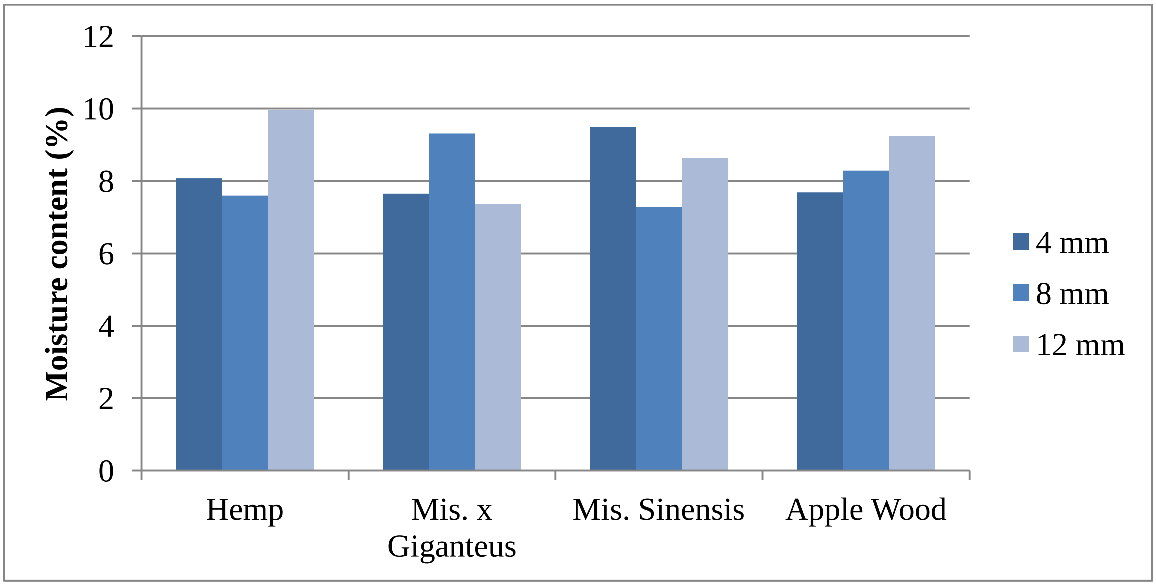

Figure 13 Biomass material moisture content

Source: Author (2017)

5.3 Analysis of briquetting process

Briquettes were made from various materials. Briquetting was accomplished by piston press Brikstar 30 - 12. The material throughput and energy consumption are among the most important processing parameters (Tripathi, et al., 2000).

5.3.1 Briquetting press throughput

The test estimates the throughput of briquetting press. The calculation was calculated by **Formula 2.** The material throughput is evident from **Fig. 14.** This figure shows some differences between each fraction. Throughput depends on particle size. Particle size 4 mm had higher material throughput than other fractions. This trend was evident within each material. Material with smaller particle size was easily pressed. The throughput for fractions 4mm is: Hemp - 28.71 kg.h^{-1}, *Mis. sinensis* - 43.16 kg.h^{-1}, *Mis. x gigantheus* - 42.40 kg.h^{-1} and apple wood - 46.30 kg.h^{-1}. *Mis. sinensis* and *Mis. x gigantheus* had similar throughput during briquetting. Briquetting throughput for apple wood was in general the highest in comparison with other materials as well as it corresponds to the best throughput of wood biomass during grinding, however the difference between throughput of wood and miscanthus materials within briquetting is not such significant like during the grinding. As in case of all the material the best briquetting throughput for apple wood showed smaller fraction 4 mm, but in case of hammer mill throughput it was different (opposite) and the fraction 12 mm had the highest throughput there. The lowest throughput was again detected in case of hemp.

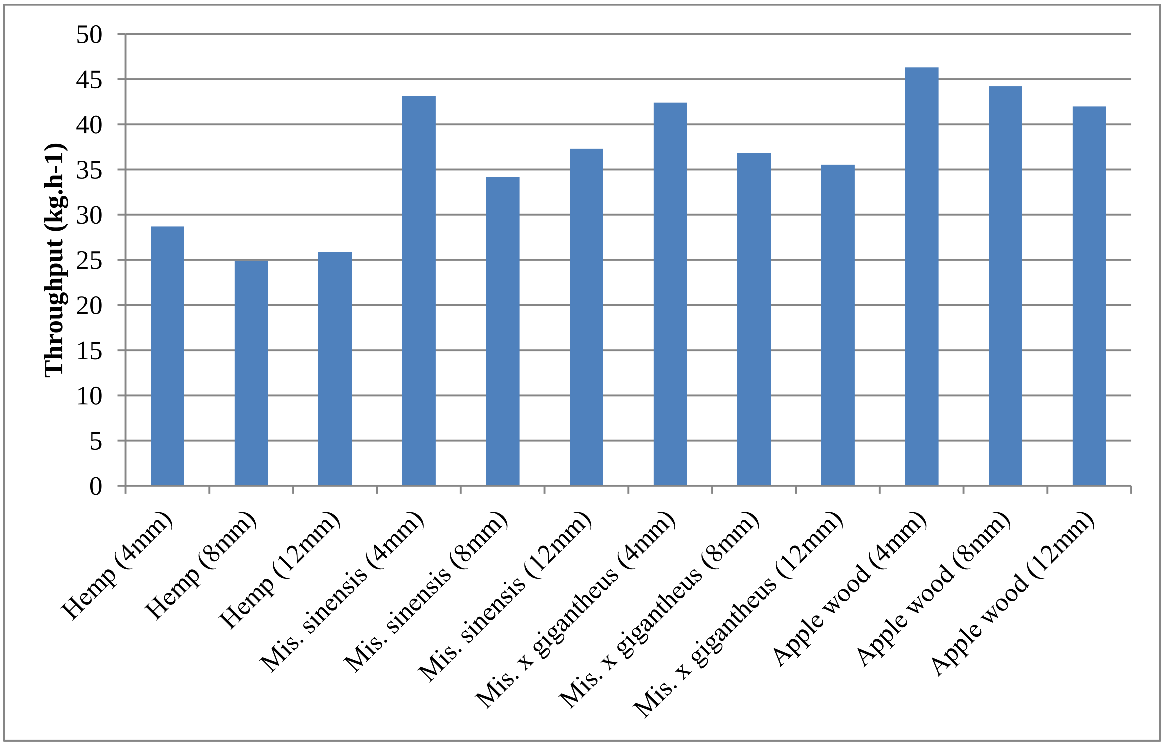

Figure 14 Briquetting press throughput of different biomass materials and different fractions

Source: Author (2017)

The piston press Brikstar 30-12 has material throughput 20 $kg.h^{-1}$- 40 $kg.h^{-1}$ (Briklis, 2011). From the **Fig. 14** is evident that the throughput is in the range, but the apple wood showed higher values **(46.30kg.h^{-1}, 44.20kg.h^{-1} and 42.00 kg.h^{-1})**. The throughput of apple wood for all fractions was higher than the maximum working throughput of Brikstar 30-12, what's for better indicators seems to beparticle size and type of material. From the **Fig. 14** is evident that Hemp with moisture content of 7.60%, 8.08% and 9.97% has the lowest values while apple wood with moisture content of 7.69% or 8.29% has higher throughput, so impact of moisture is now visible. Additionally, it should be mentioned that hammer mill throughput was in genetalnotably higher than throughput of briquetting.

5.3.2 Briquetting press energy consumption

The energy required for compaction of materials into briquettes at different particle sizes is shown in **Fig. 15.** The energy consumption was in the range of43.91

kWh.t^{-1} to 115.24 kWh.t^{-1}. From the energy consumption is evident which material is more suitable for briquettes production. The **Fig. 15** shows four types of biomass materials and their energy consumption. The highest energy consumption has Hemp fractions 4 mm and 8 mm (115.24 kWh.t^{-1} and 107.00 kWh.t^{-1}). Positive results, i.e. relatively low consumption and generally the best values comparing to apple wood and hemp, have *Mis. sinensis* and *Mis. x gigantheus* for all fractions. Energy consumption for these materials is in the range of 43.91 kWh.t^{-1} to 64.67 kWh.t^{-1}. Briquetting process is more energy intensive than grinding process in case of *Mis. sinensis* and *Mis. x gigantheus*. Apple wood energy consumption was: 4mm - 80.65 kWh.t^{-1}, 8mm - 78.00 kWh.t^{-1} and 12 mm - 80.67 kWh.t^{-1}. Apple wood has higher energy consumption then miscanthus, but lower then hemp. Ivanova et al. (2013) said that the specific energy consumption of briquetting press is in the range of 44 kW.t^{-1}to 70 kW.t^{-1}. The energy consumption of *Mis. sinensis* and *Mis. x gigantheus* is in this range.

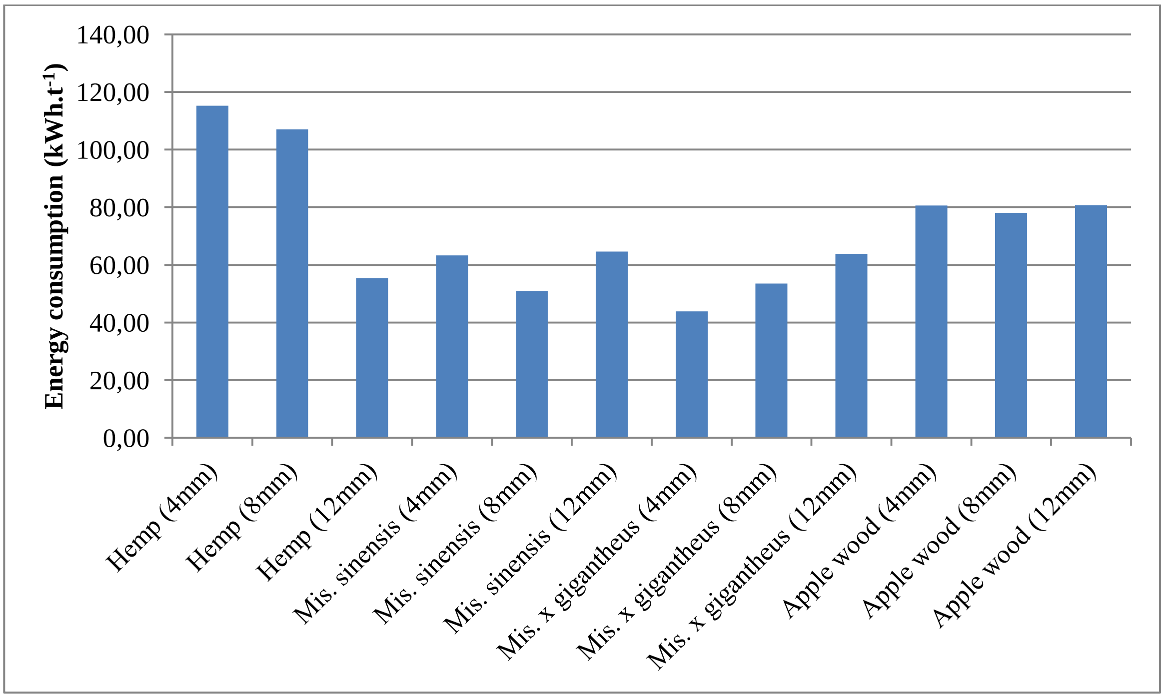

Figure 15 Energy consumption of different biomass materials and different fractions

Source: Author (2017)

5.4 Evaluation of mechanical durability of produced briquettes

The mechanical durability was done according to EN 15210-20 (2010). The results are represented in **Fig. 16.** Mechanical durability is one of the most important mechanical parameter of solid fuels (Brožek, et al., 2012). It characterizes the resistance of the fuels during transportation and other manipulation (Grover et al., 1996). Mechanical durability of Hemp was 98.34%, 98.29% and 96.36% while apple wood has 92.36%, 95.13% and 95.39%. From the point of view of the mechanical durability the briquettes from apple wood showed average values (even the lowest durability), while Hemp showed the best. According to Brožek et al., (2012), sawdust and shavings (woody materials) had mechanical durability of 91% (sawdust) and 92% (shavings). The interesting fact is in contrast between briquettes made from hemp and other materials it can be probably explained by its structure - by better connection of fibrous materials particles.

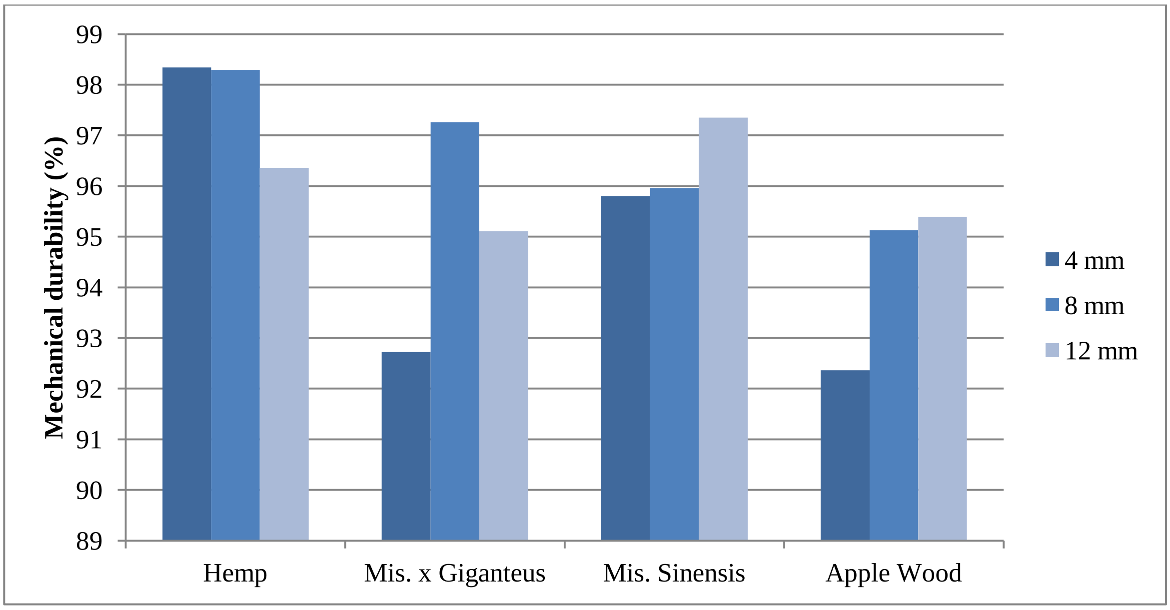

Figure 16 Mechanical durability of briquettes

Source: Author (2017)

5.5 Summarization of grinding and briquetting processes of used materials

5.5.1 Throughput evaluation of grinding and briquetting process

The throughput is an indicator of material profitability (Hu et al., 2014). This indicator recognizes which material is suitable for briquettes production. From the **Fig. 17** is evident that the most useful material is apple wood. Apple wood throughput was measured for each fraction (4 mm- 277.80 kg.h^{-1}, 8 mm - 339.87 kg.h^{-1} and 12 mm 462.00 kg.h^{-1}), while Hemp had lowest material throughput (4 mm - 109.11 kg.h^{-1}, 8 mm - 66.40 kg.h^{-1} and 8 mm - 77.57 kg.h^{-1}).

Mis. sinensis and *Mis. x gigantheus* had similar material throughput. The throughput is in the range of 171.00 kg.h^{-1}to 192.05 kg.h^{-1}.

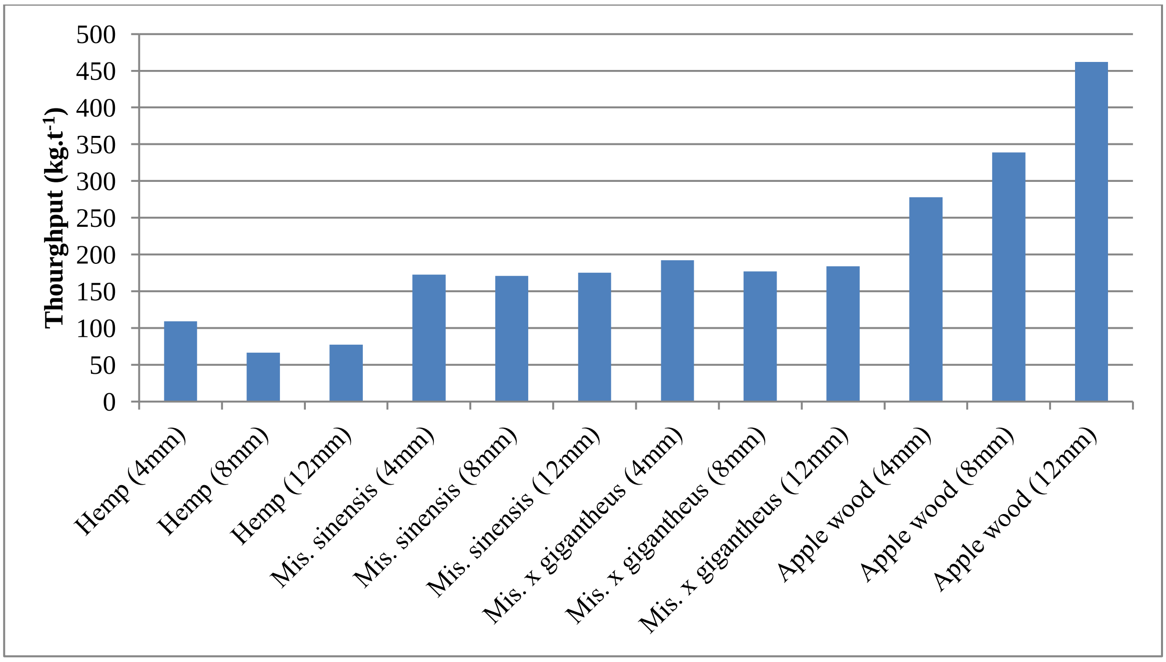

Figure 17 Throughput of grinding and briquetting process

Source: Author (2017)

5.5.2 Energy consumption evaluation of grinding and briquetting process

Energy consumption indicates the value of used energy. The **Fig. 18** shows total value of energy consumption. Research revealed that the apple wood had similar energy consumption as hemp. Total value for apple wood is: (4 mm - 221.90 $kWh.t^{-1}$, 8 mm - 174.29 $kWh.t^{-1}$ and 12 mm - 210.19 $kWh.t^{-1}$) and for hemp: (4 mm - 181.21 $kWh.t^{-1}$, 8 mm - 224.47 $kWh.t^{-1}$ and 12 mm - 122.28 $kWh.t^{-1}$).

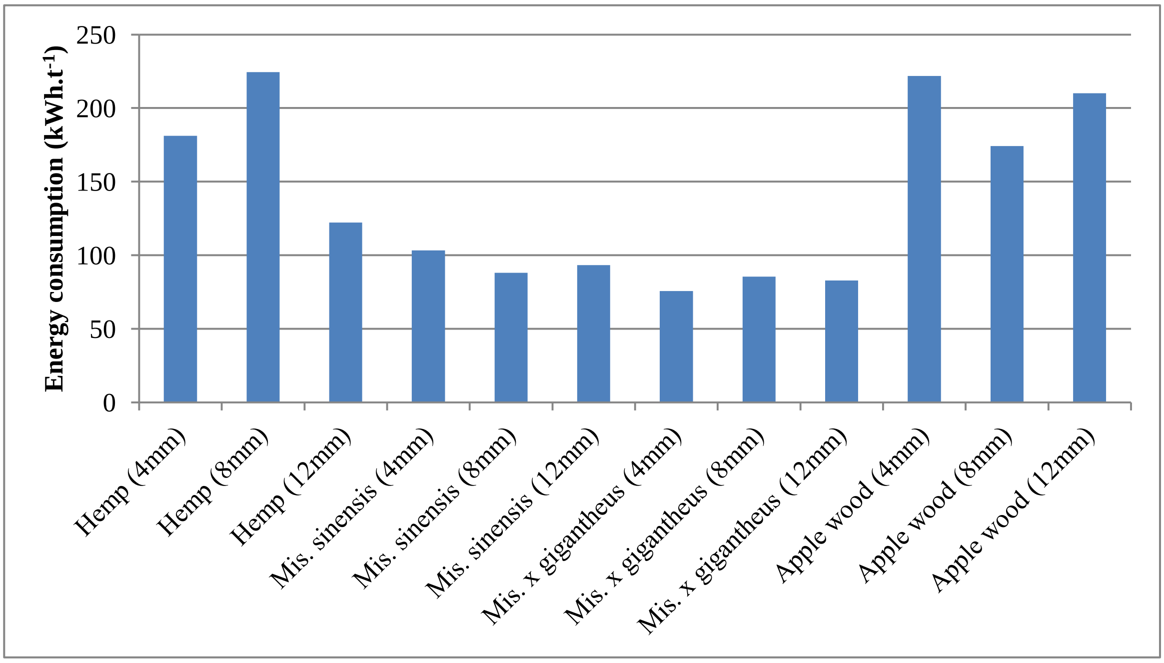

Figure 18 Energy consumption of grinding and briquetting process

Source: Author (2017)

Fig. 19 shows comparison between material throughput and energy consumption during whole production process (grinding and briquetting). Material throughput should not to be higher than energy consumption. For briquettes production, apple wood has positive results (fractions 8 mm and 12 mm), but it is also possible to use *Mis. sinensis* and *Mis. x gigantheus* (fractions 4 mm, 8 mm and 12 mm)

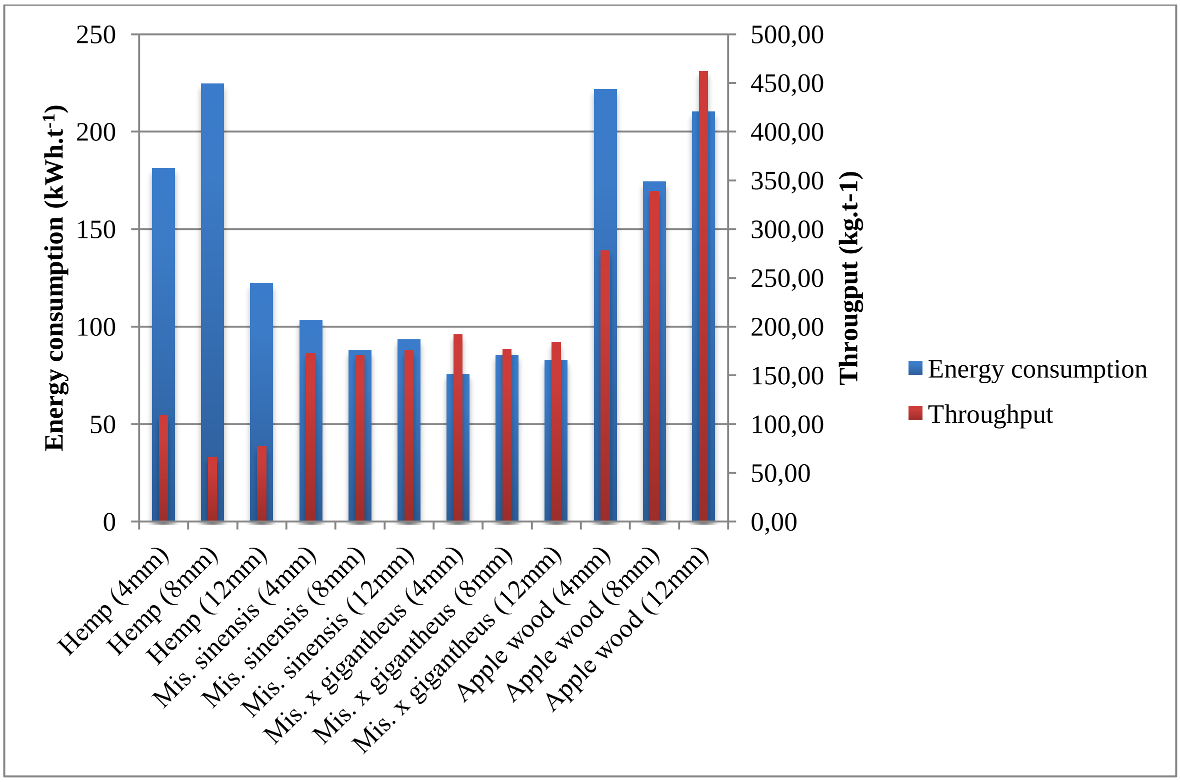

Figure 19 Evaluation of throughput and energy consumption

Source: Author (2017)

6 Conclusion and recommendations

Solid biofuels are environmental friendly sources of energy. Solid biofuels have many benefits. Briquetting technology is one of the solutions to replace the fossil fuels.

Presented diploma Thesis was focused on material throughput and energy consumption of grinding and briquetting process. Overall, four types of materials were used for briquetting. As materials investigated were Hemp (fibrous material), *Mis. sinensis*, *Mis. x gigantheus* (herbaceous biomass) and Apple wood residues. Those materials were grinded by hammer mill and briquetted by piston press with diameter of pressing chamber 65 mm.

6.1 Conclusion on Hypothesis

Research confirmed the first hypothesis. During the evaluation of throughput of different materials, in both processes (grinding and briquetting) the best results showed apple wood, very similar throughput was between two types of Miscanthus (herbaceous biomass) a significantly worse throughput had the hemp (fibrous material). According to the used material, energy consumption during grinding and briquetting can also differ. The lowest consumption had the herbaceous biomass. The highest energy consumption was recorded during grinding of hard wood and during briquetting of hemp.

Research partly confirmed the second hypothesis. During the evaluation of the influence of the fractions to throughput, the best throughput had materials with fraction of 4 mm. during briquetting process the significant difference between fractions was visible on wood where on the contrary the higher fraction caused better throughput. From the energy consumption point of view, the finer the fraction was during grinding, the higher was the energy consumption. During briquetting any typical trend was not visible.

Research partly confirmed the third hypothesis. In was confirmed in case of wood, where energy consumption during grinding was significantly higher than during briquetting. On the contrary, during briquetting of two types of miscanthus, the energy consumption was higher (almost double). Average energy consumption during grinding and briquetting of hemp was similar, slightly higher during briquetting.

6.2 Recommendations

Material throughput of *Mis. sinensis, Mis. x gigantheus* or hemp during briquetting is probably possible to improve by adding some other material such as woody material or saw dust.

There is an idea that further improvement of piston press throughput is possible to do by pre-heating the machine in briquetting chamber.

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8 Annex

Table 1 Hammer mill throughput of different biomass materials and different fractions

Material	Fraction (mm)	Throughput (kg.h^{-1})
Hemp	4	80.40
Hemp	8	41.50
Hemp	12	51.71
Mis. sinensis	4	129.48
Mis. sinensis	8	136.80
Mis. sinensis	12	138.00
Mis. x gigantheus	4	149.65
Mis. x gigantheus	8	140.29
Mis. x gigantheus	12	148.64
Apple wood	4	231.50
Apple wood	8	294.67
Apple wood	12	420.00

Source: Author (2017)

Table 2 Hammer mill energy consumption of different biomass materials and different fractions

Material	Fraction (mm)	Time (min)	Energy consumption (kWh)	Energy consumption ($kWh.t^{-1}$)
Hemp	4	60	5.30	65.97
Hemp	8	60	4.88	117.47
Hemp	12	60	3.46	66.85
Mis. sinensis	4	60	5.19	40.08
Mis. sinensis	8	60	5.07	37.06
Mis. sinensis	12	60	3.96	28.70
Mis. x gigantheus	4	60	6.49	43.40
Mis. x gigantheus	8	60	4.49	31.98
Mis. x gigantheus	12	60	2.84	19.08
Apple wood	4	60	13.62	141.25
Apple wood	8	60	12.84	135.29
Apple wood	12	60	11.47	129.52

Source: Author (2017)

Table 3 Biomass material moisture content of different biomass materials and different fractions

Material	12 mm	8 mm	4 mm
Hemp	9.97%	7.60%	8.08%
Mis. x gigantheus	7.37%	9.31%	7.65%
Mis. sinensis	8.63%	7.29%	9.49%
Apple Wood	9.24%	8.29%	7.69%

Source: Author (2017)

Table 4 Briquetting press throughput of different biomass materials and different fractions

Material/Fraction	**Fraction (mm)**	**Moisture Content (%)**	**Throughput ($kg.h^{-1}$)**
Hemp	4	8.08	28.71
Hemp	8	7.60	24.90
Hemp	12	9.97	25.86
Mis. sinensis	4	9.49	43.16
Mis. sinensis	8	7.29	34.20
Mis. sinensis	12	8.63	37.30
Mis. x gigantheus	4	7.65	42.40
Mis. x gigantheus	8	9.31	36.83
Mis. x gigantheus	12	7.37	35.54
Apple wood	4	7.69	46.30
Apple wood	8	8.29	44.20
Apple wood	12	9.24	42.00

Source: Author (2017)

Table 5 Mechanical durability of different biomass materials and different fractions

	12 mm	8 mm	4 mm
Hemp	96.36	98.29	98.34
Mis.xgigantheus	95.11	97.26	92.72
Mis.Sinensis	97.35	95.96	95.8
Apple Wood	95.39	95.13	92.36

Source: Author (2017)

Table 6 Energy consumption of different biomass materials and different fractions

Material	Fraction (mm)	Moisture Content (%)	Energy consumption (kWh)	Energy consumption ($kWh.t^{-1}$)
Hemp	4	8.08	2.01	115.24
Hemp	8	7.60	2.16	107.00
Hemp	12	9.97	2.31	55.43
Mis. sinensis	4	9.49	2.12	63.24
Mis. sinensis	8	7.29	2.07	50.95
Mis. sinensis	12	8.63	2.19	64.67
Mis. x giganteus	4	7.65	2.04	43.91
Mis.x giganteus	8	9.31	2.09	53.50
Mis.x giganteus	12	7.37	1.93	63.87
Apple wood	4	7.69	2.34	80.65
Apple wood	8	8.29	1.44	78.00
Apple wood	12	9.24	1.62	80.67

Source: Author (2017)

Table 7 Grinding and briquetting throughput

Material	Fraction (mm)	Energy consumption (kWh)	Energy consumption (kWh.t^{-1})
Hemp	4	7.31	181.21
Hemp	8	7.04	224.47
Hemp	12	5.77	122.28
Mis. sinensis	4	7.31	103.32
Mis. sinensis	8	7.14	88.01
Mis. sinensis	12	6.15	93.37
Mis. x gigantheus	4	8.53	87.31
Mis. x gigantheus	8	6.58	85.48
Mis. x gigantheus	12	4.77	82.95
Apple wood	4	15.96	221.90
Apple wood	8	14.28	213.29
Apple wood	12	13.09	210.19

Source: Author (2017)

Table 8 Grinding and briquetting energy consumption

Material	Fraction (mm)	Throughput (kg.t^{-1})
Hemp	4	109.11
Hemp	8	66.40
Hemp	12	77.57
Mis. sinensis	4	172.64
Mis. sinensis	8	171.00
Mis. sinensis	12	175.30
Mis. x gigantheus	4	192.05
Mis. x gigantheus	8	177.12
Mis. x gigantheus	12	184.18
Apple wood	4	277.80
Apple wood	8	338.87
Apple wood	12	462.00

Source: Author (2017)

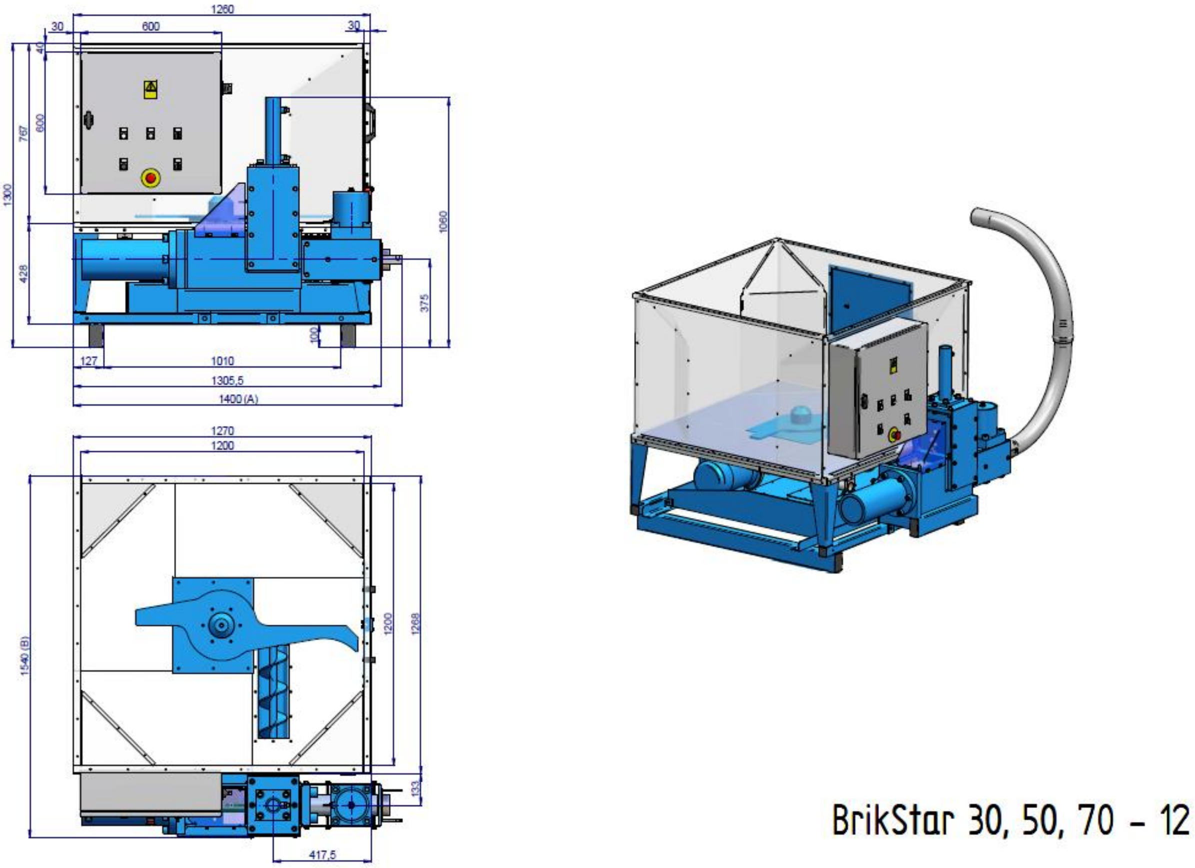

Figure 1 Briquetting press Brikstar 30-12 scheme

Source:Briklis, (2011)