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Influence of Densification Process and Material Properties on Final Briquettes Quality from Fast-Growing Willows

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***Abstract*—**Biomass treatment through densification is very suitable and helpful technology before its effective energy recovery. Densification process of biomass is significantly influenced by various technological and material variables, which are ultimately reflected on the final solid biofuels quality. The paper deals with the experimental research of the relationship between technological and material variables during densification of fast-growing trees, roundly fast-growing willows. The main goal of presented experimental research is to determine the relationship between compression pressure and raw material particle size from a final briquettes density point of view. Experimental research was realized by single-axis densification. The impact of particle size with interaction of compression pressure and stabilization time on the quality properties of briquettes was determined. These variables interaction affects the final solid biofuels (briquettes) quality. From briquettes production point of view and from densification machines constructions point of view is very important to know about mutual interaction of these variables on final briquettes quality. The experimental findings presented here are showing the importance of mentioned variables during the densification process.

***Keywords*—**Briquettes density, densification, particle size, compression pressure, stabilization time.

I. Introduction

THE densification technology is a suitable option of biomass treatment prior to energy recovery. On the other is densification is very complicated process, because in solid biofuels manufacture technological and material variables influence the densification process and thus also the final solid biofuels quality (briquettes). Quality of briquettes is defined and given by EU standards [1], and is evaluated by mechanical and thermo-chemical indicators. Our department is attempting to develop new densification machines, and trying to optimize the biomass treatment process prior to densification. The development of densification machines is more effective if information about variables effect during densification process is available.

Among renewable resources, residual biomass is envisaged to play an important role in the new energy conception since agricultural and forest residues are a local energy resource with an important production throughout the world [2]. Requirements of solid biofuel production demonstrate that another important factor to take into consideration is the type of the material for compression. Each different type of raw material requires a separate approach. The aim is to develop such densification machine, which can produce biofuels from different type of raw material to the required quality according to technical standards [1]. Different raw material properties cause different conditions during densification process, and this causes that the final quality of biofuel produced to be very different [3]. For each raw material is necessary to find the optimal parameter settings for densification. This is reason why is so important to realize the experimental research to determine the impact of technological and material variables on the final quality of the biofuel during densification.

General purpose of this paper is to determine the relationship between technological and material variables, and the final quality of solid biofuels, specifically briquettes, made from fast-growing willow sawdust. The impact of these technological variables, especially compression pressure, and also of the material parameters (particle size and moisture content) can generally be observed during biomass densification in the quality indicators, where the abovementioned variables have a significant influence, especially on the mechanical indicators of quality (briquette density, mechanical durability, etc.). This paper presents the results of experimental research dealing with determining the relationship between the technological and the material variables during densification of fast-growing willow sawdust. The main goal of the paper is to determine the mutual interaction between compression pressure and material particle size. The influence of the particle size interacting with compression pressure on the final briquette density was determined. The research findings obtained should prove valuable in briquette production and in the engineering of densification machines.

II. Variables for Investigation

As mentioned above, the raw material properties and composition is necessary to take into consideration during the densification. The production of high quality briquettes is more effective if the material properties are respecting [3]. Moreover, the technological variables of densification according to the type of raw material to be compressed have to be adjusted. Each type of material has different mechanical

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and thermal properties and different chemical composition. Several variables, which influence the densification process, can be detected. These also influence the final briquettes quality, which is mainly evaluated by density. Theoretical analysis of influencing variables impact significance was undertaken, and variables for the experimental research were chosen. These variables are compression pressure "p", compression temperature "T", raw material particle size "L", and raw material moisture content "w_r". Because the task is huge and complicated, the experimental research to the two phases was divided. Aim of the first phase was to determine the compression pressure influence, particle size influence, and their mutual interaction. In the second phase, also the influence the compression temperature and influence of moisture content will be investigated. Multi–variables experimental research and design have to be built up. The goal of this research work is to determine the impact of the aforementioned variables on the quality of the final briquette.

The main reason for compression pressure and particle size choosing are as follows. The compression pressure is one of the most important variables affecting the resulting briquette strength [4]. With increased pressure, the briquette tends to become stronger until the yield strength of the material is reached [5]. This also reduces the tendency of the briquette to absorb moisture when stored. It is important to find the optimum combination of force and force vector direction in order to obtain a highly compact briquette [6]. Analysis of the pressure is interesting and complicated. To obtain a high quality briquette, it is necessary to ensure maximum pressure within the pressing chamber. This value represents the pressure needed for densification and the smooth feeding of the briquette through the chamber. Biomass under pressure undergoes two types of deformation: elastic and plastic. Elastic deformation returns to its original position once the pressure is released. However, plastic deformation permanently deforms the material. The compression pressure with interacting of others variables has a direct effect on the elastic and plastic deformation [7], [8].

The size of the input particle also has an important effect on the densification process because larger input particles increase the energy needed for densification [9]-[11]. Briquettes formed from large input particles also have less homogeneity and strength [11]. On the other hand, a large number of fine particles provide better material densification. The resulting briquette is uniform, of high quality, and displays higher volumetric density. With increasing particle size, the bond strength between particles decreases, causing them to crumble [7], [8]. As a result, the quality of the briquette decreases and the compression pressure necessary to counteract this drop in quality increases. During compression, especially without additives, the surfaces of the particles must have contact over the greatest possible area [7]. The size of this contact area increases as the particle size becomes finer and higher compression pressures need to be applied. In the material, particles exist which deform and load mainly the contact regions, due to external forces [11]. In terms of densification, it is very important that bonding forces are created between the particles. The strength of the resultant bonds increases with decreasing particle size. However, the optimum particle size changes in relation to the densification technology employed, and the raw material used. Therefore, it is important to investigate the effects of particle size on the resulting density of the briquette. Thus, particle size was one of the variables that this research attempted to identify and verify in the experiments.

III. Experimental Research Conditions

Sherwood (*Salix viminalis x Salix eriocephala) x (Salix schwerinii x salix viminalis*) and Gudrun (*Salix dasyclados*) varieties of fast-growing willows were chosen for this experimental research. These varieties of fast-growing willows are originating from Sweden, but for our purposes have been grown in Northern Slovakia. Pieces of willows were disintegrated to a suitable form using an S120x400-R1/30 wood chipper and a MN300 cutter mill. Initially, the particle size distribution was analyzed using an AS 200 Vibrating Sieve Shaker. The raw material particle size distribution was calculated by weight, Fig. 1.

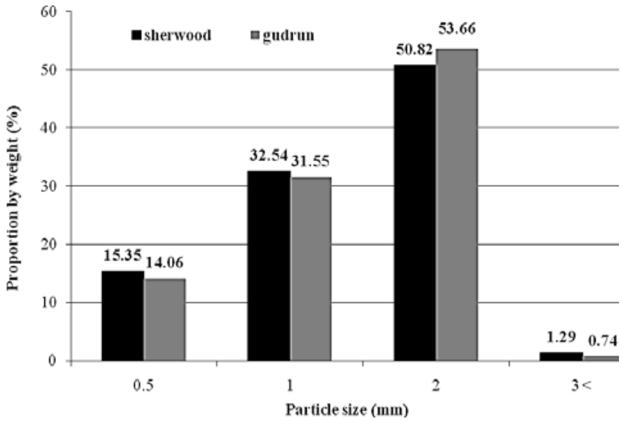

Fig. 1 Raw material particle size distribution

The moisture content of the fast-growing willows sawdust was measured prior to undertaking the experimental research using a MRS 120-3 balance. This measurement was based on heating the material (gravimetric method of moisture content measuring) at 105 ± 2°C until a constant weight was achieved [12]. Due to the experimental design (two phases of experiment) only one moisture content level was used in this phase of the experiments (w_r = 9 %), so the impact of moisture content on briquette quality was not investigated or calculated in our experiments.

Briquettes were produced using a vertical hydraulic press, which was modified with the use of an experimental pressing stand (Fig. 2). The experimental pressing stand consists of a base frame, a cylindrical pressing chamber with a 20 mm diameter die, a heating device with a temperature sensor for temperature control, and the backpressure plug. In our case no additional temperature was used, the experimental research was executed under laboratory conditions (T=25°C). The raw material was fed into the chamber and compression with a hydraulic piston commenced. The hydraulic press made it possible to set the compression pressure in the range 31 MPa to 318 MPa, from this range in 5 levels of compression pressure (63 MPa, 95 MPa, 127 MPa, 175 MPa and 222 MPa) research was executed. Adhering to the experimental plan for each experiment setting, seven briquettes were produced. This number was chosen to satisfy standard mathematical and statistical methods for experiment evaluation. The described hydraulic press with stand allowed experimental settings over a wide range of compression pressures. Densification of the fast-growing willows sawdust was increased gradually in order to achieve the optimum results.

Fig. 2 Hydraulic press with experimental pressing stand

Briquette density was calculated using the ratio between briquette weight and its volume. The weight, length and diameter of each briquette were measured with a digital caliper and an electronic balance. The volume of the briquettes was calculated as the volume of a cylinder with dimensions (length and diameter), according to EN 16127 [13]. Average density was calculated for each sample briquette.

Fig. 3 Briquettes produced from fast-growing willow sawdust

All the results in this phase, showing the interrelation between the different variables, were depicted graphically, as seen in Figs. 4-14. The results of this experimental research are applicable at engineering design of densification machines, and gave a comprehensive overview of the behavior of different variables during the densification process.

IV. Results and Discussion

The interdependence of briquettes density from compression pressure can be seen in Fig. 4. This figure describes results related to Sherwood variety sawdust densification. As the compression pressure increases so too does the briquette density. This interdependence also highlights the importance of briquette stabilization time. Briquette stabilization time is the time interval during which dilatation occurs and also during which the briquette became stable [15]. Briquette stabilization time takes approximately 24 h depending on the type of compressed material and the densification technology used, but it can also take longer. The DIN 52182 Standard [14] describes the conditions and process for detecting briquette density after stabilization time. After compression, the briquettes had to be placed under stable climatic conditions.

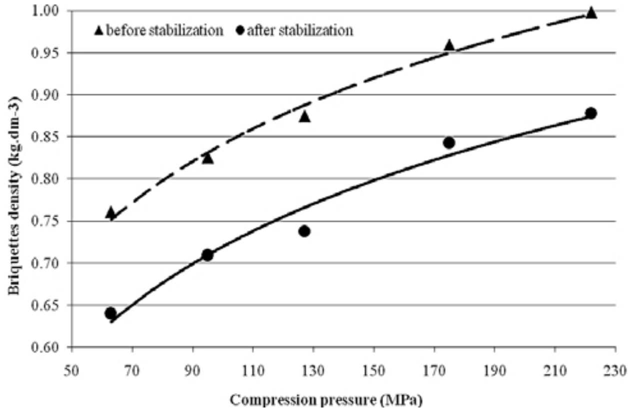

Fig. 4 Briquette density of Sherwood variety sawdust, related to compression pressure at 25 °C(w_r = 9%; L = 2 mm)

During this stabilization time the briquette dimensions (length and diameter) were frequently measured and its weight and density were evaluated. If the briquette weight had changed by no more than a maximum of 0.1% during the last 24 h, the briquette was considered stable [14]. Briquette dilatation is a process during which the briquette's dimensions (diameter, length) and weight undergo a change [8]. These changes result from the internal variables of the briquette material, and from the external variables of the densification technology. Dilatation has a direct influence on the briquette density because the density was calculated from the aforementioned briquette dimensions [15]. The dilatation effect is produced when the compression pressure is removed, and, because of the relationship of the interactions between the compression temperature, material moisture, and input particle size [8].

Two of these interdependencies can be seen in Fig. 4, one for densities evaluated immediately after releasing the briquettes from the compression chamber, i.e., before stabilization, and the second for densities evaluated after the stabilization time. The briquette density changed significantly, and dilatation negatively influenced the briquette density in this case. Average density difference of 13.94% was determined. Similar experiment also for Gudrun variety sawdust was executed, where the average density difference of 13.31% was determined.

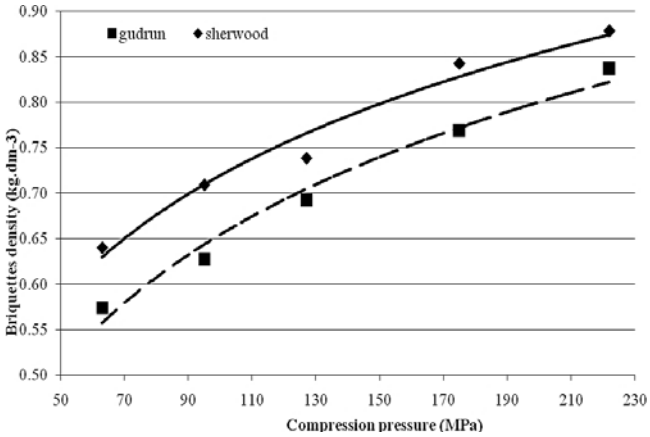

Fig. 5 Briquette density of both varieties sawdust, related to compression pressure at 25 °C(w_r = 9%; L = 2 mm)

In Fig. 5, it can be seen comparison of briquettes densities between both fast-growing willow varieties. We can recognize the differences between final densities, which arising from a chemical composition (mainly lignin content, cellulose and hemicelluloses content) of raw materials [8]. Highest densities after stabilization time by densification of Sherwood variety sawdust were obtained. Briquette density is important from the point of view of material particle cohesion. During densification, lignin, which acts as a natural glue, is released from the biomass [10]. If the briquette is not created under optimally adjusted conditions, dilatation of the briquette can also significantly influence the absorption of moisture from its surroundings [8]. In practice, the stabilization time can be reduced by cooling.

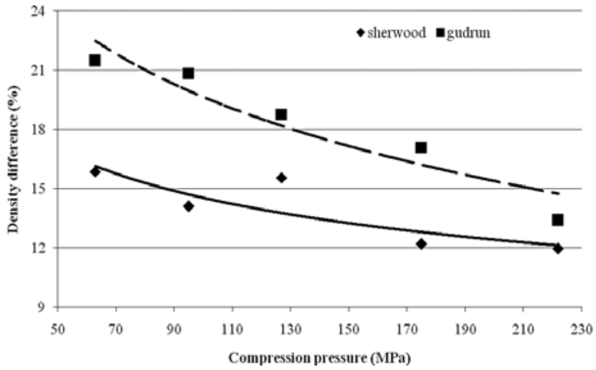

Fig. 6 Density difference of both varieties sawdust, dependent on compression pressure at 25 °C(w_r = 9%; L = 2 mm)

In Fig. 6, the interdependence between differing densities, both before and after stabilization, and compression pressure for both varieties, can be observed graphically. This dependence clearly evidences the impact of compression pressure on briquette dilatation and means that with increasing compression pressure briquette dilatation is reduced.

A very important part of the experimental research was also studying the impact of raw material particle size on briquette density. The influence of particle size on briquette density (Fig. 8) has shown that reducing the particle size positively influences the increase in briquette density. The figure shows that with increasing particle size, briquette density changes. Also it is important to note that for these results, the measurements were taken while compacting without any increase in temperature during the process, and at five levels of compression pressure.

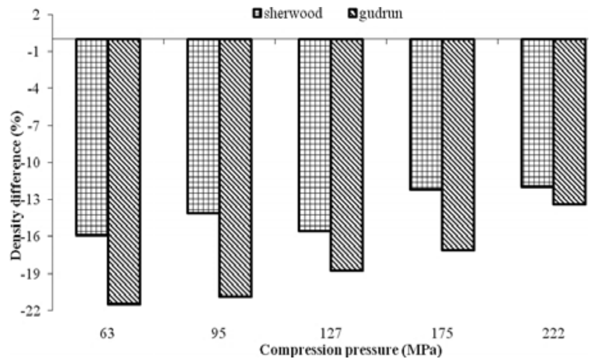

Fig. 7 Graphical density difference of both varieties sawdust, dependent on compression pressure at 25°C (w_r = 9%; L = 2 mm)

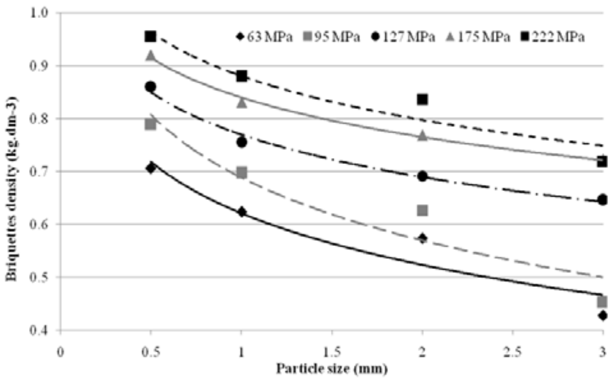

Fig. 8 Dependence of briquette density from Gudrun variety sawdust on particle size (w_r = 9%; T = 25°C)

In the case of particle size, the fast-growing willows sawdust compressibility factor is an important variable. The compressibility factor characterizes one of the basic properties of sawdust – compression. Sawdust compression is defined as the tendency of bulk sawdust to change volume under the effect of an external force [4]. This means that the magnitude of this compressibility or compression factor is affected by the pressure acting upon it [5]. The results of the experiments show (Fig. 9) that increasing the compression pressure for fast rowing willow sawdust of equal particle size increases the briquette density. In addition, it was proven that by increasing the particle size the briquette density decreases. These results imply that important variables affecting the compression factor are the pressure applied and the particle size. Similar results also at Sherwood variety sawdust were obtained; Figs. 10 and 11.

The interdependency of briquette density and compressive pressure during densification of different particle sizes can be seen in Fig. 9 for Gudrun variety sawdust and in Fig. 11 for Sherwood variety sawdust. It was proven that by reducing the particle size and increasing the compression pressure, briquette density also increases. This result demonstrating the interaction between particle size and compression pressure is extremely significant from the point of view of friction. These two variables influence the friction conditions in the pressing chamber, because the force needed to eject the briquette from the pressing chamber is changing. The process of densification of biomass is caused by the piston moving from one end of the chamber, and by the frictional resistance of the briquettes through the chamber. The increased friction, depending on the length of the chamber, causes a higher compression pressure on the raw material. The determination of the force needed to eject the briquette from the chamber depending on the material and technological variables chosen will be a secondary aim of this research. The interactions investigated influence the binding forces produced between the material particles. In Figs. 9 and 11 can be seen also results for unsorted (mix) raw material, which consists of single fractions according to particle size distribution (Fig. 1). In comparing with others particle sizes, densification of unsorted raw material wasn't the best from briquettes density point of view, but we obtained very nice results – "2nd place" in comparing with others particle sizes. We can imagine how important the treatment before densification is also.

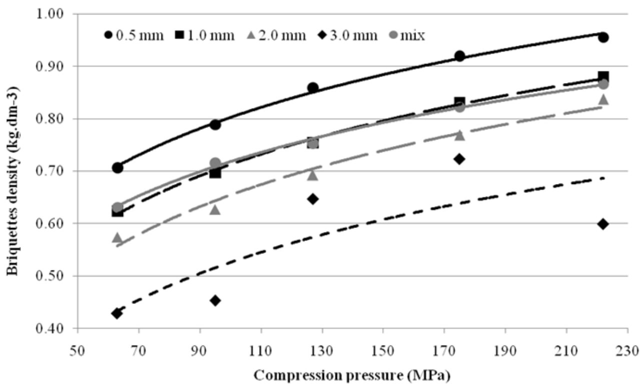

Fig. 9 Briquette density of Gudrun variety sawdust, related to compression pressure (w_r = 9%; T = 25 °C)

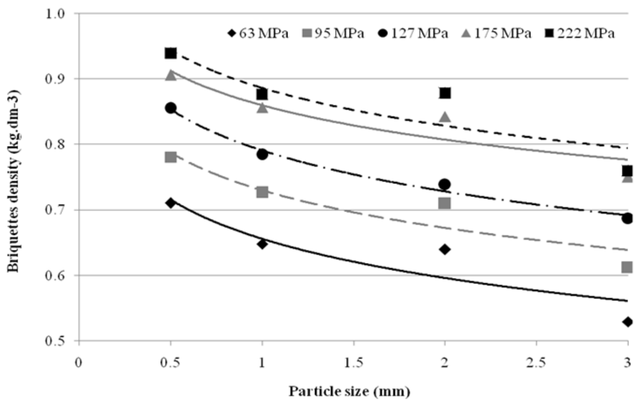

Fig. 10 Dependence of briquette density from Sherwood variety sawdust on particle size (w_r = 9%; T = 25°C)

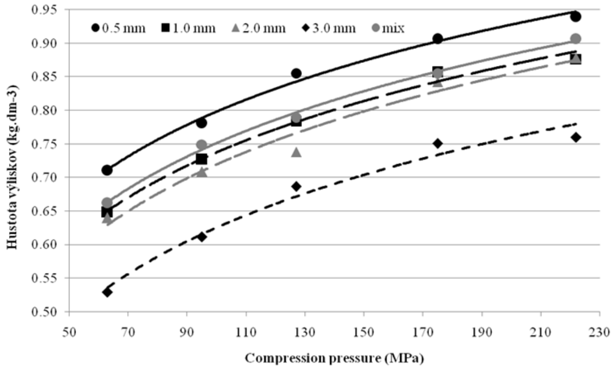

Fig. 11 Briquette density of Sherwood variety sawdust, related to compression pressure (w_r = 9%; T = 25°C)

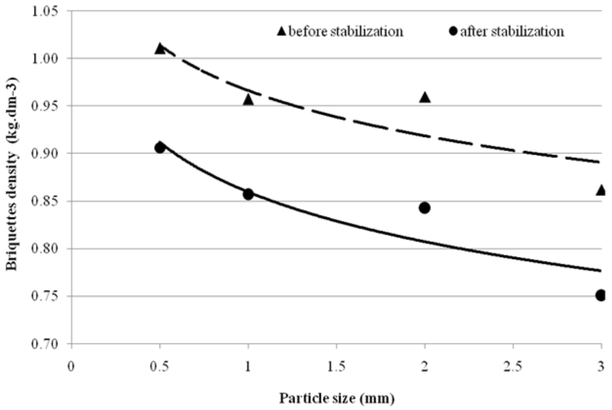

Fig. 12 Briquette density of Sherwood variety sawdust, related to particle size at 25°C (w_r = 9%; p = 175MPa)

The interdependence of briquettes density from particle size at one compression level can be seen in Fig. 12. This figure describes results related to Sherwood variety sawdust densification. As the particle size reduces so increases the briquette density. This interdependence also highlights the importance of briquette stabilization time. Than we can notice that also particle size has significant influence on briquettes dilatation. Very similar results with the same interdependence character by densification on all compression pressure levels were obtained.

Particle size and particles distribution in a volume influences the size of binding mechanisms between raw material particles. Briquette dilatation is reduced with decreasing of particle size and with increasing of compression pressure. This can be seen in Fig. 13, where the situation at Gudrun variety sawdust densification can be seen. The biggest size of dilatation (in a negative direction) was achieved during densification of ø 3.0 mm particle size. Despite the fact that briquette dilatation is reduced the size of dilatation is still high and the briquette density was decreased after dilation. A similar result at Sherwood variety sawdust densification was obtained. Moreover, the difference between two types of willow can be noticed.

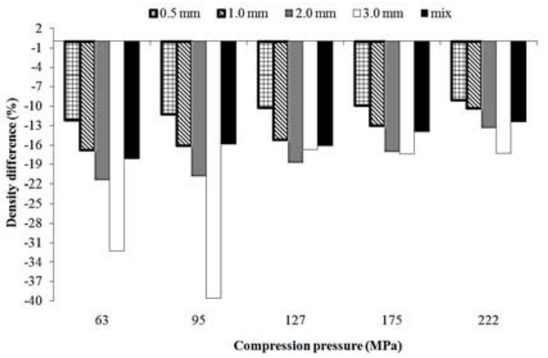

Fig. 13 Graphical density difference of Gudrun variety sawdust, dependent on compression pressure (w_r = 9%; T = 25°C)

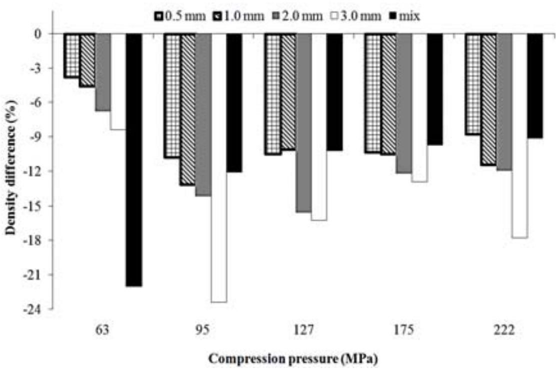

Fig. 14 Graphical density difference of Sherwood variety sawdust, dependent on compression pressure (w_r = 9%; T = 25°C)

V. CONCLUSIONS

Research into selected fast-growing willows (Sherwood and Gudrun Variety) densification for energy recovery were investigated in this research. The main conclusions that can be drawn from this study are as follows:

- All of the investigated variables have a significant effect on final briquette density. Increased compression pressure and reduced particle size, increase the density of briquettes from both varieties.
- The density value laid down in the technical standard (1.14 kg.dm^{-3}) [1], [14] cannot be achieved only by adjusting of investigated variables (compression pressure, particle size), but according to [10] we can expect that can be achieved under induced compression temperatures.
- Both of investigated variables (compression pressure, particle size) significantly affect briquettes dilatation during stabilization time. The only negative dilatation resulting to the decrease of briquettes density was achieved. According to [10] we can expect that the positive dilatation resulting to the increase of briquettes density can be achieved under induced compression temperatures.

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