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USE OF DISC SPRINGS IN A PELLET FUEL MACHINE

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Abstract. The use of biomass fuel pellets is becoming widespread as a renewable and environment-friendly energy. Pellet fuels are produced in various pellet machine types. Pellet machines encounter problems such as pressure irregularities and choke at the initial start for different kinds of biomass feedstock. In this study, disc springs are integrated into a vertical axis pellet machine for a pressure regulation and design optimization. Force-deformation and stress-deformation relations of disc springs are investigated using analytical and finite element methods. Pelletizing pressures were calculated based on disc spring force values using the Hertzian stress formula. Utilized disc springs ensured the pressure regulation, production efficiency increase and damage prevention on the die-roller mechanism.

Keywords: biomass pellet; pellet machine; disc spring; Almen–Laszlo; FEA; pelletizing pressure.

1. Introduction

Biomass is one of the alternative and renewable energy sources in today's world where fossil fuel sources rapidly decrease and environmental effects increase. Biomass is defined as a renewable energy source that consists of organic materials as wood, plant, manure and sewage sludge residues and has a capacity to be utilized as fuel [1]. Carbon dioxide emitted during biomass combustion is absorbed by green plants and is used in photosynthesis and its natural cycle is maintained [2]. Moreover, in contrast to fossil fuels such as coal, its nitrous and sulphur based gas emission is very low. Thus, biomass is considered as a valuable energy source today.

Biomass needs to be processed to be utilized as solid fuel. This process is listed in three main stages: dehumidification/humidification, grinding, and pressing. Pressing stage has a major importance, because it is the last step of the process, during which the final product is obtained. There are two types of common solid biomass pressing techniques - briquetting and pelletizing. For briquetting technique, fuel pieces produced in various dimensions and geometries, such as prismatic, cylindrical along a continuous line, spherical and pillow-shaped, are also bigger than pelletized end-products. In pelletizing technique, only compressed cylindrical pieces are produced in particular lengths, which is more common and efficient than briquetting. Examples of briquetting and pelletizing presses and end-products are shown in Figure 1.

Pelletizing machines work on the basis of pressing grinded biomass through a perforated die by the compression of rotating cylindrical rollers (commonly 2 or 3). Pellet presses are classified into two groups (ring die press, disc die pellet press) based on the type of the dies, as shown in Figure 2. Both types have cylindrical channels on dies and have rotating rollers on them. Also, it is possible to classify pellet presses

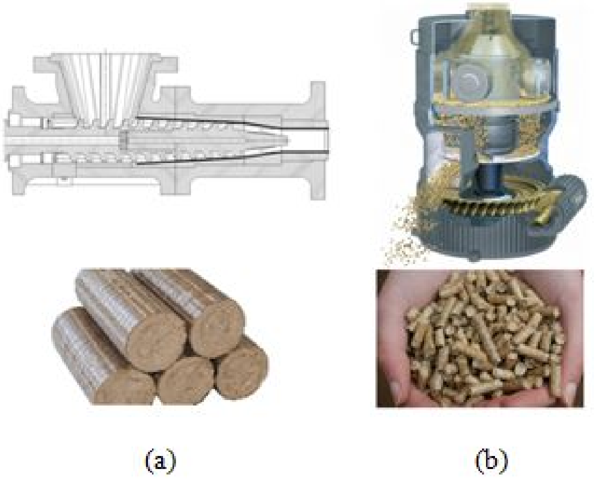


Figure 1. (a) Briquetting press [16] and briquettes. (b) Pelletizing press and pellets.

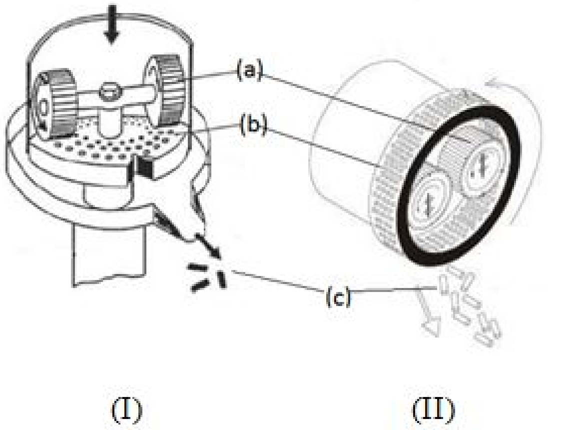


Figure 2. (I) Disc die (vertical axis) pellet press; (II) ring die (horizontal axis) pellet press; (a) rollers, (b) die, (c) Pellet outlet.

according to the die/roller motion. For the first type, the die rotates and rollers remain in a constant position and merely rotate on their axis. For the latter, the die remains in constant position and both of the rollers rotate on their axis and move around the die.

In pellet presses, various kinds of feedstock can be processed and pelletized. Each biomass kind has its own pelletizing parameters. These parameters are feedstock moisture, grinded particle size, pelletizing pressure and binder addition. Working with precise parameters is vital for obtaining durable and combustion efficient pellets. For instance, when the pressure and moisture of the feedstock is too low, biomass will not be able to be pelletized, or the produced pellets will be too loose and non-durable. There are many studies on pelletizing various biomass feedstocks. Some of the current studies are summarized below.

Serrano et al. [4], have examined the effects of the feedstock moisture ratio, particle size and pine sawdust addition on barley straw pellets. For dense barley straw pellets, optimum feedstock moisture rate is indicated in the range of 19–23 %, and within this interval, the obtained pellet durability was 95.5 %. Adding a pine sawdust at a rate of 2, 7 and 12 % improved the pellet durability up to 97–98 %. Their study has unveiled that addition of a woody biomass to a herbaceous biomass feedstock can improve the pellet quality.

Gilbert et al. [5] have studied the effects of pelletizing pressure and temperature on the pellet density, mechanical strength and durability using a switchgrass biomass. The effects of temperature on the pellet density were observed only between 14 °C and 50 °C. Increasing pelletizing pressure from 55 to 552 bar enhanced the pellet density and durability.

Mani et al. [6] have observed the effects of the particle size reduction, compressive force and moisture ratio on pelletization of wheat straw, barley straw, corn stover and switchgrass at 100 °C using a laboratory scale pellet press. Except for wheat straw, with a reducing particle size, denser pellets were obtained. However, the moisture ratio and compressive force are more effective on pellet density. Increasing the moisture ratio from 12 to 15 % and increase of the compressive force have resulted in denser pellets.

Relova et al. [7] have revealed that the pelletizing pressure is the most important factor affecting the pellets' drop resistance by using statistical data from 32 kinds of pine sawdust pelletization. Moisture ratio is less effective than the pelletizing pressure and the particle size is less effective than the moisture ratio on determining the pellets' drop resistance.

Larsson et al. [8] have examined the effects of the moisture ratio, bulk density after pre-compaction, steam addition and die temperature on pelletizing of reed canarygrass. The factor that has the biggest impact on the durability and density of pellets was found out to be the moisture ratio.

Using binders in pelletizing process provides a durability and resistance to outer factors. Various organic and inorganic binders are preferred in pelletizing processes. Binders are used necessarily, or sometimes optionally, to maintain a superior pellet quality. Kong et al. [9] have pelletized a spruce sawdust under 6 MPa pressure and 25 °C using binders of lignin, $Ca(OH)_2$, NaOH, $CaCl_2$, and CaO. Among these binders, combination of 5 % $Ca(OH)_2$ + 10 % Lignin by mass increased the pellets' water resistance. Furthermore, catalysis of hydroxide, contained within $Ca(OH)_2$, provided polymer chain growth into three-dimensional cross-linking that strengthened the bonds in pellet microstructure.

Puig–Arnavat et al. [10] have pelletized six different biomasses using a single pellet press. For all types of biomass, the optimum moisture ratio they determined for pelletizing is 10 %. Higher moisture ratios have deteriorated pellet quality. They observed that the friction in the die increases when the die temperature increases from the room temperature to 60–90 °C. In higher temperatures, friction decreases.

Biomass is subjected to a pre-treatment before pelletizing, which, in some studies, consists of heating up to 200–300 °C in inert gas atmosphere. Thus, low moisture, volatile-free and high energy density biomass is obtained. Also pre-treated biomass has a better grinding performance [12, 13]. Larsson et al. [14] have pre-heated spruce sawdust to high temperatures (270–300 °C) and pelletized it in a small scale pellet press. Produced pellets had comparable bulk densities (630–710 kg/m^3), but lower pellet durability (80–90 %) in comparison to conventional pellets. Also, the energy consumption for pelletizing was 100 % higher. It was observed that pellet production speed is positively correlated with the die temperature. The feedstock moisture rate was not significantly effective on pellet quality and the production speed; however, adding water to the feedstock worsened the flow properties and did not provide a benefit. The same effect was also observed in coal powder by Abou–Chakra et al. [15]. Water addition to coal powder decreases flowability while free water particles increases this impact.

Different biomass kinds have their own pelletizing parameters due to their characteristic bulk/particle density and microstructure. For instance, the woody biomass has a higher content of the lignin component than the herbaceous biomass. Lignin is a vital constituent providing inner pellet bonding. The biomass feedstock, which is pressed in die channel layer by layer, has a frictional movement relation with the wall of the die channel. Depending on temperature, every kind of biomass forms its own pelletizing characteristic in a frictional material-machine relation. This is shown in Figure 3, the effective forces F_1, F_2, and F_3 on the biomass under pelletizing pressure in a cylindrical channel.

Kováčová et al. [16] have derived pressure relation equations of a pressed biomass through a cylindrical

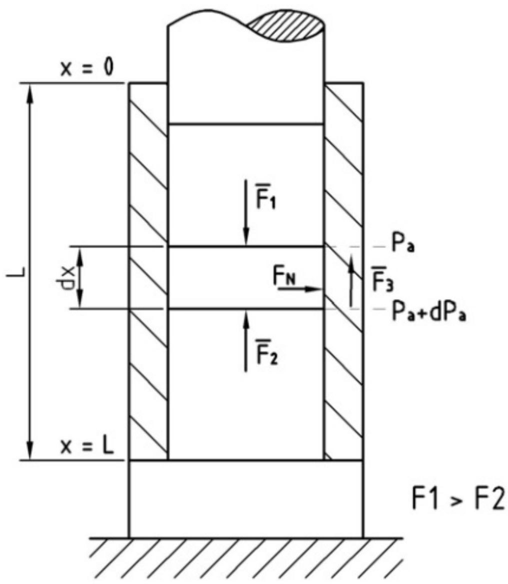


Figure 3. Effective forces on biomass in a die channel [16].

die channel based on the force equation in Figure 3.

$$P_{\mathrm{a}}(L) = P_{\mathrm{ap}}\mathrm{e}^{-\frac{4\mu\lambda}{d}L}, \tag{1}$$

$$P_{\mathrm{ap}}(L) = P_{\mathrm{a}}\mathrm{e}^{+\frac{4\mu\lambda}{d}L}. \tag{2}$$

In equations (1) and (2), symbols are defined as μ — friction coefficient between the biomass and die, λ — radial/axial pressure ratio on biomass, d — hole diameter, L — die length, P_{a} — outlet pressure, P_{ap} — internal pressure. In the equations, d/L parameter, which is dependent on die geometry, stands out. Choosing a convenient die according to the biomass type is important.

Friction force in die channel is a temperature dependent parameter, which is determined by Stelte et al. [17]. They have observed that when the temperature increases the pelletizing pressure drops. In high temperatures, they identified hydrophobic extractives on the pellet surface by monitoring the infrared spectrum. These extractives act as lubricants between the biomass and die and reduce the needed pelletizing pressure.

One of the common faced problems in pellet production is the choking of the machine. This condition is instructed in many pellet machine manufacturers' handbooks. For instance, an animal feed pellet machine manufacturer company gives a rule of thumb about the moisture ratio being 18 % and this is accepted as a limit value for the choking of the machine. Moisture ratios greater than this value cause the machine to choke. Particularly, moisture addition to the herbaceous biomass increases pelletizing temperature to 20 °C per 1 % increase [18]. Naturally high moisture containing biomass types may not reach required pelletizing temperature in pellet press due to the effect of heat absorption of high moisture.

In pellet fuel literature, there are numerous studies conducted about the pelletizing pressure, temperature, moisture ratio, feedstock species, particle size, heat values and environmental effects. One of the most important problems for commercial presses used in the pellet fuel production is the pressure irregularity and consequent choke. In this study, a pressure regulation of vertical axis pellet machines was performed by utilizing disc springs inside them. An improved design of pellet fuel machines for an effective and quality pellet production was established.

2. Material and method

In this study, a pellet press driven by a 35 kW power and with a capacity of 400 kg/h production rate was employed. Pressure regulation of the pellet press was maintained by integrating disc springs into the fixed die- rotating rollers system. Disc springs are able to bare high loads with small deformations. Their simple and modular geometry promotes their use in many areas where a damping of high forces is necessary. A novel usage of this element was unveiled in this study.

Optimum conditions for pellet production are obtained after while after the first start, especially when the die and related components reach a particular temperature. This is because; the friction between biomass and die lowers and enters a regular regime at high temperatures. Furthermore, components in internal structure of biomass activate with high temperatures for bonding mechanism. The moisture extracted from biomass at high temperatures reduces the friction between the biomass and die [17]. Also, lignin, a main constituent of woody/herbaceous biomass, gains flowability above the glass-transition temperature, thus maintains internal bonds for mechanically durable pellets [5]. It is known that lignin polymer's glass-transition temperature is 65–75 °C at 8 % moisture ratio. After this temperature, lignin in biomass softens and its binding effect increases [19].

Pellet presses are exposed to an overloading at initial start of the system. This may cause choking of the system at the beginning of the process or a high


(a) (b)

Figure 4. (a) Broken roller teeth. (b) Deformed washers that got into the press.

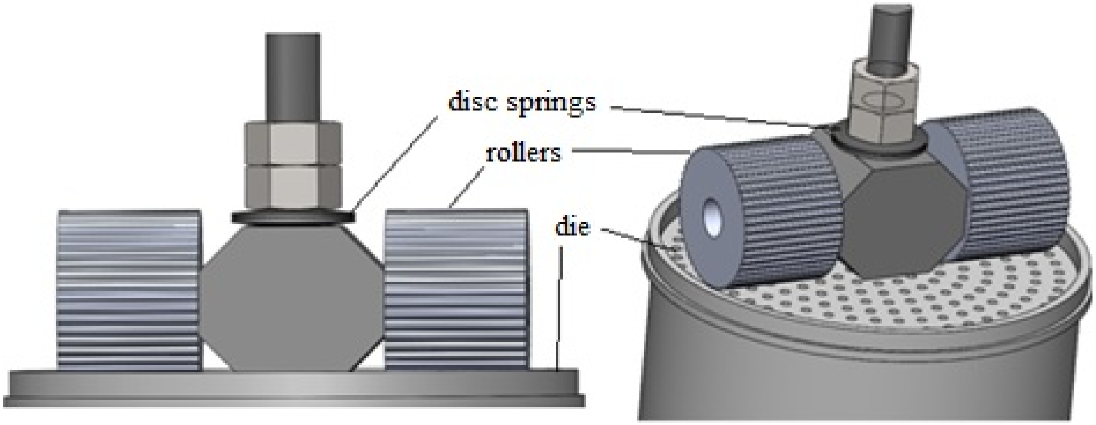


Figure 5. Integrating disc springs to pellet press.

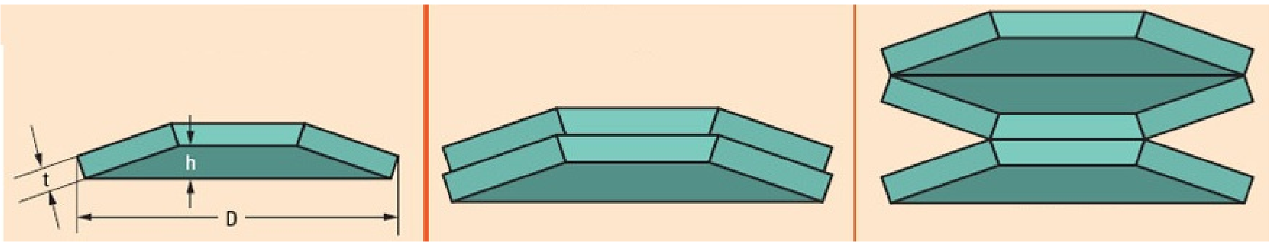


Figure 6. Disc springs: (a) single, (b) parallel, (c) in series.

consumption of energy. The biomass type is an important factor in determining the system's operating pressure. For high-hardness valued biomass, friction between the feedstock and die wall is high, thus the system overloads and may choke at first.

The biomass may contain foreign matters that may escape when collected from its natural environment. Impurities like small stones and metal pieces having high-hardness may damage the system by getting stuck between the roller and die (see Figure 4). In this case, disc springs are deformed and system protects itself from irreversible damage.

In our study, disc springs are utilized in pellet presses as shown in Figure 5. This provides rollers to press on the die. Disc springs are positioned under the tightening nuts and pre-deformed to maintain a constant contact and pre-load between the roller and die. In conventional pellet presses, the gap between the roller and die is set to 0.5–1 mm as a rule of thumb. This gap partially protects the system from unexpected pressure rises. Disc springs constantly push down rollers on the die; however, in unexpected pressure rises (stone/metal gets into the machine, feedstock change, system choke) they are deformed and prevent the system from damage. In the case of impurities getting into the machine, system is to be stopped and cleaned so that the spring flexed system is not damaged.

The pelletizing pressure required for different biomass species is automatically regulated by flexion of disc springs. In this particular study, pine tree residues (branch, needle, cone, bark etc.) that require high pelletizing pressure were pelletized.

2.1. Disc spring selection and calculations

Disc springs' outer diameters may vary between 8–600 mm according to the DIN 2093 standard. Custom disc springs can be manufactured in desired dimensions when needed.

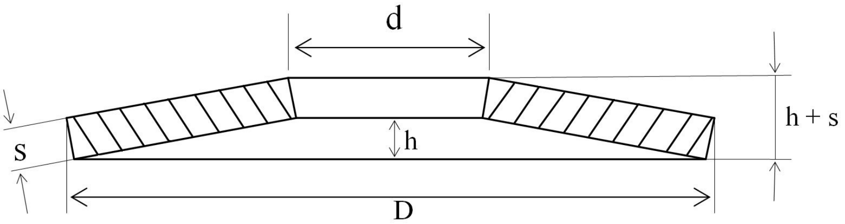
In this study, in accordance with press dimensions, a standard sized disc spring with 125 mm outer diameter and 71 mm inner diameter is used. In Table 1, all parameters of the disc spring are demonstrated. Depending on the operating conditions, disc springs may be used as a single piece, combined in parallel or in series (see Figure 6). When stacked in series, the total deformation of springs increase and the load carrying capacity remains constant. Accordingly, the deformation of springs remains constant, load carrying capacity is positively proportional with the spring number.

The first and still-used calculation method for disc springs was developed in 1936 by Almen and Laszlo [20]. Including DIN 2093 standard, among many manufacturers and users, the Almen–Laszlo (A-L) algorithm for disc springs is widely used. The force-deformation relation for a disc spring according to A-L algorithm is formulated as

$$F = \frac{4E}{1-\nu^2}\frac{\delta}{mD^2}\big((h-\delta)(h-\delta/2)s + s^3\big). \tag{3}$$

When the disc spring becomes flat, the needed force is described as a critical force

$$F_{\mathrm{cr}} = \frac{4E}{1-\nu^2}\frac{hs^3}{mD^2}. \tag{4}$$



Outer diamter D [mm]	**Inner diameter** d [mm]	**Cone height** h [mm]	**Thickness** s [mm]	**Total height** $h+s$ [mm]	D/d	h/s
125	71	2.9	8	10.9	1.76	0.3625

Table 1. Dimensions of used disc spring and related parameters.

Deformation		F [kN]			$\sigma_{\text{comp.}}$ [MPa]		
[mm]		**A-L**	**FEA**	**Dev.**	**A-L**	**FEA**	**Dev.**
$0.25h$	0.725	74.16	85.74	13.5 %	881.78	977.04	9.7 %
$0.50h$	1.45	143.28	166.93	14.1 %	1707.31	1942.5	12.1 %
$0.75h$	2.175	209.03	264.04	20.8 %	2476.60	2976	16.8 %
h	2.9	273.1	354.06	22.8 %	3189.62	3990	20 %

Table 2. A-L method and FEA results for parallel stacked two disc springs.

The compression stress at the inner edge of the spring is

$$\sigma_{\mathrm{c}} = \frac{4E}{1-\nu^2}\frac{\delta}{mD^2}\big(m_1(h-\delta/2)+m_2 s\big). \tag{5}$$

Tension stress at the outer edge of spring is

$$\sigma_{\mathrm{t}} = \frac{4E}{1-\nu^2}\frac{hs^3}{mD^2}\big(m_1(h-\delta/2)-m_2 s\big), \tag{6}$$

where

$$m = \frac{6}{\pi \ln D/d}\Big(\frac{D/d-1}{D/d}\Big)^2, \tag{7}$$

$$m_1 = \frac{6}{\pi \ln D/d}\Big(\frac{D/d-1}{\ln D/d}\Big), \tag{8}$$

$$m_2 = \frac{6}{\pi \ln D/d}\Big(\frac{D/d-1}{2}\Big), \tag{9}$$

Calculations based on given formulae are compared with Finite Element Analysis (FEA), results of disc springs will be given in tables in the next chapter. Calculations were made for deformations of 0.25, 0.5, 0.75, and 1 fold of cone heights and presented in Table 2. Practically, the disc spring deformation should not exceed 0.75 of cone height. In our study, it is assumed that this value will not be exceeded. Parallel-stacked two disc springs were used to maintain sufficient pelletizing pressure on the die. Calculations and analysis were made based on parallel disc springs.

FEA analysis was made on the scanned CAD data of disc springs. Material is modelled as a spring steel with 206 GPa Young's Modulus and 0.3 poisson ratio. Meshing was made using 20-node hexahedrons, constituent of 5695 nodes and 938 elements. Two disc springs stacked in parallel, defining contact region between one spring's convex surface and other's concave surface. Friction coefficient (μ) is defined as 0.4 between spring surfaces [21]. As boundary conditions, displacement of the bottom circle of the lower spring is restricted in the vertical axis and set free in the horizontal axis. Deformations of 0.25, 0.5, 0.75, and 1 fold of cone height is given at the top circle of the upper disc. Force reactions at the top circle and maximum equivalent von-Mises stress values are analysed and shown in Table 2.

3. Results and discussion

The analytical calculation (A-L method), FEA results and comparison of them are given in Table 2. Difference between the A-L method and FEA force values increases with the deformation ratio. Maximum stress is formed on the inner edge of the disc spring's top surface as seen in Figure 7. Likewise, for force values and inner edge stress values the difference increases with deformation. Based on these values, it can be concluded that the A-L method is more effective on small deformations. This arose from neglecting radial stresses while only considering tangential stresses when forming the A-L equations. With increasing deformation, radial stress on disc spring becomes more effective. In high deformations the A-L method gives more erroneous results.

Friction forces occur in contact areas of the disc springs when used in parallel. Thus, in frictional conditions, springs bear more loads than in the frictionless conditions for the same deformation value.

In Table 3, both conditions are compared in force and stress values. Friction coefficient (μ) is defined as 0.4 by Ozaki et al. [21] in a similar study. In force

Deformation [mm]		F [kN]			$\sigma_{\text{comp.}}$ [MPa]		
		Frictionless	**Frictional**	**Dev.**	**Frictionless**	**Frictional**	**Dev.**
$0.25h$	0.725	81	85.74	5.8 %	926.89	977.04	5.4 %
$0.50h$	1.45	162	166.93	3 %	1853.8	1942.5	4.8 %
$0.75h$	2.175	243	264.04	8.6 %	2780.7	2976	7 %
h	2.9	324	354.06	9.3 %	3707.6	3990	7.6 %

TABLE 3. Frictional/frictionless FEA results for parallel stacked two disc springs.

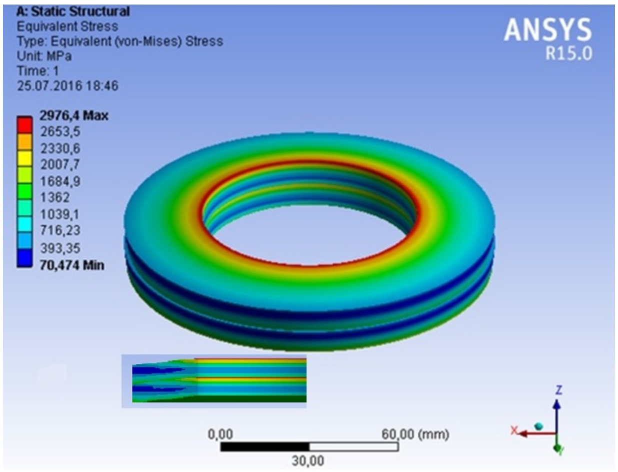


FIGURE 7. FEA stress distribution on parallel stacked two disc springs (for $0.75h$ deformation).

values, there is a deviation between 3–9 %, in stress values, the deviation is 5–8 %.

3.1. PELLETIZING PRESSURE CALCULATION VIA HERTZIAN STRESS

Pressures occurring when a cylindrical surface contacts a planar surface can be calculated with Hertzian stress calculations. As seen in Figure 8, a contacting cylinder-plane model is considered for the roller-die relation. Hertzian stress calculation is made based on material properties and dimensions of contacting surfaces and the applied force.

Hertzian stress is calculated by the following formula [22]:

$$b = \sqrt{\frac{2F}{\pi l} \frac{(1 - \nu_1^2/E_1) + (1 - \nu_2^2/E_2)}{1/d_1 + 1/d_2}}, \tag{10}$$

$$P_{\max} = \frac{2F}{\pi b l}. \tag{11}$$

Material properties are: $E_1 = E_2 = 210\,\text{GPa}$, $\nu_1 = \nu_2 = 0.3$ and the roller dimensions are $d_1 = 145\,\text{mm}$, $l = 110\,\text{mm}$. Equation (11) results

$$P_{\max} = 2.146\sqrt{F}. \tag{12}$$

Disc springs work in the interval of $0.25h$–$0.75h$ deformation. There are two rollers employed in the pelletizing system. Thus, the force applied by disc springs is divided in two. Hertzian stresses given in deformation intervals are calculated as

$$P_{\max} = 444.33\,\text{MPa} \quad \text{for } 0.25h, \tag{13}$$

$$P_{\max} = 779.74\,\text{MPa} \quad \text{for } 0.75h. \tag{14}$$

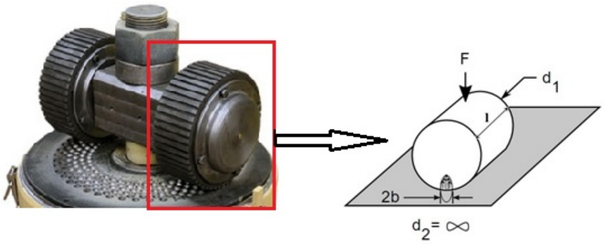


FIGURE 8. Hertzian stress between die and roller and defining parameters: b — contact surface half-width, d_1 — cylinder diameter, l — cylinder length, F — applied force.

The calculated pressure is the maximum value of stress formed in between the die and roller. The pelletizing pressure of biomass may be considered as a half of this value as a practical and easy-applicable approach. Thus, the pelletizing pressure is between 220–390 MPa in the operating range of disc springs.

4. CONCLUSION

Although there are various studies about pellet production parameters (biomass kind, temperature, moisture) and the final product quality, there is no significant study about improvement of pellet mills, prevention of damage and production process.

Regarding pellet presses, mostly encountered problems are choking, pressure irregularity and determining optimum gap between the die and roller during the production process. In this study, these problems are aimed to be solved by integrating disc springs into presses. Disc springs maintain the required compression for rollers and also deflect adequately to protect the system from undesired damage by impurities (stone and metal particles etc.).

Also, the pelletizing pressure can be estimated by hertzian pressure occurring between the roller and die, which is calculated through the disc spring force.

A pellet press of 35 kW having a capacity of 400 kg/h production was used in this study. Two disc springs with 125 mm outer diameter, 71 mm inner diameter, 8 mm in thickness and 2.9 mm cone height were stacked in parallel and integrated in the pelletizing system. A commonly used analytical A-L method and the FEA were used to analyse disc springs' force/stress-deformation relations. With increasing deformation, differences between the A-L method and FEA results increase. Radial stresses, which are neglected in the A-L method, become more effective on disc springs with increasing deformation. Thus, the A-L method gives more accurate results for small deformations.

Disc springs are preloaded by tightening nuts, initially deforming at 0.25 of its cone height. In operating conditions, the occurring maximum deformation was assumed as 0.75 of its cone height. For 0.25 deformation 75 kN (A-L) and 85 kN (FEA) force values were obtained. For 0.75 deformation 209 kN (A-L) and 264 kN (FEA) force values were obtained. Hertzian stress was calculated under roller cylinders based on the FEA force values. While pelletizing operation comes to approximately 444–780 MPa, maximum pressure occurs under each roller. For the mean pelletizing pressure, half of this value (222–390 MPa) may be considered as a practical and easy-calculated value.

Maximum stress is formed on the inner edge of the top surface of disc spring during compression. Based on the FEA, stresses of 977.04 MPa and 2976 MPa occurred for the $0.25h$ and $0.75h$ deformations respectively.

When stacked in parallel, friction forces occur between the springs. These forces help damping the vibrations during the machine operation. In frictional conditions, springs' load should be greater than in frictionless conditions to reach same deformation value.

A novel utilization of disc springs was realized in this study. In this way, common problems of pellet presses, such as choke, roller damage and pressure regulation, were eliminated.

List of symbols

F	Force
P	Pressure
$\sigma_{\text{comp.}}$	Compression stress
E	Young's modulus
ν	Poisson ratio
δ	Deformation
D	Outer diameter of disc spring
d	Inner diameter of disc spring
s	Thickness
m	Auxiliary coefficient

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