Development of the compaction machine for the production of new shapes of pressed biofuels

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Abstract. Briquettes and especially pellets became the fuel of the 21st century. These are pressed biofuels made from the biomass which have the required heat, shape, size, density and mechanical properties. Today, these pressed biofuels are made in the form of a block, cylinder, n-angle octagonal, either without or with the holes. Several analyses confirm that neither a block, nor the cylinder is the optimal shape for the production of pressed biofuels, both in terms of the production, storage, automated transport in the combustion process and the optimum combustion process. For this reason, we began to analyse different shape, size, density and mechanical properties of briquettes and pellets. In the first part of this article, the biofuel is described from these points of view. The result of this analysis is the new optimized spheroid shape of the pressed biofuels. The goal of the second part of the article is the construction design of a new compacting machine for manufacturing of the optimized shape of the compacted piece. The task is demanding due to the fact that in comparison to the production of cylindrical or square-shaped compacted pieces, the manufacturing of ‘quasi-spherical’ compacted pieces is discontinuous. Furthermore, unlike the standard types of compaction presses which compact the material between the two cylinders, it is necessary to hold the compacted piece for certain time under high pressure and at the high temperature. In this way, the lignin contained in compacted raw material becomes plastic and no further binding material needs to be added. The kinematics of a new compactor was therefore divided into two stages- ‘the stage of compacting’ and ‘the stage of load bearing capacity. This article describes an innovative and patent protected principle of compactor construction. The prototype of a designed machine has already been produced in our department. The first test results of this machine production as described in the conclusion of the paper confirm that kinematics and compactor construction were both correct.

1. Introduction
Prehistoric man uses nature as a source of raw materials and energy. Firstly this was wood, then crude oil, natural gas and other materials that mankind was, over a period of time, capable of processing. Compacting technologies have been in operation for over 150 years. The first patent for the production of wood briquettes comes from the year 1864, [1]. Wood briquettes have been used in the USA for 75 years. One of the best fuel logs (briquettes) was manufactured and sold as the ‘pres-to-log’ in 1933. In recent times there has occurred a worldwide ‘boom’ in using refined material, mostly in the form of pellets. The main advantage of pellets is the possibility of fully-automated delivery in the process of combustion, along with very precise regulation of the combustion process, even for low-performance furnaces. Until the present, pellets throughout the world are produced just in a cylindrical shape. But often the question is asked: Is the cylindrical pellet, with its dimensions, optimal from the standpoint of size and shape? The goal of the presented paper is to search out an answer to this question.
2. Types of refined bio-fuels
Among the best-known technologies of compaction, we class briquetting, pelleting and compaction. The resultant products of these technologies are briquettes, pellets and granules (figure 1).

Figure 1. Technologies of compaction.

2.1 Briquettes
Briquettes in the past were the most widespread type of. A great advantage of these refined fuels, in comparison with classic fuels, is that according to need we can in their production change all three decisive parameters: shape, size and density and thereby optimize expenses for their production or requirements for shipping or storage, but also the requirement from the standpoint of their optimal energy recovery.

On the other hand, however the production of a briquette press falls dramatically (up to 30%) as a result of the openings.

Briquettes are manufactured on mechanical, hydraulic or screw briquette presses. The highest quality and strength of briquettes is achieved on screw briquette presses. But with this method there is greater wear on the working equipment – the screw press. The molds produced are generally in the form of cylinders, blocks or n-angles. In conformity with DIN 51731 the characteristic size is greater than 30 millimeters.

Briquettes are suitable for kitchen stoves, brick ovens, level and central heating and for fireplaces. Burning time of briquettes is from 30 – 60 minutes, depending on their shape and size. Larger pressed fuels catch fire less easily, burn worse, and their combustion tends to be less ideal. Briquettes with larger diameters are also made with holes (figure 2).

Figure 2. Actual shapes of briquettes

2.2 Pellets
The percent share of pellets on the refined fuels market is increasing dramatically. Currently pellets are made exclusively in a cylindrical shape, with diameters of 6-25 millimetres and lengths The percentage of pellets on the refined fuel market is increasing dramatically. Currently, pellets are made in a
cylindrical shape, with diameters of 6-25 millimeters and lengths of pellets equals to two to five times the diameter (figure 3).

![Figure 3. Pellets](image)

Greater sized pellets are used only for combustion in large furnaces and cement-making. The greatest advantage of pellets is that, due to the size and homogeneity of the fuel, a fully-automated combustion process is possible. The disadvantages of pellets are the high ratio of the fuel’s surface to its volume. With this is related the burning of volatile materials even at low temperatures (above 200ºC), the very rapid burning process (10 – 20 minutes), and also high wear on the functioning parts (die, roller ...) of the pelleting mills. Another disadvantage is the high demand associated with the production technology. The material must be of high quality, homogeneous, able to disintegrate into very small particles, and to have optimal humidity. The high investment costs associated with the manufacture of the fuel and with its usage are also disadvantageous. The input power for a unit of volume output “\(P_{j,w}\)[W/(kg h\(^{-1}\)] is lower for pellet presses than for briquettes. This has to do with the fact that the ratio of the area of the press openings to the total area of the die on which the press pressure acts is less than one. Only in special furnaces is it energy-effective to recover pellets. The very high demands on investments also apply to the user of the fuel. The construction of an entire heating system, including the storehouse, the feeders, the furnace, and the monitoring and management system, is a great barrier to a more rapid increase in users of this fuel in Slovakia.

2.3 Granules
Compacting is the technology for compressing waste whose tractability and humidity fit the parameters required for pressing between two counter-revolving smooth or grooved rollers. The results of compacting are granules or agglomerates of a slab shape which, after slicing into granules, are usable in further processing, primarily in the chemical and metallurgy industries. Granules are produced in various sizes and shapes, from cylindrical to spherical. Granules have a very convenient shape as regards the requirements for automated feeding. The ratio of the surface to volume is also advantageous with respect to the combustion process and wear on functioning parts.

The classic compacting technology is not very adapted to the compression of biomass. This is because the fundamental binder in biomass is lignin. In order for lignin to work as a binder, two basic conditions must be met. At the moment of compression, the lignin must be in a plastic state (temperature around 100 ºC) and at the same time the pressed fuel must be subjected to very high pressure for a determined period of time. In compacting, the main problem is to ensure the required cooling of the molding under great pressure. So to achieve the required strength of the pressed materials, a binder is added.
3. Optimization of shape, size and density of pressed fuels

The quality and success of using refined biofuel (figure 5) depends in particular on:

1) the material properties of the compacted material (kind of material, size of the compacted particles, humidity, ...),
2) compaction technology used, (size and shape of the pressed fuels, working pressure, speed of compaction, temperature, endurance, energy consumption, wear on functioning parts, ...),
3) combustion conditions (sort, type and size of the combustion equipment, ...),
4) requirements for feeding in the combustion process (size, shape, ...),
5) requirements for storage (minimization of volume and space requirements).

Requirements for dimensional and mechanical properties, chemical composition and emissions are defined by DIN 51731, or Ö-NORM 7135 standards. Another mark of alternative pressed fuels is the possibility to influence their:

1) shape (block, ball, n-angle, cylinder, with or without openings),
2) size (from 6 millimeters to several dozen centimeters),
3) density (of the pressed fuel itself minimally > 1 kg dm\(^{-3}\), pouring density),
4) humidity (maximum 15%),
strength (abrasion < 3%, mechanical strength under bending and pressure).
3.1 Surface to volume ratio optimization

It is interesting to compare the ratio of the surface area to the volume \( S/V \) of the pressed fuel. This is the function of the shape and size of the pressed fuel. With a higher ratio \( S/V \) (small pressed fuels) it is possible to more accurately manage the process of combustion, but the fuel burns more rapidly (10 – 20 min.), which is influenced, in addition to the large surface, by the combustion of the volatile materials at lower temperatures (over 200 ºC). But disadvantages include the higher interface areas between the processed raw material and the pressing machines, therefore more rapid wear on the functioning areas (die, roller, piston,...) of the compaction machine. Other disadvantages are the increased requirements on the quality and uniformity of the processed particle of the processed raw material, and requirements related to the production technology. The material must be homogenous, disintegrated into very small particles, must have optimal humidity, and the optimal temperature must be assured during compacting. Unsuitable raw material or incorrect parameters during compaction will cause stoppage and complicated cleaning of the clogged die. High investment costs associated with the production of the fuel and with its usage are also problematic. The high demands on investments for the user of the fuel are too not negligible.

The cylinder is the most frequently produced shape of pressed fuels. Accordingly, we will compare how the ratio of the surface \( S_c \) to the volume \( V_c \) changes with a change of the diameter \( d \) or the height \( h \). The volume of the cylinder is defined by the relation

\[
V_c = \pi r^2 h \quad (m^3)
\]

and the roller surface

\[
S_c = 2\pi r^2 + 2\pi rh \quad (m^2)
\]

then the ratio of the surface to the volume is defined by the relation

\[
\frac{S_c}{V_c} = \frac{2(r+h)}{rh} \quad (m^{-1})
\]

The first example illustrates how the \( S_c/V_c \) ratio will change with a constant height \( h=50 \) mm and with a change of the diameter \( d \) in the range 10-25 millimeters. The result of the analysis is clear from figure 6. From the graph it is clear that with an increase of the diameter the surface to volume ratio will change by 55% from 440 to 200 (m\(^{-1}\)).

Figure 6. Change in \( S_c/V_c \) in dependence on change of the diameter “d” at constant height “h”

With the second example, with an increase of the diameter we proportionally also increased the height of the pressed fuel “h”, in the ratio “h=3d” (figure 7). Pellets with a diameter \( d=10 \) mm and height \( h=30 \) mm correspond to the smallest diameter, and on the other hand the largest diameter briquettes with a diameter \( d=100 \) mm and height \( h=300 \) mm correspond to the largest diameter. From the figure it
is clear that with an increase in the diameter “d” and the height “h” the surface to height ratio fell by one order.

3.2 Density optimization
In conformity with international standards, the density of refined pressed fuels must be in the range of 1÷1.4 kg dm⁻³. So it is generally valid that with an increase in the density of a pressed fuel the quality increases from the standpoint of resistance to interruption during transport, storage and in the automated feeding in the process of combustion. For the stated reason refined fuels must also fulfill requirements for abrasion and mechanical strength. Resistance against atmospheric moisture increases proportionally with increasing density of the pressed fuels. It is for this reason that with higher pressing power the compacted material overheats, the lignin melts down uniformly in the inner structure of the pressed fuel, and a large part of it flows to the surface which as a result becomes shiny and without pores. This causes an increase of the mechanical strength of the pressed fuel and at the same time prevents a leaking of humidity into the content of the compacted pressed fuel. With a negation of high density (>1.2 kg/dm³) there occurs higher strain and wear on the compaction machine. Very high density can have an unfavorable influence on the burning process – imperfect combustion.

3.3. Shape optimization
From the standpoint of pressed fuel shape, the ball is optimal (figure 9a). The monitored ratio of pressed fuel surface to the unit volume is minimal. From this it follows a low wearing of the functional areas and a favorable burning method. The ball also has an optimal shape as regards automated transport of the pressed fuels. The problem however is production of such a pressed fuel. In classic compaction machines, maintaining the shape of the pressed fuel when cooling under pressure.

The changing ratio of the surface area to volume is not merely dependent on the change in the size of the particular geometric figure but also on the change if its shape. Let us compare, for instance, changes in the surface area of a cylinder and sphere in dependence on the change of their sizes. The surface area of a sphere is calculated according to the formula:

$$S_s = 4\pi r^2$$

(4)
and the volume according to

$$V_s = \frac{4}{3}\pi r^3$$  \hspace{1cm} (5)

The ratio of the surface and volume may be calculated as follows:

$$\frac{S_s}{V_s} = \frac{3}{r}$$  \hspace{1cm} (6)

In order to compare the ratio of changing surfaces of monitored figures, let us assume that the volumes are of the same magnitude, i.e.

$$V_c = V_s$$  \hspace{1cm} (7)

Subsequently, the mutual relation between the ratios of surface areas may be calculated as

$$S_s = S_c \frac{3h}{2(r+h)}$$  \hspace{1cm} (8)

The diagram in figure 8 illustrates the change in their respective, mutual sizes. The basis for the comparison is the ratio of the diameter 'r' to the height 'h'.

Figure 8. Relation between the ratios of surface sphere and cylinder “$S_s/S_c$”

Assuming that “$h < 2r$”, the surface area of the sphere ‘$S_s$’ must be lower than that of the cylinder ‘$S_c$’. The equilibrium of the surfaces occurs at “$h=2r$”. Upon further increase of “$h$”, the surface area of the sphere ‘$S_s$’ will be higher than the surface of the cylinder ‘$S_c$’.

However, the particular surface areas of machine presses in the process of sphere manufacturing are higher than those created in the pressing of cylinders with higher length, ($h>2r$).

The intersection of two cylinders has a somewhat greater ration of pressed fuel surface to volume (figure 9b). The pressed fuel is also suitable for automated transport. Moreover, the sharp edges at the intersection of the cylinders provide better burning of the pressed fuel. For this pressed fuel shape it also possible to solve the maintenance phase problem.

In direct connection with the goals of the task, in 2011 a testing prototype of a compacting machine based on the principle of pressing between two rotating rollers was designed (figure 10). At present the
The prototype is in the finishing stage, where it will have a driven exterior annulus, [5], [6]. Compaction occurs between the rollers on the inner side. The compaction machine consists of a pressing ring (1) with axial half-cylindrical recesses along its inner circumference and a second pressing disk (4) with a pressing roller groove on its circumference. The axial axes of the half-cylindrical recesses of the press ring (1) and the die roll (4) are rotated by 90 °. The output of the press roll (4) follows a calibration segment (3) encircling the axially polar recesses, which ensure that the pressings are cooled under pressure. The shape of the pressed fuel and the construction of the machine also address the maintenance problem by a so-called calibration zone (3). The heat needed during the pressing is obtained by friction. Finished fuel is selected by a breaker (2).

![Prototype parts](image)

**Figure 9.** New pressed fuel shapes [4], [5].

We are currently working on the design of the multidimensional adjustable compacting machine, which presupposes and involves, on the one hand, the scalar change of the ratio between the radius of the pressing disk and the ring, and on the other hand, the change in the number of shape sequences of the ring and the disk.

4. Conclusion
The focus of the presented paper is optimization of the shape and dimensions of pressed fuels. The pressed fuels analysed were considered from the standpoint of the optimal ratio of the surface to the volume, the optimal density and optimal shape such that the standards required for automated feeding, and optimal combustion processes were fulfilled. The result of the optimization is the design of a new principle for a compaction machine which is characterized by:

1) sufficient pressure maintenance during the compaction of the pressed fuels, which assures the needed function of lignin as a binder,
2) minimal machine input with respect to a unit of output,
3) less sensitivity of the pressing technology to the type of material, particles and humidity,
   the possibility of variable changes to the machine’s output,
4) minimal wearing of the functioning areas of the compacting machine.

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