# The method for selection of the working system components for a pellet press with flat die

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**Introduction**

The pressure pelletising is the technology that attracts more and more interest in Poland since the technology is suitable for manufacturing products in the form of pellets made up of biomass and composite solid fuels (containing solid fossils and biomass). First and foremost it results from the need to increase content of biomass in fuels, which is associated with the need to utilise wastes of vegetable origin. Composite solid fuels can be successfully subjected to the gasification process. There is also demand for other pelletised products, such as granulate of ceramic pastes or adsorbing agents of various types. Overall dimensions and properties of these products disable application of such machines as stamping of rolling presses as raw materials that are used for production of pellets differ from each other in terms of properties that substantially affect the course of the agglomeration process. Consequently, the required degree of material compaction ranges within broad limits, alike the pressure affecting the material during the compaction process and, in consequence, loads applied to components of the working system. The pressure granulation process may involve granulating machines with a ring die (Pulp Moulding Presses – PMP), a flat die (GMP) or some devices that combine advantages of PMP pellet presses and rolling presses that are chiefly designed to integrate materials of mineral origin and post-production wastes [1, 2, 4, 5]. The GMP pellet press is a solution that offers great opportunities for further development. The acquired experience shows that efficient operation of GMP pellet presses is determined by number of factors, including geometrical features of rolls and shaping sockets, the way how sockets are deployed within the die and condition of the die surface after machining, kinetic properties of the working system as well as mechanical properties of structural materials that are used for production of the machine components. Investigation of these relationships is the subject of research studies that have been undertaken by the Chair of Manufacturing Systems of the AGH University of Science and Technology with the aim to develop fundamentals for design of a GMP pellet press. This manuscript reports a fragment of overall studies where the attention is focused on determination of angle of nip and selection of suitable material and geometrical features for working subassemblies of that GMP pellet press.

**Characteristic properties of a granulating machine with flat die**

An example of a die press with a flat tool is shown in Figure 1. The working system of the machine is made up of a disk that incorporates appropriately shaped mesh and two rolls that are meant for compaction of the stuff. The mentioned components together with the enclosure make up a chamber where pellets are shaped. The die is fixed and can be supported both at the outer and inner sides. The chamber houses a head with compacting rolls attached to it on bearings. The machine is driven by means of a gear motor. The pellet press is supplied with incoming materials by gravitational charging from the machine top.

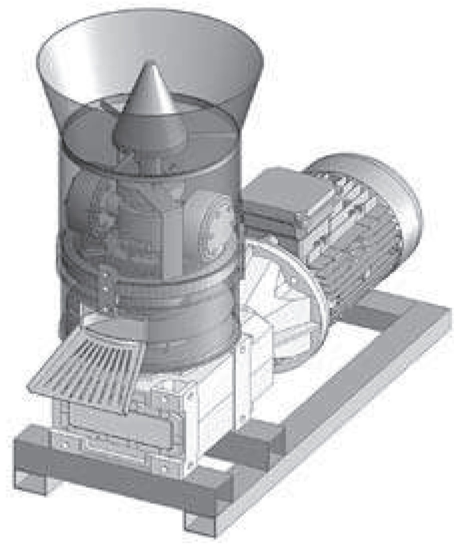

**Fig. 1. Example of flat-die pellet press**

The force that is exercised on a sloped material layer positioned between a roll and a die expels pellets to leave via die mesh. Other design solutions of a similar die press are also known [2, 3] where either only a die is driven or both the die and rolls are in motion. The solution depends on the machine size, the die type and properties on the input material to be pelletised. The head together with rolls constitute one construction set. The most recent solutions provide the possibility to automatically adjust the distance between the roll and the die and the number or rolls is as high as five. The speed of a roll running on the die perimeter ranges from 1.6 to 3 m/s.

**Determination of the angle of nip within the working system of a pellet press**

The available literature references made it possible to find out that the appropriate method for determination of an angle of nip within a working system of a pellet press is still missing. It was the motivation to embark on deliberations intended to resolve the problem. It was assumed that compaction of the material between a flat die and a roll (Fig. 2) may occur when the condition related to the angle of nip is fulfilled. Due to difficulties with mathematical description of the phenomena associated with the process of material compaction and integration the considerations are limited to a segment of a material volume with a curvilinear contact surface between a material and a roll is substituted with a flat plane. It was also assumed that elimination of internal slips of the material that may take place within the compaction area is an indispensable condition to achieve the correct flow of the compaction process. The attention was focused on the initial fragment of the contact zone, i.e. on the location where a working surface of the roll enters into the contact with the material. Stress distribution on the surfaces of an elementary segment of the material volume is shown in Figure 3.

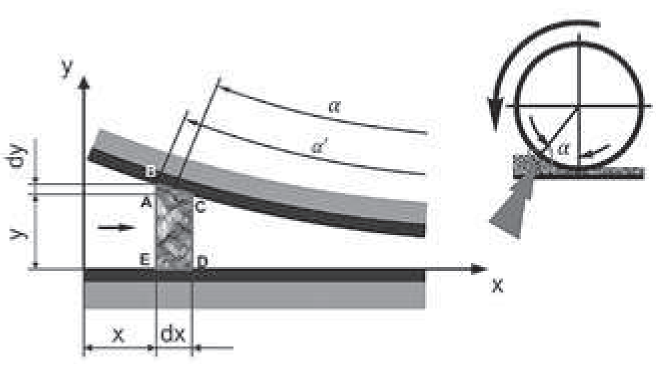


**Fig. 2. Diagram for compaction of material in a flat-die pellet press**

The critical AC cross-section of the material was determined that prevents from shearing phenomenon. The cross-section plane splits the elementary segment of the material volume into 2 parts (Fig. 3).

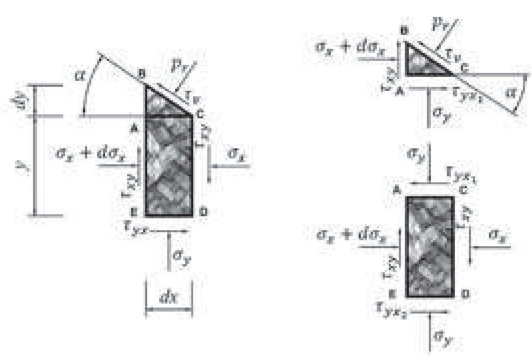

**Fig. 3. The stress vectors acting on the surfaces of the elementary segment of the material**

The undertaken considerations assumed the following definitions:

- $\alpha'$ - angle of nip
- $\alpha$ - slope angle between the equivalent (substitutive) flat plane to the horizont
- $\mu$ - coefficient of external friction
- $\xi$ - coefficient of internal friction
- $\sigma_x$ - normal stress acting down the X axis
- $\sigma_y$ - normal stress acting down the Y axis
- $\tau_v$ - tangential stress that occurs on the contact surface between material and the roll
- $\tau_{yx1}$ - tangential stress that acts down the X axis within the cross-section plane of the material under compaction
- $\tau_{yx2}$ - tangential stress that acts down the X axis on the contact surface between material and the die
- $p_r$ - unit force exercised by a compacting roll

The considerations related to the equilibrium conditions for the two parts of an elementary material segment. The account was also taken to the connections that result from the interrelationships between values of certain parameters. All these deliberations have led to the following system of equations (1.1):

$$\begin{aligned}
&(\sigma_x + d\sigma_x)dy + \tau_{yx_1}dx - \tau_v \frac{dx}{\cos\alpha}\cos\alpha - p_r\frac{dx}{\cos\alpha}\sin\alpha = 0\\
&\sigma_y dx + \tau_{xy}dy + \tau_v\frac{dx}{\cos\alpha}\sin\alpha - p_r\frac{dx}{\cos\alpha}\cos\alpha = 0\\
&(\sigma_x + d\sigma_x)y - \tau_{xy} + \tau_{yx_2}dx - \tau_{yx_1}dx = 0\\
&p_r \cdot \mu = \tau_v\\
&\sigma_y \cdot \xi = \tau_{yx_2}\\
&\sigma_y - \sigma_x = 2p_r\\
&\tau_{xy} = \tau_{yx_1}
\end{aligned} \qquad (1.1)$$

Resolving of the equations system (1.1) leads to the relationship (1.2) that enables to calculate values of the tangential stress that act within the AC cross-section:

$$\tau_{yx_1} = \frac{p_r\mu\left(1+\left(\frac{dy}{dx}\right)^2\right)+\left(2p_r+\frac{p_r\xi}{y}(dx-\mu dy)\right)\frac{dy}{dx}}{1-\left(\frac{dy}{dx}\right)^2+\frac{dx+\xi dy}{y}\cdot\frac{dy}{dx}} \qquad (1.2)$$

The sophisticated form of the (1.2) equation makes the formula rather unsuitable for practical applications. Therefore the assumption was made

$$\sigma_y = p_r \qquad (1.3)$$

to simplify the real physical circumstances.

The simplifying assumption (1.3) will not be a reason for significant errors since the acquired experience serves as the proof that the angle is usually pretty low. Upon substitution of (1.3) to (1.2) and elimination of components with negligible low values the following equation is achieved (1.4)

$$\tau_{yx_1} = p_r\left(\mu + 2\frac{dy}{dx}\right) \qquad (1.4)$$

The shearing stress $\tau_{yx1}$ should be less, or, for boundary cases, equal to the shearing strength of the material under compaction:

$$\tau_{yx1} \le \tau_f \qquad (1.5)$$

Since α is slighty higher than α' it is permissible to assume that:

$$\tan\alpha' = \frac{dy}{dx} \qquad (1.6)$$

Upon substitution of (1.5) and (1.6) to (1.4), the following inequality is obtained: (1.7):

$$\tan\alpha' \le \frac{1}{2}\left(\frac{k_t}{p_r} - \mu\right) \qquad (1.7)$$

The ratio of the shearing stress and the acting force is the coefficient of internal friction, which is taken into account for the inequality (1.7) that adopted the form of (1.8):

$$\tan\alpha' \le \frac{1}{2}(\xi - \mu) \qquad (1.8)$$

Thus:

$$\alpha' \le \arctan\left(\frac{1}{2}(\xi - \mu)\right) \qquad (1.9)$$

The foregoing considerations demonstrate that it is possible to determine the angle of nip within the working system by means of theoretical calculations if the coefficients of internal and external friction are already known.

**Selection of design parameters for working components of pellet press**

The pellet dies are usually made of alloy steel grades, such as X46Cr13, 20MnCr5 and 18NiCrMo5. When steel of the X46Cr13 is used it is first vacuum quenched and then tempered to achieve the hardness of 53÷55 HRC for both the surface and the core layer. The dies of the 20MnCr5 and 18NiCrMo5 steel grades are manufactured in another way. They are subjected to the carbonising process and then quenched to the hardness of 60÷62 HRC to the depth of 0.8 – 1.2 mm. The dies made of such steel grades demonstrate better durability when pelletisation of materials with the hardness above 65 HB is the case. The condition demonstrated by the working surface of the die is also a matter of substantial importance [6]. Appropriate selection of the die needs familiarity with properties of the material to be compacted as well as of the final product.

The rolls are usually made of alloy steel grades, i.e. NC11LV. They are subjected to the throughout quenching procedure until the hardness of 58÷60 HRC. The average lifetime of the rolls is about 500 hours, however intense efforts are pending on selection of better design materials to double the roll lifetime. The shape of the working surface of rolls is also an important thing [7].

Pellet presses of industrial (heavy duty) types are furnished with dies with their diameters ranging from 175 and 1250 mm. The perforated surface of such meshes varies from 600 to 5900 $cm^2$ and the penetration factor (mesh ratio) reaches the value from 0.38 to 0.60, whereas the factor of installed power ranges with respect to the perforated surface of the die falls within the limits of 20 to 67 $W/cm^2$. The diameters of depressing rolls are from 175 to 450 mm with their width from 70 to 190 mm.

Selection of geometrical design parameters for working subassemblies of a pellet press should comprise determination of the minimum radius for the compacting roll. It can also be done by the theoretical way. For that purpose the relevant considerations were carried out with the assumption that the existing friction forces prevent from slipping of rolls against the material as well as the material against the die.

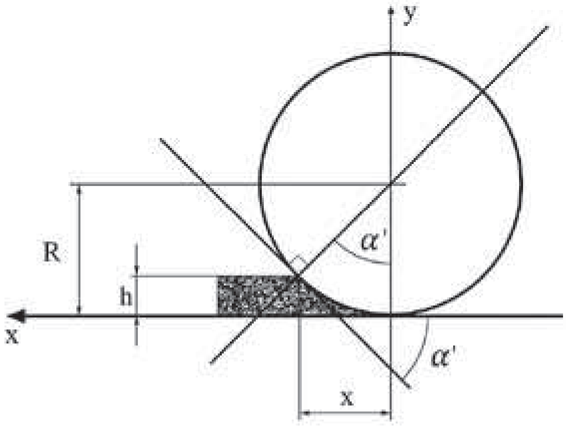


**Fig. 4. The diagram of the compaction system made up of a flat die and a roll with the adopted denominations**

The considerations to geometrical relationships within the compaction system made up of a flat die and a roll (Fig. 4) as well as to the relationship (1.6) leads to the following system of equations (2.1).

$$\begin{cases} x^2 + (y-R)^2 = R^2 \\ \dfrac{dy}{dx} = \tan\alpha' \end{cases} \quad (2.1)$$

Transformation of the equation system (2.1) results in the quadratic equation (2.2):

$$(\tan\alpha')^2R^2 - 2h\left((\tan\alpha')^2+1\right)R + \left((\tan\alpha')^2+1\right)h^2 = 0 \quad (2.2)$$

The equation (2.2) has two real roots:

$$R_{1,2} = \frac{h\left(\left((\tan\alpha')^2+1\right) \pm \sqrt{(\tan\alpha')^2+1}\right)}{(\tan\alpha')^2} \quad (2.3)$$

Due to design reasons one solution where $R \approx 0$ must be rejected, whilst the second solution was used to determine the relationship between the radius of the compacting roll and the angle of nip as well as the thickness of the material to be compacted. The revealed relationship is shown in Figure 5.

Application of the inequality (1.8) as well as the equation (2.3) made it possible to calculate the minimum radius of a compacting roll as a function of both the internal and external friction coefficients. The achieved results are shown in Figure 6. The analysis of these results allowed for concluding that the higher discrepancy between the two friction coefficients, the smaller diameter of the roll is sufficient. However, reduction of the roll diameter entails quality deterioration of the pellet press.

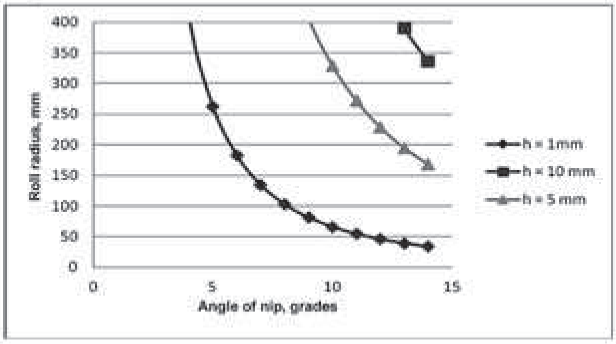


**Fig. 5. The relationship between the roll radius and the angle of nip as well as the thickness of the material layers at the point of nip**

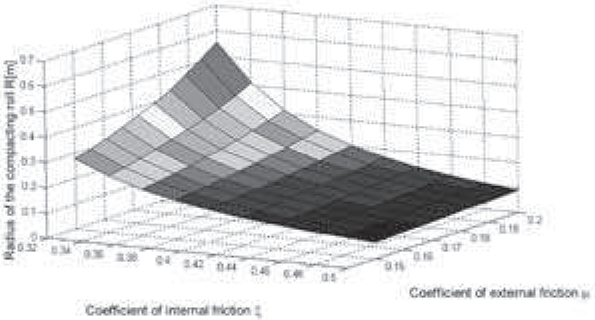


**Fig. 6. The example of the relationship between the roll radius and the internal and external friction coefficients for the feed height of 1 mm**

For feeds that demonstrate much higher coefficient of internal friction than the ones of external friction it is recommended to apply rolls with purposefully profiled working surface of rolls [7]. The productivity of the pellet press depends on the angle of nip and, in consequence, the layer thickness of the material to be compacted as well as on the roll width. Increased roll width leads to premature abrasive wear of working subassemblies, which entails drop of the system lifetime. Therefore it is preferred to apply narrow rolls with their radius only slightly exceeding the minimum threshold. Such a solution makes it possible to work with thicker layers of the material feed that is then pulled beneath the rolls.

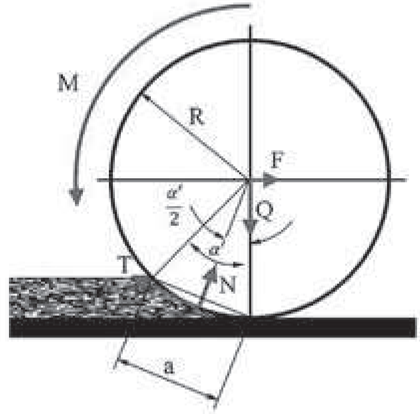


**Fig. 7. The system of forces acting on a compacting roll in the continuous motion**

Another significant problem is to find out the friction force momentum that acts on the contact surface between the roll and the material to be compacted. With the denominations as in Figure 7 the value of the *N* force exercised by the material onto the roll is expressed by the relationship (2.4):

$$N = p_{r\,śr} \cdot a \cdot b \quad (2.4)$$

where:

$p_{r\,śr}$ – average force acting on the contact surface between the roll and the material

a – length of the chord that corresponds to the arc of nip

b – roll width

With $\mu$ standing for the coefficient of external friction for the friction pair made up of a roll and material, the value of the friction force equals to:

$$T = p_{r\,śr} \cdot a \cdot b \cdot \mu \qquad (2.5)$$

The relationship (2.5) is correct when the working surface of the roll is plain. The coefficient of external friction can be increased by application of special profiles (corrugations) to roll surfaces. In case of such a measure it is necessary to use the equivalent coefficient of external friction $\mu_z$. The momentum for the force of external friction can be determined with sufficient accuracy with use of the following equation (2.6):

$$M_T = p_{r\,śr} \cdot a \cdot b \cdot \mu_z \cdot R \qquad (2.6)$$

It should be emphasized that the force exercised by the roll onto the material under compaction is of superposition nature, where determination of its average value $p_{r\,śr}$ presents a separate problem. It will be a subject matter of subsequent investigations and theoretical deliberations that will also take into account the determination of equivalent coefficient of external friction $\mu_z$.

Extension of the theory has enabled determination of the algorithm for selection of components and subassemblies for the working system of a pellet press, where the entire algorithm is shown in Figure 8. The algorithm comprises 5 phases, where the first one assumes assessment whether compaction of a specific material with use of a pellet press with a flat die is feasible. Such an assessment is to be carried out on the basis of laboratory tests. When the results of such tests are passed, the second phase is commenced with the aim to find out the coefficients of internal and external friction, which is to be done by experiments. The third phase is dedicated to selection of key geometrical parameters and the most suitable materials for design of a die. The last two phases comprises determination of the nip angle and then other design parameters of the roll are selected. It should be noted here that in case when the assessment results of the feasibility to compact and pelletise the material are negative, it is first necessary to make an attempt to alter its properties and then retest the material with use of a laboratory pellet press.

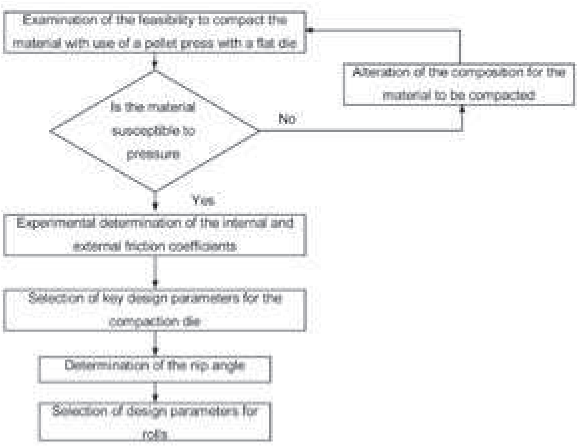


**Fig. 8. The algorithm for selection of design parameters for working subassemblies of a flat-die pellet press**

## Recapitulation

Design advantages of pellet presses with a flat die as well as opportunities to expand their application area posed the motivation to commence research studies on improvements of their structures. Some outcomes of these studies, in particular the ones dedicated to determination of the nip angle and adjustment of the roll diameter with respect to properties of the material to be pelletised are revealed in this paper. These achievements served as the basis to formulate initial assumptions and then to develop the engineering design for a domestic pellet press. The machine prototype is currently under further operational tests. The experimental investigations shall be continued and are intended to find out the preferable deployment of sockets in the die, to select their best geometrical parameters and the penetration factor (mesh ratio) that are the most suitable for the material to be pelletised. It is also expected that the investigation results shall contribute to development of a technology that enables the manufacture of composite solid fuels for the needs of their further gasification and for combustion thereof in household applications.

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