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DEVELOPMENT OF (PLASTIC-, BIO- AND FIBROUS) ENERGY-MATERIALS GRINDING

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Abstract

Summary: A general method of plastics-, bio-, and fibrous-materials grinders' development for energy engineering has been presented in this article. The method includes two beings: mathematical aiding an invention and working of a novelty. The common set is composed of characteristics, structure, relationships of knowledge about states and transformations, effectiveness and progress of the devices and machinery engineering, e.g. breaking up in the energy-materials recycling process. This innovation theory is identified by the valuation, estimation, testing and creative archiving the elaborated character and structure of the invention and grinders construction development.

***Key words**: Grinding of waste, modelling of effectiveness, innovation, invention*

1. Introduction

The proposition of a devices construction, development methodology, applicable to polymer-, bio- and fibrous- energy-materials (PBFm) milling for energetic aims is discussed in this work. More then 7 million tones, or 30,3% of the post-consumer plastics waste, and 600 million tones of bio-, fibrous materials waste, was recovered as energy in EU25+Norway and Switzerland, up 1,5%% against 2008. Municipal incinerators remain the most common means of energy recovery. Capacity has been added as a consequence of the Landfill Directive and countries like Switzerland, Denmark, Germany and Sweden have above 75% of their post-consumer waste treated in energy recovery plants. Austria, the Netherlands and Belgium are all achieving around 60%. Other countries have less than 20% of their post-consumer waste recovered in energy recovery plants. This includes not only new Member States but also countries such as Finland, Greece, Ireland, Spain and the UK.

The methodology of the mathematically aiding: devices innovation in plastics and biomaterials wastes recycling for energy engineering, based on the system models (eq.1) needs the fulfilment of the methodical conditions and improvement possibilities: of the grinder and wastes beings in the recycling process [2, 11, 12]. The proposition of a devices construction, development methodology handles mathematical models of the beings.

The mathematical models of the machinery in the waste-energy engineering is the purpose of this study, and they include: elements and relations of the machinery, materials, processes, grinding and energy purposes, consequences of action as well as environment (and system self) influence, e.g. the ontology of invention of the (PBFm)-waste grinders in the recycling process.

2. Method of grinding development

The development of the devices and machinery design-construction in the innovation of the energy wastes engineering depends on an environment and system knowledge. The eco-energy development of grinding special system is carried on methodically, on the basis of the operation mathematical model [4].

The versatile equation including all the novelty beings in the operating systems, from idea till elimination, has the form:

$$L(\bar{H}, \bar{E}, \bar{R}, \Theta, t) = R(\bar{s}, \bar{z}, \Theta, t - t_0), \quad (1)$$

where:

$\bar{H}$ - performance, operation, functioning, working, action characteristics as output quantities (efficiency),

$\bar{E}$ - inner elements ((nS) construction) and outer elements (ready markets),

$\bar{R}$ - connections between/of elements (relations, reactions, correlations of machine, waste, environment and others system elements),

$\Theta -, (t_1 - t_0) -$ time,

$\bar{s}$ - intentional control of environment; acting-, information- and logistic system,

$\bar{z}$ - disturbances.

The left side of equation (1) (model) describes the properties of the devices, of the waste processing and product engineering, their features of physical nature that is adequate for the given action class in environment. These properties depend on the elements E_1, E_2, ..., E_m, on connections, relation between these elements R_1, R_2 , ..., R_n, and they are functions of Θ and t (of the action and dynamical process time). The unknowns are the elements and relations of the set of energy characteristics H as output quantities, on which depends the evaluation of the innovation values of the idea, technology of the general efficiency of human, technical, energy-material, controlling action $P_d(t)$ and impact – also on generation of further novelties (inclusive of those from a PBF waste materials):

$$H = P_d(t)$$

The right side of equation (1) is a description of the inner and outer interference. It may depend on a form of the wilful action – control by means of the signals from the set $\bar{s}$ (computer aided, actively), of the interaction: reciprocal action of the sets: waste, material – grinding and thermo process – system and technical conditions – environment - …objective; of the tension action – action of tensions (connected with potential difference), that causes compensatory processes (e.g. on a financial market); it may also occur as a disturbance of the system action expressed by $\bar{z}$, or as consumption, state transformations in time.

Action characteristics - models

According to designation, the functional PBF-waste recycling for energy engineering spheres as technical system – is the whole of its external operating possibility:

- human potential $P^L(t)$,
- technical potential $P^T(t)$,
- energy – material (PBF-waste) potential $P^E(t)$,
- controlling potential $P^S(t)$.

Function of operating potential:

$$P_d(t) = \Phi\left[P^L(t), P^T(t), P^E(t), P^S(t)\right], \quad (2)$$

The following ones belong to indicators describing the operating potential (the description is limited to controlling potential exclusively, as the basic concept tool of designer's activity):

- temporary course of real executive possibilities, $\pi_d(t)$
- volume of operation used actively, usefully $M_d(t)$
- theoretical possibilities and operations needs, ε,

and especially:

$$P_d(t) = \pi_d(t) \cdot M_d(t) \cdot \varepsilon, \tag{3}$$

Operating (energy) environmental-system potential model - equation in the period (t_0,T):

$$P_d(T) = P_d(t_o) - \int_{t_o}^{T} p_d^E(t)dt - \int_{to}^{T} p_d^L(t)dt + \int_{t_o}^{T} p_d^R(t)dt, \tag{4}$$

where:

$P_d(t_o)$ - initial operating potential,

$p_d^E(t)$ - density of effectively used stream of potential,

$p_d^L(t)$ - density of lost stream of potential ,

$p_d^R(t)$ - density of recovered (or obtained from the environment) stream of potential.

Taking energetically PBF-waste grinding for energy engineering aims into account we obtain:

$$P_{em}(T) = P_{em}(t_o) - \int_{t_o}^{T} p_{em}^E(t)dt - \int_{t_o}^{T} p_{em}^L(t)dt + \int_{t_o}^{T} p_{em}^R(t)dt, \tag{4a}$$

where:

$P_{em}(t_o)$ – initial energy-material potential (*e-m*) of PBF-waste grinding system,

$p_{em}^E(t)$ – flux density of effectively used *e-m* raw, PBF-waste potential,

$p_{em}^L(t)$ – flux density of wasted and lost *e-m* PBF-waste potential,

$p_{em}^R(t)$ – flux density of *e-m* recreated potential, (or only retrieved from environment).

For design-construction development of grinder, the energy consumption, in technical system of PBF-waste grinding is represented as design-estimator and was calculated using the formula:

$$E_R = \frac{P_R v_R t'}{\eta_S \eta_P}, \tag{5}$$

where:

E_R - energy consumption of grinding by machine, kJ·kg^{-1};

P_R - load exerted on the material by the grinding force, N;

v_R - grinding velocity (the linear edge velocity), m·s^{-1};

t' - cycle time for disintegration of the material mass, s·kg^{-1};

η_s-, η_p - denote the efficiency of the motor and transmission, respectively, -.

This relation, like others found in the literature so far, does not take account of the specific characteristics of grinding in the case of recycling, arising from the objective of increasing the multiplicity of reuse of materials.

In the case of analysis of the overall effectiveness of multi discs grinding we employed the model [6, 7, 13]:

$$e_r = \frac{(\eta_{q-ś} - \eta_o) \cdot E_{brutto} \cdot \eta_s \cdot \eta_p}{(k_j \cdot v_r + \tau_{q-ś} \cdot A_{q-ś} + \varepsilon \cdot A_{q-ś} \cdot v_r^2) \cdot v_r \cdot t'}, \tag{6}$$

whereas in the case of special analysis - with the aim of modernization and development of the design of multi-disk PBF-waste shredders operating on the quasi-cutting principle - we employed a model representing an object-oriented relationship [11, 12, 14]:

$$e_r = \frac{\eta_{q-ś} \cdot E_{brutto} \cdot \eta_s \cdot \eta_p}{(k_j \cdot v_r + \tau_{q-ś} \cdot A_{q-ś} + \varepsilon \cdot A'_{q-ś} \cdot v_r^2) \cdot v_r \cdot t'}, \tag{7}$$

where:
E_{gross} - energy contained in the PBF-materials being processed, MJ·kg^{-1};
k_j - coefficient of resistances to dead motion, N·s·m^{-1};
τ_{q-s} - quasi-cutting stresses, N·m^{-2};
A_{q-s}-, A_{q-s}' - instantaneous and seconds cross-sectional PBF-waste area of quasi-cutting, m^2;
ε - proportionality factor, N·s^2·m^{-4};
η_{q-s} - material efficiency of the process of thermodynamic conversion of the quasi-cut product:

$$\eta_{q-ś} = \frac{T'_{wy/q-ś}}{T_{we/q-ś}}, \tag{8}$$

where:
$T'_{wy/q-s}$ - mass of the output material after quasi-cutting, kg;
$T'_{we/q-s}$ - mass of the input material before quasi-cutting, kg;
η_o - material efficiency of the conversion process without quasi cutting of the material:

$$\eta_o = \frac{T'_{wy}}{T_{we}}, \tag{9}$$

where:
T'_{wy} - mass of the output material without quasi-cutting, kg;
T'_{we} - mass of the input material without quasi-cutting, kg.

The energy effectiveness is defined thus:

$$E_e = \frac{L_{oi} - L_{oij}}{\frac{L_{oi} + L_{oij}}{2}} \tag{10}$$

where:
L_{oi}-, L_{oj}- successive instantaneous increments of the work of quasi cutting, N·m.

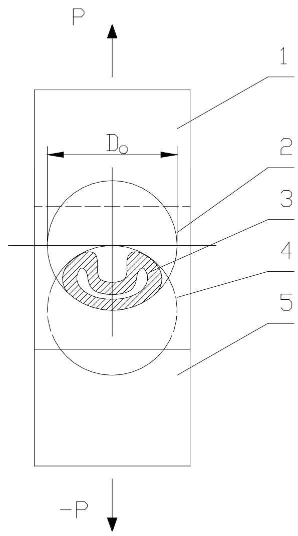

Fig.2: Intensive deformations (relations) model of pipe's as recycling element; v_R =0.01 m·s^{-1} (except for rigid PVC-waste), 1 - motionless slat, 2 - draft of the hole in motionless slat; 3 - investigated sample; 4 - draft of the hole in moveable slat; 5 - moveable slat.

The mathematical descriptions of the variables given in equations (6) to (10) are obtained from experiments or from data contained in processing tables. The following characteristics of motors and transmissions are determined in operational trials:
- the kinematics' transmission, ratio of angles speed:

$$i_k = \frac{\omega_2}{\omega_1}, \tag{11}$$

- the dynamic transmission, ratio torque moment M_2 and M_1:

$$i_d = \frac{M_2}{M_1}, \tag{12}$$

- power N_1 and N_S at transmission input, equal to the power at the output of the motor:

$$N_1 = N_S = \omega_1 \cdot N_1, \tag{13}$$

- power N_2 and N_R at transmission output, equal to the grinding power:

$$N_2 = N_R = \omega_2 \cdot N_2, \tag{14}$$

- efficiency of the motor:

$$\eta_s = \frac{N_1}{N_E} = \frac{\omega_1 \cdot M_1}{N_E}, \tag{15}$$

- efficiency of the transmission (gears):

$$\eta_p = \frac{N_2}{N_1} = \frac{\omega_2 \cdot M_2}{\omega_1 \cdot M_1}, \tag{16}$$

- efficiency of the PBF-waste grinding process:

$$\eta_r = \frac{E_{m/q-ś}}{E_r}, \tag{17}$$

where:

$E_{m/q-s}$ - unit energy consumption for quasi-cutting in the conditions of the physical model (s. fig.2) to a defined form of the grinded product, $kJ \cdot kg^{-1}$;

E_r - unit energy consumption for quasi-cutting in machine conditions, $kJ \cdot kg^{-1}$;

N_E - electric power supplied to the motor, W.

The energy efficiency of PBF-waste grinding and thermo processing is determined similarly. The input energy of processing E_{we} is the sum of the energy contained in the charge material E_{we1}, and the energy supplied to it E_{we2} ($E_{we} = E_{we1} + E_{we2}$). The energy at process output E_{wy} is reduced by the energy losses E_{st}:

$$\eta_{ep} = \frac{E'_{wy}}{E_{we}} = \frac{E_{we} - E_{st}}{E_{we1} + E_{we2}} = \frac{E_{we1} + E_{we2} - E_{st}}{E_{we1} + E_{we2}}, \tag{18}$$

In the case of processing efficiency, the instantaneous values and the values occurring over the longer term are important. The mean value of the energy efficiency (or the mean energy efficiency) is sometimes called the energy efficiency in the literature [1, 2], but this is only justified when both efficiencies are equal to one another, e.g. in the case of auto-thermal processing.

Action characteristics – results and discussion

ERCO.net (*System of Efficient Administration of Energy Media Management*) is a modern information technology tool that enables the main objectives to be achieved for monitoring the states and transformations of energy in the break-up engineering, and that also allows the actuators to be controlled according to the rules and policy for the energy management system.

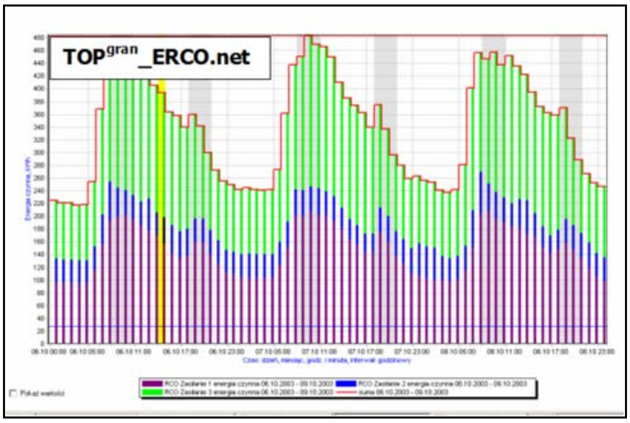

Fig.3: Characteristics-diagram of grinding and thermo process energy monitoring

This methodology is formation of the bases of knowledge about structural conceptions of multi-discs plastics-, bio- and fibrous-wastes grinders, and formations of energy-materials in recycling process (acc. to the IE-TEST-07 procedures, fig.4 [4]). Characterization of solutions - specific, unique and suitable - for using them in similar conditions of the mechanical wastes processing into the set geometrical form and dimensions of the granulated for energy product.

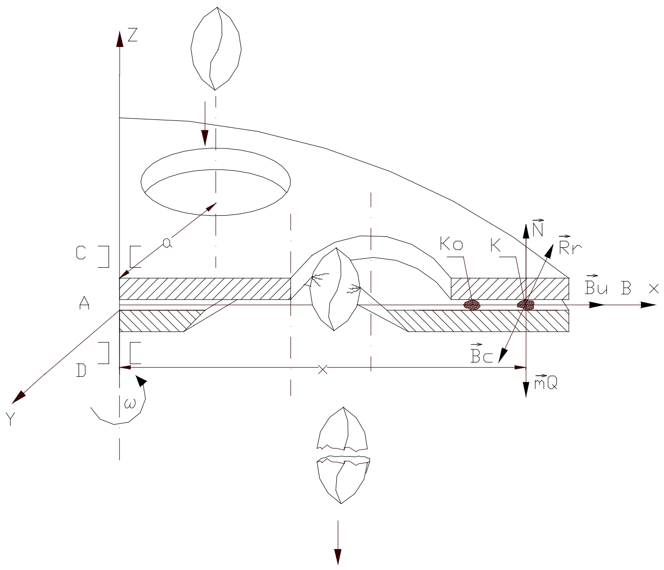

Fig.4: Solution: multi-discs grinders design-new-constructions for PBF-waste; elements and relations

Given from experimental investigations results make up principles to shows selection onto settlement regarding to most suitable way of disintegration and solutions estimation of energy, work, effectiveness, energy consumptions and loads (Table 1).

Tab.1. Energy, effectiveness and efficiency grinding characteristics of plastics- biomaterials- and fibrous waste

No.	Estimators of grinding development	Plastics waste	Biomaterials and waste	Fibrous waste
1.	Energy consumption of grinding by machine, E_R, kJ·kg^{-1}	655,4	137,8	212,9
2.	Effectiveness of multi discs grinding, e_r, -	68,7	116,1	98,6
3.	Material efficiency of the conversion process, η_0 -	0,14	0,13	0,07
4.	Efficiency of the PBF-waste grinding process, η_r, -	0,06	0,11	0,09
5.	Energy efficiency of PBF-waste grinding and thermo processing, η_{ep}, -	0,28	0,27	0,14

Also discerning analysis of sub-ranges of chart gives aids to selection optimal grinders' construction and way of disintegration. However general solution for every chart characteristics, described by 4-th degree equation assigned area of possible search:

$$H = a\,\Delta l^4 + b\,\Delta l^3 + c\,\Delta l^2 + d\,\Delta l + e$$

for $R^2 > 0,95$

The constructive features of the working set of the multiple discs grinder should be selected in such a way that the function achieves the maximal value (because of the e_R, η_0, η_r, η_e, indicator value) or minimal (because of the value of the unit energy consumption indicator E_R).
The point where the function value fulfils the required criterion is called problem solution: $x^* = (x^*_1, \ldots\ldots, x^*_n)$. The solution is, of course, from the permissible area:

$$x^* \in \Phi$$

The principle of the optimization support in the direction of getting the extreme solution can be defined:

$$\left\{X^{*}\in\phi\right\}:\left\{\bigwedge_{x\in\phi} Z(x)\geq Z\left(X^{*}\right)\right\},$$

in the case of minimization of energy consumption ($Z=E_R$)

$$\left\{X^{*}\in\phi\right\}:\left\{\bigwedge_{x\in\phi} Z(x)\leq Z\left(X^{*}\right)\right\}$$

in the case of maximization of energetic milling indicator, material and energy efficiency ($Z=e_R,\eta_0,\eta_r,\eta_e$).

Solution

We attribute a great part to creative individuality- building, to aiding formation processes, by modern systems of grinding design development, design engineering, production, operation, recirculation, tests and estimation. A specific area of coexistence of the (Pw) plastics-, (Bw) biomaterials-, (Fw) fibrous waste and machinery construction, grinding parameters (LT, LO, LR, PK, PR, PLOT, PLOR, PPMT, PPMR, GPK, ST) is the engineering of wastes break-up in recycling process (tab.2). Many thousands years of tradition, ontology and construction development of the grinding, mills ensure better and better setting in order and pro-innovation conjectures. There is constantly so much to be composed and innovated.

Tab. 2. The PBF-waste grinding and grinders parameters

Symbol	TOP^{gran}_TEST_07 - New Solutions, Product conception	Pw	Bw	Fw
LT	Number of shields, -	5	5	5
LO	Number of openings in the first row of the first shield, -	9	9	9
LR	Number of rows, -	2	2	2
PK	Angular velocity, $rad\cdot s^{-1}$	11,34	8,83	21,5
PR	Row radius, m	0,065	0,065	0,065
PLOT	Increase of the number of openings between shields, -	2	2	2
PLOR	Increase of the number of openings between rows, -	2	2	2
PPMT	Increase of the radius of rows between shields, m	0,003	0,003	0,003
PPMR	Increase of the radius of rows in a shield, m	0,002	0,002	0,002
GPK	Angular velocity gradient, , $rad\cdot s^{-1}$	2,00	1,50	4,00
ST	Shields' diameter, m	0,255	0,255	0,255

3. Summary and comment

The use of plastics, biomaterials fibrous materials is expected to continue and increase, driven by: potential for development, innovation, energy saving potential and positive contribution to climate protection, quality of life enhancement, enabling of affordable products.

Our most important task in the waste management area is to divert combustible waste from landfill. Plastics are particularly important to recover, as they offer many options including recovering the calorific content of the material. For recovery, mechanical recycling will remain the preferred method for homogeneous plastics waste streams, whereas for a number of mixed streams different energy recovery options are preferable. Both methods save resources and CO_2 emissions. The methodology of the devices development in plastics, biomaterials, fibrous materials recycling for energy engineering, based on the system model (1) needs the fulfilment of the methodical conditions and improvement possibilities: of the grinder and PBFm and materials beings in the recycling process.

The first condition of development of the product creative methodology of PBF-waste break-up in the recycling process for energy engineering is model description of the objective, of the solution essence (idea), processing of the conception, construction, production and monitoring of the machine novelty, e.g. in the $\mathbf{TOP}^{\mathbf{gran}}$ computer environment corresponding to the idea of the systems for integrated manufacturing of the machinery components.

There exists discrepancy between the calculated construction indicators and energetic efficiency indicators – determined for the machine built on the basis of the carried out support procedures. The discrepancy achieves the value of even several percent (the obtained result is the most adventageous when the discrepancy between the calculated construction and the constructed mill with the energy – consumption E_R = 655,4kJ·kg^{-1} – with the criterion E_R<700 kJ·kg^{-1} is 6,4%).

In the process of searching for processing machines properties, it is necessary to include the following procedures:

- to use the scientific basis of machine construction and exploitation,
- to create new solutions on the basis of individual ideas taking into consideration the nature of needs,
- to take into consideration the complexity of technical systems to implement the stated processing function – steering, drive, service, repairing, power supply, damages, scrapping and others.

Plastics make up around 10% by weight of the feed but as much as 50% of the calorific content thanks to their high specific calorific value. The last 10 years have seen a remarkable change in the approach to waste management across Europe. As a result, there has been a significant increase in the recycling of all materials as well as more recovery of energy from combustible waste. The situation with respect to PBF-waste is no exception, and as this work demonstrates, both recycling and energy recovery of plastics-, bio- and fibrous waste continue to increase.

References:

1. Kamyk, W., *PhD-Work (in polish),* UTP Bydgoszcz, 2008,
2. Chun, J.J.Yi, Moon, Y.H., *Application of neural networks to predict the width variation in a plate mill,* Journal of Material Processing Technology, April 2001,
3. Flizikowski, J.B., *Dissertation on construction (in polish),* Publishers ITE, Radom 2002,
4. Flizikowski, J.B., Flizikowski, A., Kamyk, W., *Ontology and Development of Food Grinder Construction. (in polish)*, Inżynieria Maszyn 20/03, pp. 223-226, Bydgoszcz 2003,
5. Flizikowski, J.B., *Global Algorithm of Machinery Innovation. (in polish),* Publishers BTN, Bydgoszcz 2006,
6. Flizikowski, J.B., Kopacek, P., *Innovation of Multi-disk Food Break-up. (in polish),* Inż. i Ap. Chem. 46, pp.46-47, No 1/2007,
7. Flizikowski, J.B., Kowalski, A., *Precise Drive of Food Grinders. (in polish),* Inż. i Ap. Chem. 46, pp. 48-49, No 1/2007,
8. Flizikowski, J.B., Lis, A., *Optimisation of Multi-disk Grinder. (in polish),* Inż. i Ap. Chem. 46, pp. 450-52, No 1/2007,
9. Kazimierczak, G., Pacula, B., Budzyński, A., *Solid Edge. Computer-aided Design. (in polish),* HELION, Gliwice, 2004,
10. Macko, M., *Effect of Design Features of Multi-disk Unit on Usable Characteristics of Breaking up Process of Plastics Pipe Recyclates. (in polish),* Dysertacja WM-ATR, Bydgoszcz 2000,
11. Mazurkiewicz, A., *Transformation of Knowledge in Machinery Construction and Operation. (in polish),* Publishers ITE, Radom 2002,
12. Ostwald, M., *The Elements of Construction Optimisation. (in polish),* Publishers PP, Poznań, 2003,
13. Xiao D., Xu, H., *An Integration of Ontology-based and Policy-based Network Management for Automation,* CIMCA-IAMTIC’06, 2006,

14. Cempel, C., Natke, H.G., *Energy model of social system with production and recycling Eco Energy Processor (EEP)*, Inter. Jour. of System Science, vol. 33, No 2, pp.87-95, 2002,