Please cite as: Inż. Ap. Chem. 2017, 56, 5, 161-163

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Analysis and eco-technological evaluation of micro-grain supersonic milling. Part I. Models and indicators

Introduction

The analyses and eco-technological evaluation, carried out in the first stage of the developmental research, involved descriptions of the most important issues and phenomena accompanying milling grain by means of a fast rotating disc tool with variable acceleration of particles including:

– blade projection,
– surface friction,
– working space infusion,
– combination of ideas/ phenomena

for micro- grain materials (polymer material filler grains) and the tool variable structure (geometric, material and dynamic characteristics of the disc) – disc element– from discovering, innovation, through modernization to optimization of the process/ phenomenon, precise construction; further – utilization of the phenomena and milling technologies – towards achievement of the highest technological and environmental usability degree (including processing, e.g. energy usability) of the innovative milling system/tool [*Niederliński, 1979; Nycz, 2004; Bieliński and Flizikowski, 2007; Flizikowski and Bieliński, 2013; Flizikowski et al., 2013; 2015;Mroziński, 2016*].

Kinetic energy of the working substance, most commonly air, is used for elementary dosing and milling. The analysis and evaluation include the design, construction and operation of an areo-kinetic mill constructed on the basis of dimensionless characteristics obtained from results of appropriate measurements.

Dimensionless characteristics of the product quality, the process efficiency and the product and process safety are quantities characteristic of dosing-milling which depend on the kinematic and dynamic transmission [*Niederliński, 1979, Sadkiewicz and Sadkiewicz, 1998; Flizikowski et al., 2013; Sadkiewicz, 2017*].

The assumed satisfactory states of milling (SP_M) can be reached according to an old or a new idea, under known or unknown structural conditions (W_K, nWk), which are to be discovered, adjusted, analyzed and evaluated by a creator-constructor.

The research goal was to make an analysis and assessment of technological conditions of the new designed aerokinetic mill (nWk) by means of technological indicators concerning the product quality, milling process efficiency and environmental estimates of safety to reach the assumed satisfactory states of milling (SP_M).

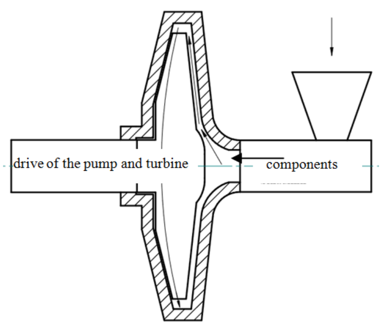
Presentation of the concept and initial evaluation

Creative behavior – in the area of design innovativeness (nWk) – involved creating new methods for dosing mixing and milling, with the use of available devices, machines, systems and components – providing new original concepts of milling disc/housing design solutions.

Aerokinetic dosing-milling is the answer and conceptual solution to the problems connected with (SP_M): quality of the milling product, the process efficiency, milling speed; and above all, due to a close workspace, it limits dusting and performs the process with low power demand per efficiency unit. Dosing-milling was assumed to be performed between surfaces of the pump-turbine, depending on the rotational speed and the rotor space filling degree, with optimal pressure controlled by expenditure (supply) and zero dusting.

One of the concepts to be used for finding a solution, including initial, expert assessment of the task, is presented in Table 1.

Table 1. Universal variables and their indicators for eco-technological evaluation of the concept of innovative aero kinetic milling



Idea, concept	Expert evaluation	
	Indicator of variable	Evaluation*
Aerokinetic dosing-milling. Dosing-milling performed between the surfaces of a rotating pump and a moving material ring, that is a virtual turbine, in dependence on the rotational speed and the rotor space filling degree, with optimal pressure, controlled expenditure, zero dusting of space.	Air pressure	6
	Expenditure of substance flow	6
	Milling expenditure	3
	Temperature	3
	Degree of finess	6
	Energy consumption	3
	no 7	27
* 0 – negative evaluation eliminates the concept		

Evaluation was performed on the basis of indicators, criteria based subjective assessment, with the use of four evaluation values: 0 – negative, excluding a concept from further consideration, 1 – merely acceptable, 3 – satisfactory, 6 – excellent for a potentially optimal solution.

On the right side: component dosage systems: micro grain input, air, to be supplied in appropriate proportions to the milling chamber from the pump housing and the turbine, according to the concept of aerokinetic devices (clutches, gears).

Indicators, technological and ecological criteria. The new concept of aerokinetic milling involving dosing-mixing (nWk) consists of three basic components: a rotor of the rotating pump and a rotor of the virtual turbine with overlapping rotation axes and, a coaxial with them, immovable housing. Their overall shape is usually similar to a torus filled with a milled substance. The pump rotor is often equipped with blades (Fig.1a). They are used to change velocity vector of the dosed, mixed substance (micro-grains with air) flowing through the inter-blade channels, and subsequently its momentum.

The changes of momentum are accompanied by acting of the dosed, mixed substances on the rotor blades which causes milling of micro grains in the rotating ring (Fig.1b) of the virtual turbine and occurrence of torques on each of them.

The dosing-mixing input shaft with structure, shown in Table 1, is connected with the pump rotor. The pump rotor blades force circulation of the powdery mass (powdery, micro-grainy mass, air, etc.). There follows a change of mechanical energy of the disc initial shaft rotation motion into kinetic energy of the dosed- mixed and milled components. The rotating ring of the milled material is a rotor of the virtual turbine.

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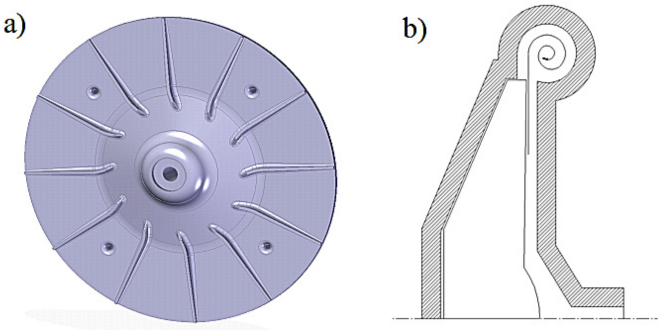

Fig.1. Working element of the mill; a) - 3D model of the milling disc (pump), b) – scheme of the drive, the pump disc supply and motion of the milling ring (turbine)

Kinetic energy of the rotating ring, fragmentarily changed into mechanical energy, is transmitted onto the housing, that is, its circumferential and ring side. The housing is an element necessary to adjust intensity of the dosing-mixing process and the value of torque between the input shaft and resistance shaft of the milled substance rotating ring. It is immovable, though its shape is adjusted to the shape of the rotor. The substance flowing between the blades is subject to momentum changes due to change in the action line of the velocity vector forced by curvature of the blades. The torque which occurs on the blades is transferred by the rotating substance ring onto immovable elements of the mill housing.

Kinetic transmission of the aerokinetic mill is defined as a ratio of angular velocity ω_2 of the rotating milled substance ring (turbine) to angular velocity ω_1 of the input shaft of pump), or as a ratio of respective rotational speeds n_2, n_1:

$$i_k = \frac{\omega_2}{\omega_1} = \frac{n_2}{n_1} \tag{1}$$

Dynamic transmission of aerokinetic mill is defined as a ratio of torque M_2, which is transmitted in the form of displacement loading of the mixing and milling input and product onto the input shaft of the aerokinetic mill, to moment M_1 which drives the input shaft:

$$i_d = \frac{M_2}{M_1} \tag{2}$$

In order to keep balance of the aerokinetic mill through its steady rotating motion, the sum of external moments acting on the components needs to be zero:

$$M_1 + M_3 - M_2 - \Sigma M_t = 0 \tag{3}$$

where:

M_3 – reaction moment acting on the housing from its mounting, [N·m]

ΣM_t – sum of moments of the aerokinetic mill friction resistance, [N·m],

M_{t1}, M_{t2}, M_{t3} – In the shaft bearings (M_{t1}) and rotary seals (M_{t2}) and the moment of the pump rotor ventilation resistance M_{t4} and the rotating milled substance ring (M_{t3}) (micrograin-air) connected with it and the housing, [N·m].

Determining:

$$M_2 = M_1 + M_3 - \Sigma M_t \tag{4}$$

from dependence (3) and substituting the obtained expression into dependence (2), it can be said that dynamic transmission of the aerodynamic mill is described by the following dependence:

$$i_d = 1 + \frac{M_3 - \Sigma M_t}{M_1} \tag{5}$$

Thus, for regular conditions of the mill operation $\Sigma M_t << M_1$, it can be assumed that:

$$i_d \cong 1 + \frac{M_3}{M_1} \tag{6}$$

The process of micro-grain milling in a disc mill is accompanied with energy dissipation. It is caused by resistance of the substance, milled in the disc-housing ducts, which flows between the rotor blades. Thus, power N_2 received by the rotating ring of the milled substance (virtual turbine), is lower than power N_1 supplied to the pump shaft. The ratio of these powers represents the overall ***efficiency of the aerokinetic mill***:

$$\eta = \frac{N_2}{N_1} = \frac{M_2\omega_2}{M_1\omega_1} \tag{7}$$

It is easy to find out, on the basis of dependences (1), (2) and (7), that the aerokinetic mill efficiency can be expressed in the following way:

$$\eta = i_d i_k \tag{8}$$

Moment M_1, needed to drive the aerodynamic pump rotor, is proportional to density of the dosed substance ρ_1, mixed and milled ρ_2 ($\rho = \rho_1 + \rho_2$), the second power of the rotor angular velocity ω_1 and the fifth power of its diameter. It results from dependencies describing the substance flow through rotors of the rotary machines and conditions of the dynamic flow similarities [*Tuliszka, 1970*]. In terms of dynamics, the milled substance flow through rotors of the aerodynamic mill, is similar for different – let it be large enough – values of the pump rotor angular velocities and for different loadings by moment M_2, if the value of kinematic transmission i_k remains the same. Therefore, the above discussed proportionality can be substituted by proportionality coefficient λ_M whose value depends on kinematic transmission, referred to as a dimensionless coefficient of moment:

$$M_1 = \lambda_M(i_k)\rho\,\omega_1^2 D^5 \tag{9}$$

where:

D – active diameter of the milling disc (pump), which is called the largest diameter of the substance milled in the pump rotor, [m].

In the aerokinetic mill there is a combination of milling efficiency (Q_m) with chamber loading (M_k), whereas the chamber loading is represented by the amount of grains currently present in the chamber:

$$M_k = Q_m t \tag{9a}$$

Efficiency of the disc mill largely depends on the time of grains staying in the working chamber.

The number of times micro-grains enter the mill chamber is calculated form the formula:

$$k_k = \frac{t v_m}{2\pi R} = \frac{M_k v_m}{Q_m 2\pi R} \tag{9b}$$

where:

v_m – average velocity of circulating micro-grain mass, [m·s^{-1}]; it is not identical for the entire thickness of the layer; it is the highest near the disc (0.4÷0.6), whereas near the housing wall it is the lowest ((0.11÷0.18) of the disc edge circumferential velocity);

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R – radius of the rotor disc, [m],
t – time, [s].

The mass of the circulating micro-grains layer with a ring cross-section is expressed by the formula:

$$M_k = 2\pi R L h_m \rho \mu \tag{9c}$$

where:
L – width of the chamber of the rotor housing, [m],
h_m – thickness of the circulating layer of micro-grains, [m],
μ – concentration of micro-grains,
ρ – density of micro-grains, [kg·m^{-3}].

A given mill is adjusted to operate with a specific working substance whose density changes, e.g. in result of micro-grain milling or temperature. Therefore, Polish literature uses coefficient of moment $f_M(i_k)$, which in the SI system has a physical dimension analogical to the dimension of density [*Tuliszka, 1970*]. This coefficient is accepted to be dimensioned as below [*Tuliszka, 1970*]:

$$f_M = \rho \lambda_M \tag{10}$$

Torque necessary to drive the aerokinetic mill can thus be defined on the basis of the below dependence:

$$M_1 = f_M(i_k)\omega_1^2 D^5 \tag{11}$$

It needs to be noted that for a given mill – with given geometric dimensions – the value of coefficient of torque remains the same for the same value of kinematic transmission. The value of torque on the pump rotor depends then only on the second power of the engine angular velocity or a subsystem of the input shaft drive system. The dependence of coefficient of torque on the value of kinematic transmission characterizes unequivocally the mill in terms of the torque value needed to drive the input shaft for a given kinematic transmission.

Dependence (6) indicates that dynamic transmission is higher than unity for such conditions of the disc operation for which the sense of reaction moment M_3 acting on the housing from its mounting, is the same as the sense of moment M_1 driving the input shaft. Dynamic transmission reaches the highest value i_{dmax} for kinematic transmission $i_k = 0$, no substance supply, when the substance ring is stopped ($\omega_2 = 0$). Value i_{dmax} is called a coefficient of transformation. A decrease in the value of moment M_2, received by the milled substance, causes an increase in angular velocity and the value of kinematic transmission. It is accompanied with a drop in the value of reaction moment M_3 (in connection with loadings resulting from dependences (9a) to (9c)) acting on the housing and a decrease in the value of dynamic transmission. The value of kinematic transmission, for which reaction moment M_3 reaches zero value, and there follows equalization of the value of moment M_1 driving the disc and the pump rotor, with the value of moment M_2 received by the milled ring, is called a kinematic transmission of coupling i_{ks}. Then, the dynamic transmission is equal to unity: $i_d = 1$. The point on the turbine milling characteristics which corresponds to kinematic transmission is called point of coupling i_{ks} In the interval of kinematic transmission values smaller than the kinematic transmission of coupling i_{ks}, the sense of moment M_3 is consistent with the sense of input moment M_1. The value of dynamic transmission is then higher than unity. In the range of transmission values higher than i_{ks}, the sense of reaction moment M_3 in an aerokinetic mill is opposite to the sense of input moment M_1. Dynamic transmission is then lower than unity and the efficiency rapidly decreases along with an increase in the kinematic transmission.

Unit energy consumption can be determined by associating power demand with a unit of micro-grain milling efficiency:

$$E_j = \frac{N_M}{Q_m} \tag{12}$$

where:
E_j – energy unit consumption, [J],
N_M – dosing-mixing (milling), [W],
Q_m – mass milling efficiency, [g·s^{-1}].

Ecological efficiency of dosing-mixing milling can be defined by the following dependence:

$$e_{EKO} = \frac{\Delta E_{EKO}}{K_{EKO}} = \frac{E_{ur}}{m_{CO_2}} \tag{13}$$

where :
e_{EKO} – ecological efficiency indicator,
K_{EKO} – consumption of natural resources,
ΔE_{EKO} – increase of ecological benefits,
E_{ur} – yearly average ecological benefit (elimination of emissions), [$g_{ekw}CO_2 \cdot kg^{-1}$ of milling product]
m_{CO2} – yearly average outlays of emission [$g_{ekw}CO_2 \cdot kg^{-1}$ of a milling product].

The presented models and indicators of variables will be used in the analysis and eco-technological evaluation of the structural solution designed for innovative supersonic micro-grain milling (Part II of the paper).

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Research project at GORDEN, Białe Błota 2014-2018