A model of torque changes during drum granulation

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Introduction

With respect to granulation, the drum filling as well as the rotational frequency of the drum should warrant the continuity of the tumbling bed, with a simultaneous forced rolling of the forming agglomerates upon the free surface. In such circumstances, during drum rotations the granular bed inside the device is retained by virtue of friction by the cylindrical wall and lifted to a certain height. In effect, the bed centre of gravity is tilted from the vertical axis at certain angle. The free surface is inclined from the horizontal plane at an identical angle.

The angle of the slope of the free surface of the bed constitutes a determinant of the energy state. In the absence of slippage between neighbouring layers, the grains located against the inner wall move [1] rotation-wise and due to internal friction raise further layers of the bed with trajectories constituting fragments of circles with a decreasing radius. The result is the reduction in perimeter speed of successive layers of the bed. An area is formed that under optimal operational conditions covers half the charge inside the drum and it is called the raising zone. After reaching the highest possible position (angular position) under specified conditions, the grains may behave differently depending on the energy conveyed to the bed. The least desirable case is the skidding of the entire bed on the inner drum wall without the circulation of the particles of the charge. The perimeter speed of the particles at the wall of the device – the value that also describes the degree of energy conveyed - is nearly zero [2].

The cyclic movement of the charge that is desirable for the process of granulation involves the particles at the drum wall being raised upwards to a maximum height and then tumbling or slipping upon the tilted free surface of the bed. During the raising motion, the grain layer directly in contact with the device wall moves along with it with a perimeter speed equal to the perimeter speed of the internal surface of the granulator (because of partitions). Successive layers of the granular bed in a drum derive the energy necessary for the upward motion from the friction between particular grains as well as the respective layers of the bulk material. At a sufficiently high value of the friction coefficient of the bulk material, their motion towards maximal position occurs nearly without slippage. The radial transfer of grains, and hence the change in their circulation trajectories, is possible in the presence of a particle speed gradient in neighbouring layers. It may occur in a zone where the grains tumble or slip after having achieved the maximal position as a result of gravity. This zone is called the mixing zone. The speed values of respective grains in the mixing zone depend on their distance from the free surface and possess components that are tangent to its contour as well as radial. The material present in this zone is wetted in order to trigger and facilitate agglomeration. Some of the bed grains never make it to the mixing zone after reaching the position maximal for their layer but circulate around a specific circulation centre. They move along constant circulation trajectories, not mixing with other grains, which impedes agglomeration of this part of the bed. Thus formed idle circulation zone is called the core [3]. After reaching a bottom position all grains and formed granules are once again raised upwards and the entire cycle repeats with the size of the granulate change as a result of the process. In summary, during raising upwards each material particle present in the charge may be ascribed a certain trajectory on a plane perpendicular to the drum axis. For most grains this trajectory ends in the mixing zone where wetting and agglomeration ensue and for the remainder – it is typical for their entire circulation (a closed line). The bed circulation described occurs at a granulation stage advanced sufficiently for a part of the charge to become an agglomerate. At the outset of the process, the dust in the bed is raised in an entire batter in line with the value of the friction coefficient of the bed processed against the device wall.

In view of the complexity of the issue concerning the effect of the forces acting on a physical body constituted by a bulk material inside a horizontal rotating drum, there are no studies that provide solutions for at least one of the processes implemented in such devices. Ball mills have received the broadest coverage with respect to process dynamics in the literature. The literature concerning mixing, in particular – granulation, is much scarcer.

For the purpose of the determining the dynamics of the granular bed system in a rotating drum, the equilibrium of forces acting on the bed raised in the device were commonly taken into account and the bed was treated as a continuous medium. Analysing the distribution of forces acting on grains in a horizontal drum device filled with bulk material, Kantorowicz [4], under many simplifying assumptions, stated that the angle of bed slope is equal to the angle of natural repose. Koroticz [5] corroborated these findings with respect to granular bed inserted in a horizontal rotary furnace.

Upon the analysis of the forces acting on the bed grains as well as their speed for the purpose of the characteristics of the dynamics thereof, the following parameters were applied: angle of the bed slope [1], grain speed [2], torque at drum shaft [6÷8], or conveyed power [9].

The studies concerning model granular materials (Heim et al.) [10] proved that torque at shaft depends on angular speed and the type of the bed motion, among other factors. It was established for all materials under investigation that the value of unit torque rises within the range analysed along with the increase in rotational speed n up to a certain maximal value to and then virtually drop to zero. This tendency is related to phenomenon of the bed rotation upon exceeding a critical speed. In case of low filling (k=10%) inertial forces are too low, as a result of a small mass of the charge, to bring the entire filling into rotation.

The above results made it possible to suggest a formula for the value of power necessary for the motion of granular charge in a drum device. The following equation was derived:

$$N = A \cdot n^{1.13} \cdot f^{\,0.20} k^{0.82} \cdot \rho^{1.07} \qquad (1)$$

Under normal working conditions of a ball mill [11], the variation in power shows a close correlation with the efficacy of milling, an increase in power is coupled with augmented efficiency of the device. Hence, power is considered to be the most significant project parameter. The power and torque of drum mills were calculated in line with dependencies based on empirical correlations, the application of the laws of mechanics to determine the trajectory of the balls flight and the assumption to the effect that the charge of the mill is a continuous medium. The classic methods of examining energy interrelations for ball mills involve the analysis of the equilibrium of the bed inside the drum or the description of the movement of respective grains, groups of grains or grinding media. Upon analyzing the value of the torque derived from gravity, Dirge [12] established the following formula for power:

$$N = 14.5 \cdot 10^{-6} \cdot D^{2.5} \cdot L \cdot \rho \cdot V_w \cdot (100 - V_w) \cdot C \cdot \sin\alpha \qquad (2)$$

where:

V_w – internal mill volume

This relation is applicable below the 75% of the critical speed of the mill. In light of the experiments that followed (including post-marketing studies) the formula (2) was modified by Rowland and Kjos (1978) [13], Harris (1985) [14], Rowland [15], Mishra and Rajamani [16], among others.

Rose and Sullivan [17] applied a dimensional analysis for the purpose of description, while Gao [18] suggested a formula that allows to calculate power in a classic basic SI system:

$$N = 7.36 \cdot 10^{-6} \cdot D^{2.5} \cdot L \cdot \rho \cdot V_w \cdot (100 - 0.937V) \cdot C \cdot \left(1 - \frac{0.1}{2^{9-0.3C}}\right) + \\ + 102 \cdot 10^{-6} \cdot L \cdot V_w \cdot \rho \cdot D^2 \cdot (1000 \cdot B_m - 2.5 \cdot D) \qquad (3)$$

The last element of the equation reflects the mass of the grinding medium B_m, with C – being the constant.

Sandvik [19] compared the power variations throughout milling in ball mills. The correlations retrieved show two local maximal values.

Another way of modelling the process assumes that the mill filling is a continuous medium, the free surface of which is inclined at drum rotations until the critical value of slope angle is reached. The mill then operates in a cascading mode with the power relative to the dimensions of the device, its rotational speed, bulk material filling and the mass of the filling. Basing on the above assumptions, Hogg and Fuerstenau (1972) [20] calculated the work required for the raising of the balls from the lowest position on through their circular motion. A model of load capacity by Arbiter and Harris [21] yielded a similar outcome. They analysed the work derived from the raising force against energy loss caused by its gravity.

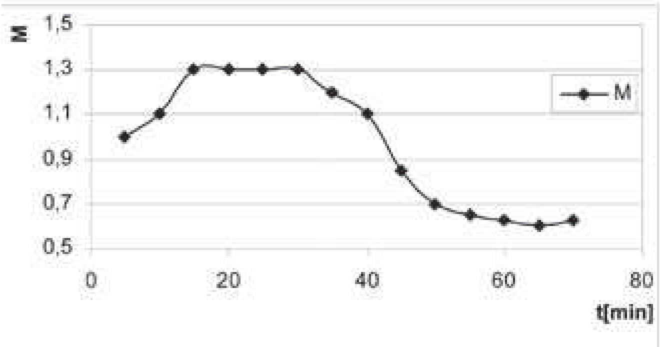

Fig. 1. Torque of ball mill vs. disintegration time

In many papers [22÷25] it was considered that a mixed cataract-cascading motion occurs during the operation of the mill. This is associated with the change in the properties of the material disintegrated inside the device, which affects the dynamics of the bed as the process advances. Kapur [26] provided several types of curves reflecting the functions of torque with respect to time upon the analysis of the operating mode of various ball mills. The characteristic feature of the said correlations is the oftentimes fixed range of torque value that indicates a steady motion of the processed bed (circulation of the cascading granulate).

According to Velamakanni [27] the variations in torque during the running of the process may differ in character depending on the stage of disintegration which is connected with the change of behaviour of the mill filling in response to the change in the properties of the bed. In both cases after the initial rise of the value of torque, a constant value set in. A drop in the value of torque to be seen in Figure 1 concerning wet milling is due to bed rotation that became attached to the inner walls of the mill. Heim et al. [28] also corroborated a fixed range of the values of torque during wet milling.

Upon the study of the milling dynamics in ball mills, Kijama 1974 [29] drew an interrelation between torque and rotational speed of the mill as well as the filling of the device with grinding media. He remarked that torque value is heavily influenced by the volume of the charge that moves cataract-wise versus the volume that moves in a cascading motion.

Similar analyses concerning power, torque and the remaining parameters describing the dynamic state of granular bed in a rotation drum were conducted for tumbling granulation [30, 31]. Drawing on the outcome of model studies, Heim et al. [10] determined the required functions for an actual granular material /bentonite/ during the process of wet drum granulation.

Measurements were made for the whole granulation cycle for two values of drum filling with granular material k. It was assumed that wetting time equals granulation runtime.

The specific (reduced) torque M* was defined by means of the following formula:

$$M^* = \frac{M - Mj}{m_s + m_w} \qquad (4)$$

The results obtained were compared with the graph M*=f(t) derived for dry material (powder) tumbling. In this study the feeding of liquid into the system was simulated through continuous addition of powder with the same mass as the wetting liquid to the drum. The comparative analysis of the results obtained proves that the reason behind the increase in torque during granulation is not the mass growth of the charge caused by the addition of liquid but the change in the character of its motion resulting from greater moisture content in the powder and its consequent agglomeration. What occurs at this point are the alterations in such properties of the processed bed as granulometric composition, bulk density and the angle of internal friction as well as the external friction coefficient.

It was also noticed that at the initial stage of granulation torque value increases, subsequently stabilizes and then drops dramatically because of the sedimentation of the wet granulate of the drum walls. Torque proves to be related to the amount of the rotating material at his point.

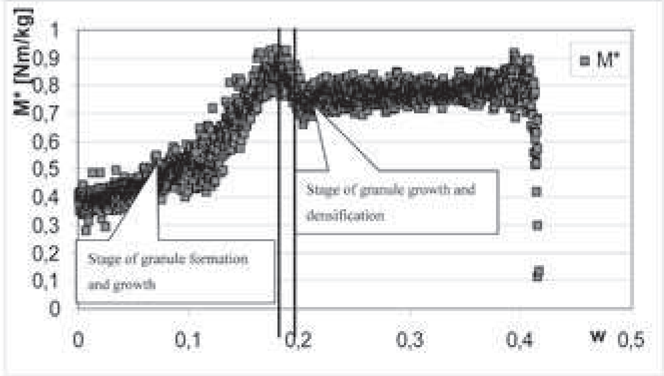

Fig. 2. Changes in the reduced moment value with changing bed moisture content

Obraniak and Gluba (32) measured momentary torque values during granulation. A sample variation in momentary reduced torque values with moisture content is show in Figure 2.

Upon the analysis of the plots derived, for each case they specified three ranges differing in terms of the variation in the correlations mentioned above. In the first range torque is relative to moisture and approximated to a square function, in the second range – a short-term decrease in its value may be seen and in the third – it may be considered stable. The third range ends with a dramatic drop in the value of torque due to the adhesion of the charge to the drum walls. Of particular interest is the initial increase in torque and its subsequent establishment at a fixed level. These changes are to be explained with reference to the changes in the properties of the granulated bed during the process. The character of torque variation is unequivocally related to the changes in the properties of the granulated bed during the process. Subject to alteration are the granule diameter, bulk density, porosity as well as the total bed mass resulting from moisture addition. It was remarked that upon a critical moisture content of the bed, further addition of liquid leads to a reduction in torque value and its subsequent establishment at a fixed level. Throughout the period of torque value constancy, the properties of the granulated bed also undergo significant changes but without impacting torque value, which may be the result of the mutual reduction of the effect of respective properties. The analysis of the results obtained supports the claim that torque value during granulation in a rotating drum during bed wetting is influenced by such process and equipment parameters as drum filling and rotational speed.

Aim and scope of study

The aim of the study was the recommendation and verification of a model of torque change throughout drum granulation.

The following parameter variation ranges were applied for the purpose of the study:

- granulator drum diameter D=0,40 m
- granular material filling k=5%-20%
- drum angular speed ω=1,41 – 2,64 rad/s.

Measurement equipment and methodology

The schematic diagram of the study rig is depicted in Figure 3. The drum (1) was driven by a gear-motor (6) by means of belt transmission and a clutch. A continuous change in rotational speed was achieved through an inverter (7), while its control was performed by means of a tachometer. Momentary torque values were measured by means of a torque meter (3) and then processed through a reader (4) and recorded on a computer (5). The granular bed placed in the drum was wetted with a sprinkler droplet-wise (2), axially inserted into the device, thus warranting homogenous liquid distribution across the entire length of the drum. The sprinkler was attached on a support stand, separate from the granulator (8). The wetting liquid (distilled water) was fed from a container (10), located at the height of 2,5m. from the drum axis and its constant flow intensity (Q= $1 \cdot 10^{-6}$ m^3/s) was controlled by means of a rotometer (9). Throughout the trials a constant liquid level in the container was maintained, ensuring stable pressure of the liquid supplied. The granular bed was wetted until the material was moist, causing its adhesion to the inner wall of the granulator. Every 120s a sample was collected and bulk density, angle of natural repose and the angle of bed friction against the inner surface of the device were measured, at which point the sample was recirculated to the drum. The granulation process was performed batch-wise, on each occasion under pre-determined process and equipment parameters: drum filling and granulator rotational speed.

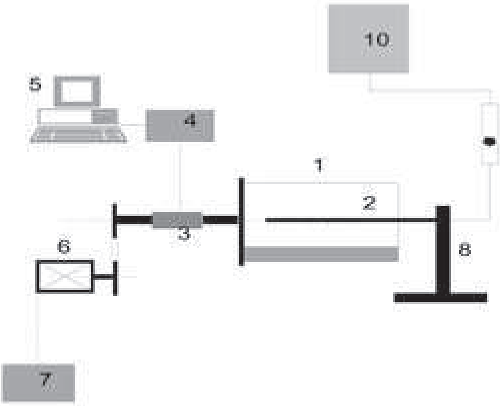

Fig. 3. Schematic diagram of the experimental rig
1- granulator drum; 2-damper; 3-torque meter; 4-reader; 5-computer 6-motor; 7-inverter; 8-support stand; 9-rotameter; 10-water container

Model

Upon the raising motion of the grains of the bed under the conditions of kinematic-dynamic equilibrium, (Fig. 4), i.e., when the centre of gravity of the granular filling raises upon the rotation of the drum to a position determined by angle β_0, the following forces acting on the bed treated as a rigid body may be discerned.

These feature gravity and centrifugal forces (applied to the centre of gravity of the bed) as well as the normal force of the device wall acting on the bed and friction (whose resultant forces are applied midway on the arch constituting the line of the contact between the bed and the drum wall).

Such an analysis of the forces system reduces to the following concentrated (resultant) forces:

- gravity -

$$G = m \cdot g \tag{a}$$

- centrifugal force –

$$F_{od} = m \cdot \omega^2 \cdot R_0 \tag{b}$$

- force of the effect of the wall on the bed –

$$N = m \cdot g \cdot \cos\beta_0 + m \cdot \omega^2 \cdot R_0 \tag{c}$$

- force of friction -

$$T = f(m \cdot g \cdot \cos\beta_0 + m \cdot \omega^2 \cdot R_0) \tag{d}$$

where:

$$R_0 = \frac{4}{3} \cdot R \cdot \frac{\sin^3\alpha}{2\alpha - \sin 2\alpha} \tag{e}$$

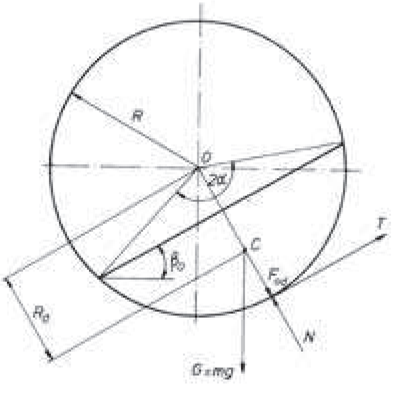

Fig. 4. Forces acting upon the granulated bed

Under the assumption that the system (granular bed) during the raising motion to a position determined by an angle β_0 behaves as a rigid body, it may be inferred that it shall reach equilibrium with the sum of effective torques equal zero. This is corroborated by the equation of the torques with respect to point 0.

$$M_T - M_G = 0 \tag{f}$$

The moment of friction forces may be described by means of the formula

$$M_T = T \cdot R \tag{g}$$

The moment derived from a component of gravity causing the slippage of the bed may be calculated on the grounds of the following correlation:

$$M_G = mg \cdot \sin\beta_0 \cdot R_0 \tag{h}$$

The moment from friction force as well as from gravity depend on many factors. By substituting the correlation (6.4.) in the formula (6.7.) we derive:

$$M_T = R \cdot f(mg \cdot \cos\beta_0 + m\omega^2 \cdot R_0) = R \cdot f \cdot m \cdot (g \cdot \cos\beta_0 + \omega^2 \cdot R_0) \tag{i}$$

The mass m of the granulated bed may be represented thus

$$m = \pi \cdot R^2 \cdot L \cdot k \cdot \rho \tag{j}$$

where:

$$k = \frac{2\alpha - \sin 2\alpha}{2\pi} \tag{k}$$

Upon suitable substitutions, moment from friction forces may be calculated in line with the following formula:

$$M_T = R \cdot f(g\cos\beta_0 + \omega^2 R \frac{\sin^3\alpha}{2\alpha - \sin 2\alpha}) \cdot 0.5 \cdot R^2(2\alpha - \sin 2\alpha) \cdot L \cdot \rho \tag{l}$$

$$M_T = 0.5R^3 f \cdot L \cdot \rho[g\cos\beta_0(2\alpha - \sin 2\alpha) + \frac{4}{3}\omega^2 R \sin^3\alpha] \tag{m}$$

Upon the analysis of the moment derived from gravity we obtain:

$$M_G = m \cdot g\sin\beta_0 \cdot R_0 \tag{n}$$

$$M_G = 0.5R^2(2\alpha - \sin 2\alpha)L\rho \cdot g\sin\beta_0 \cdot \frac{4}{3} \cdot R \cdot \frac{\sin^3\alpha}{2\alpha - \sin 2\alpha} \tag{o}$$

Tests results

For each of the granulation trials, the established character of changes in torque values as well as the development of the process were in line with the findings of Heim [8] and Obraniak [32]. In order to render the results presented clearer, the measurements of torque were plotted as mean calculated from 60 consecutive measurement points. In view of the variability with respect to the mass of the processed bed on different trials, it was decided to compare the torque values as calculated per charge mass unit. A sample comparative analysis of the reduced torque (in accordance with correlation (4)) is depicted in Figure 5.

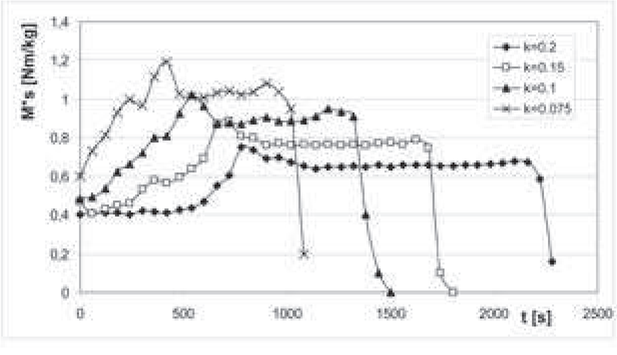

Fig. 5. Comparison of changes in the reduced moment as a function of time for different drum filling k

The study presents a comparative analysis of model theoretical correlations with the torque values M*s obtained by way of measurements performed with a torque meter mounted on the granulator shaft. The theoretical results were derived by means of the formula (4). The following model correlations were applied for the purpose of determining torque change:

M*t – correlation (m), - the value of the friction coefficient was taken to be the coefficient of internal friction calculated as the tangent of the angle of natural repose of the granulated bed for a specific process run-time.

M*t(m) – correlation (i), - the value of the friction coefficient was taken to be the coefficient of internal friction calculated as the tangent of the angle of natural repose of the granulated bed for a specific process run-time.

Mg* – correlation (o), - the value of the friction coefficient was taken to be the coefficient of internal friction calculated as the tangent of the angle of natural repose of the granulated bed for a specific process run-time.

M*t(f) – correlation (m), - the value of the friction coefficient was taken to be the coefficient of external friction of the bed against the drum wall measured for a specific process run-time.

M*t(mf) – correlation (i), - the value of the friction coefficient was taken to be the coefficient of external friction of the bed against the drum wall measured for a specific process run-time.

M*g(f) – correlation (o), - the value of the friction coefficient was taken to be the coefficient of external friction of the bed against the drum wall measured for a specific process run-time.

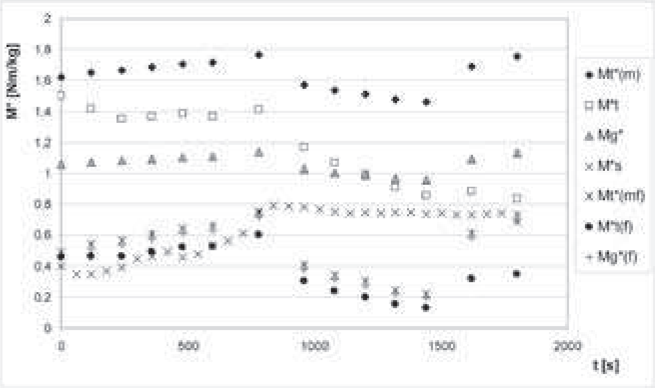

Fig. 6. Comparison of reduced moment obtained experimentally and calculated from eq. (i,m,o)

The analysis of the correlations obtained reveals that none of the modelled correlations sufficiently approximates the actual measurements throughout the entire run-time of the process.

This may be due to the differences in the behaviour of the processed granular bed at respective stages of granulation. This in turn follows from the development of a process which results in the creation and growth of granules, affecting the properties of the granulated charge. Literature research as well as observations allow to indicate the differences in the character of the motion of the filling circulating in the horizontal drum device resulting from the variation in such bed parameters as bulk density, friction coefficient or the angle of natural repose. The bulk material that is a granulate in its entirety circulates continuously after raising the bed to an angle that may be identified with the angle of natural repose. Whereas at the outset of the process when most of the charge is not granulated a frequent phenomenon is the "detachment of a whole batter of the granulated bed from the inner wall testifying the great effect of the coefficient of the granular material friction against the inner wall of the device.

The analysis of the correlations provided in Figure 6 yields the observation that although none of the correlations proposed reflects the changes in torque throughout the entire process, the model results sufficiently approximate the actual values within the respective periods identical with the defined [32] granulation ranges.

The study was aimed at suggesting a model taking into account the above described phenomena and assuming various friction coefficient values for the consecutive characteristic process stages.

For the initial stage associated with nucleation and agglomerate formation as a result of build-up, the model correlations involved the coefficient of the friction of the bed against the device material, and for the stage involving the growth of the granulate formed previously and its densification resulting from the mutual interaction between granules and the walls, the coefficient was taken that was calculated with reference to the angle of natural repose. The results obtained are demonstrated in Figure 7.

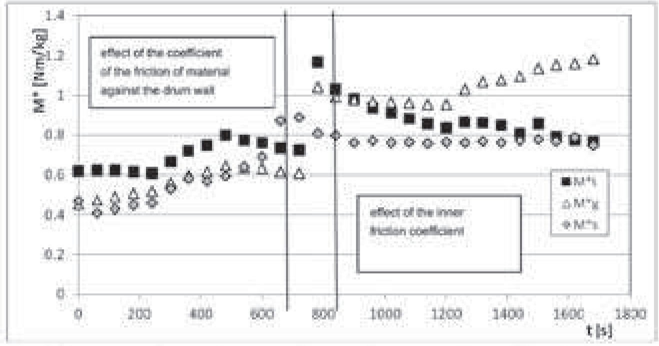

Fig. 7. Comparison of reduced moment obtained experimentally and calculated from eq. (m,o)

It may be stated that both theoretical models of torque changes (M^*_g, $M^*_t(f)$) are of use for the purpose of the estimation of the change of torque values throughout drum granulation. During the initial stage actual results are better approximated by the model M^*_g based on the correlation (o), while for the final stage actual measurements are better approximated by means of $M^*_t(f)$ as calculated from the correlation (m).

Conclusions

1. In view of the complex character of the motion of the granulated bed during respective stages of the process, no universal correlation is capable of approximating the variations in torque values.
2. Theoretical correlations applied for the calculation of the moment of friction forces and torque derived from gravity may serve to assess the changes in torque as while taking into account a suitable friction coefficient for each process stage.
3. If the anticipated changes in the dynamic parameters of the bed are to comply closely with theoretical results, theoretical equations shall be supplemented by corrective coefficients.

Symbols

A – constant
D – drum diameter
L – drum length
M* - reduced torque
N – power
R – drum radius
R_0 – distance of the centre of gravity of the granular bed from the drum axis
V – drum capacity
V_w – inner drum volume
f – friction coefficient
g – gravity
k – drum filling with material
m – bed mass
n – rotational speed
t – operation run-time
2α - central angle
β_o – bed slope angle
ρ - bulk density
ω – angular frequency

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The 4th International Symposium on Structure-Property Relationships in Solid State Materials will be held at the University of Bordeaux 1 in Bordeaux, France from June 24 to June 29, 2012. This international symposium follows the previous symposia held at Bordeaux (2006), Nantes (2008), and Stuttgart (2010).

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