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Investigations into the movement of milled medium in the bowl of a ring-roller mill

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ABSTRACT

This paper presents the results of testing the grind material movement in a ring-roller milling system. The tests were carried out in a 1:4 scale model of an RP-1043x milling system. The aim of the test was to determine material bulk shapes within a range of parameter changes of a model grinding system i.e. table–roller distancing, pile-up ring height, coal feed and table's rotary speed. Based on the measurements of material layer thickness on the table, its average radial velocity was calculated. The results were then supplemented with tests based on the movement of markers over the surface layer of the coal bulk. These tests enabled the material's average radial and tangential velocities in the surface layer to be determined.

1. Introduction

Ring-roller mills are considered to be an important element in heat and electric-power production technology. The efficiency and dynamics of the milling machines directly affect the power and flexibility of the whole unit, and the milling quality has an influence on the boiler's efficiency and the NOx emission level. An analysis of the present state of knowledge, as well as observations of mills currently in use lead to the conclusion that the quality and efficiency of the milling processes and the wear of the milling elements are affected by the movement of the material on the mill's table.

Mroczek and Czepiel [1–3] studied the impact of the table's angular velocity on the milling effect and the efficiency of the ball-ring mill. These authors point out that there is an optimal rotary velocity of the table corresponding to the highest obtained milling effect. Increasing the velocity above this boundary value results in the exclusion of a certain part of the material feed from the milling process. This is caused by a faster material outflow from the milling system and a decrease in the thickness of the crushed layer which, consequently, results in a smaller crushing area and number of milling cycles the layer undergoes.

It is frequently emphasized that an increase in material fed onto the table should be respectively followed by an increase in the table's rotary velocity [1–4]. Operating in this way prevents an excessive accumulation of material on the table, and, in an extreme case, the milling system from being covered. There are, of course, systems for controlling the table's rotary velocity but, in practice, one particular velocity is predominantly applied. Thus, it is essential to determine the optimal table rotary velocity that guarantees the maximal milling efficiency within the range of the unit's usual charge [1,5,6]. Feige [5] and Höffl [6] point out that an increase or decrease of velocity from this optimal value results not only in lower efficiency but also in more powerful consumption by the mill.

An inappropriate choice of rotary velocity may also considerably precipitate the wear of the milling elements [7], and consequently also decrease the mill's efficiency.

It is important to note that optimization of the rotary velocity in ring-roller and ring-ball mills should be met in relation to the ring's height. It is the ring that controls the thickness of the material on the table; therefore, the use of high-profile rings should go together with an increase in the table's rotary velocity [5,6,8,9].

Experiments and observations confirmed that the bulk shape of the material on the table explains a lot about information on its movement [10]. Determining this shape and carrying out appropriate calculations enables the material's average radial velocity to be found. Going further, observation of the movements of markers over the bulk surface brings additional information about the outer layer of the material. The shape of the bulk material itself also gives a lot of information on the amount of material gathering on the table, and on changes of its accumulation related to changes of the table's rotary velocity.

In order to observe and register the above interrelations, a 1:4 scale model of an RP-type ring-roller mill was constructed, including a measurement system for determining the thickness of the bulk material as a function of its radius. The model allowed experiments to

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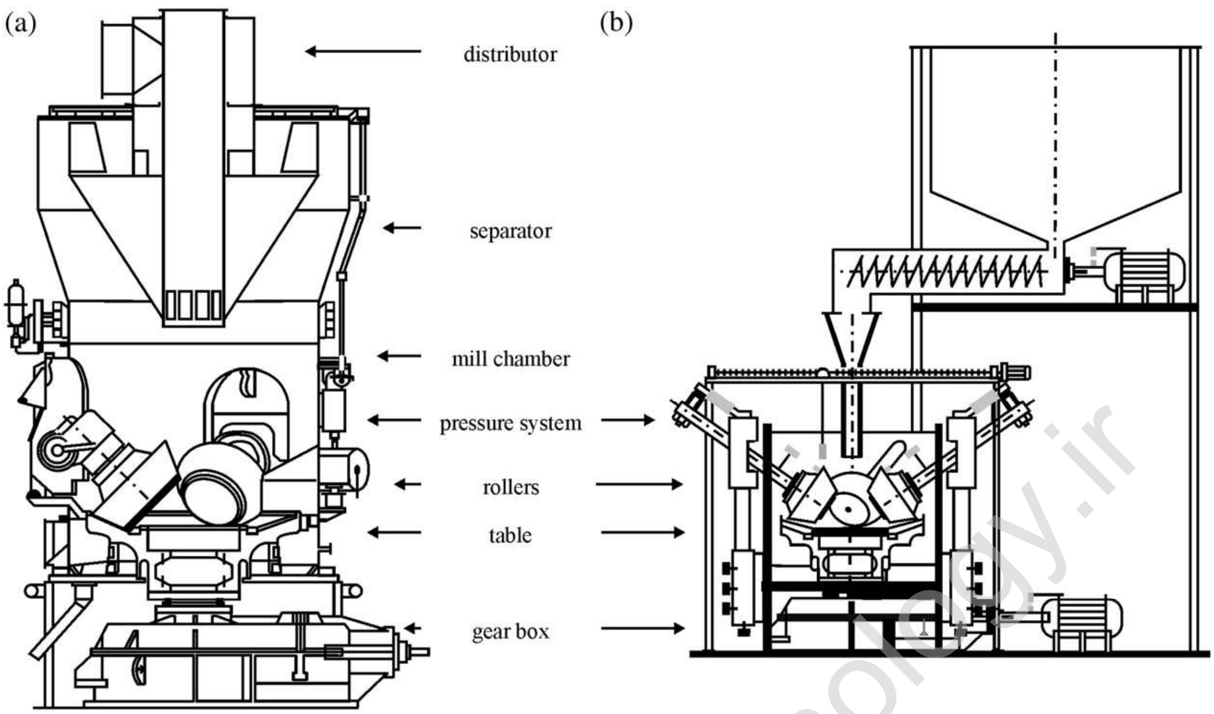

Fig. 1. Pictorial schemes of (a) industrial ring-roller mill, (b) 1:4 scale model of the milling system (distributor, separator, mill chamber, pressure system, rollers, table, gear box).

be performed using a wide range of operational parameters of the mill.

2. The test stand

In order to carry out this research, a 1:4 scale model of an RP-1043x`milling system was built. The basic elements of the RP-1043x` mill and the test stand are schematically shown in Fig. 1 and Plate 1. The constructional and operational parameters for both the industrial unit and the model are given in Table 1.

The main elements of the milling system are the table with a slanted track and a set of three cone-shaped rollers. During the test, the stream of material was fed by a conveyor, through a hopper, onto the rotating table. The conveyor's shaft was driven by a 4 kW DC motor coupled with a motor reducer. Adjustments of the conveyor's revolutions were set by means of a measurement card. Between the hopper and the conveyor there was a truncated cone-shaped orifice with built-in rings to dispense the grind material uniformly onto the table's centre.

An electric motor propelled the table's rotation through a two-stage angular gear. Changes of the table's rotary velocity were controlled by means of an inverter, also connected to the measurement card. A pile-up ring (with adjustable height) was mounted around the edge of the table. The shaft coupling the gear to the table was equipped with blades for raking the milled product that poured out over the ring.

The rotary velocity of the rollers, as well as that of the table and the feeding screw, was measured with reed relay transmitters. Measurements of the pressure on the grinding material were performed by means of strain gauges mounted on the brackets parallel to the axles

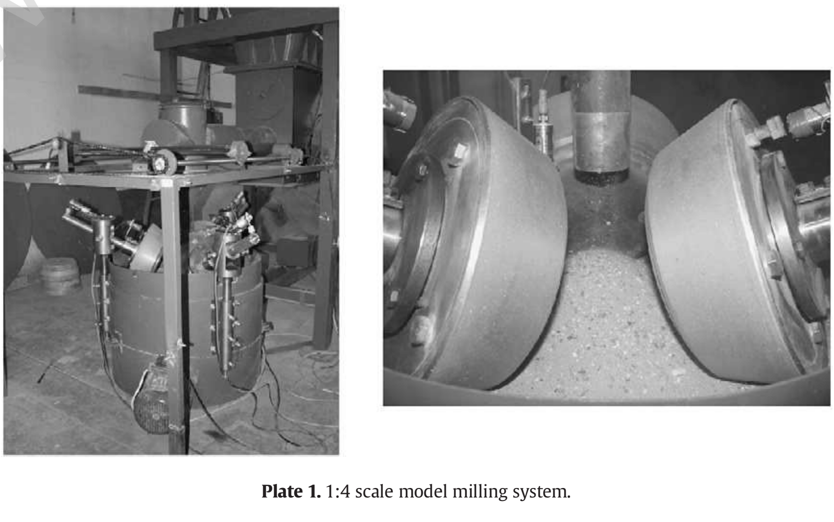

Plate 1. 1:4 scale model milling system.

Table 1
Basic construction and operational parameters of an industrial and a model RP-1043x` milling system

Parameter (unit)	Milling system RP-1043x`	1:4 model milling system
Roller diameter—front/back (mm)	1080/1410	270/350
Roller width (mm)	540	130
Table diameter (mm)	2800	700
Table rotations (rev/s)	0.35–0.65	0.7–1.3
Linear velocity	2*v*	*v*
Number of rollers	3	3

of the rollers. The gauges were coupled with the axles by means of rigid-screw couplings. The couplings enabled the thickness of the grinding material under the rollers to be accurately controlled.

The considerable amount of dust produced in the tests, the system's dynamics (roller, table movement) and safety requirements were decisive in selecting a non-invasive method of measuring the bulk shape of the material. A system was designed and constructed specifically for this purpose. It contained a measurement head with an ultrasonic gauge, a frame and three threaded shafts for the head to move along. On the frame were installed two motors that were to put shafts into rotation. The motors were controlled by means of a driver that was programmed to control the head's movement.

The ultrasonic gauge used in this test was control-verified towards an impact of the kind of surface on the measured distance. The gauge calibration stand consisted of a millimeter scale rule. There were holes drilled in the rule which enabled the gauge to be mounted at different distances from the appliance's base. In the test a steel plate was used together with a vessel filled with quartz sand or hard coal. The gauge was mounted at different heights on the rule and the measured signal values were registered (Fig. 2).

Fig. 2(b) shows the results of measurements for quartz sand and a steel plate, which indicate that the suppression of the ultrasonic wave in the superficial layer of the sand is insignificant. The same was concluded in the case of hard coal.

While performing the pre-tests the ultrasonic gauge's movement track was also determined. The ultimate positioning of the measurement track is shown in Fig. 3. In this position the rollers and other elements of the milling system or its vibrations did not show any effect on the measurement signal.

Testing the thickness of the material layer on the table consisted in measuring the time taken for the ultrasonic wave to pass between the gauge transmitter head and the bulk surface of the material. The time of the signal passage was converted into an electric impulse in a measurement transducer and sent to the data acquisition and processing system. The system also registered the following values: rotary velocities of the rollers and table, pressure and coal feed stream. The algorithm of the developed system consisted of the following issues:

- filtration of the measured data;
- data pre-handling, analysing the data at 100 ms cycles, where the values differing by over 0.5% were rejected (the registered differences resulted from, e.g. the system's vibration or irregular material feed onto the table);
- change of the measurement signals by means of pattern functions, i.e. transfer into SI systems;
- mapping all the measured values (thickness of material layer on the table, rotary velocities of the rollers and table, pressure force and material feed stream) against the actual ultrasonic sensor position on the table;
- registration of the measurement data in the data base.

All the measurable parameters were visualized on-line in order to react instantly to disturbances connected with, e.g. instability of the material feed system or the milling system. Fig. 4 shows an example of the registered signal data.

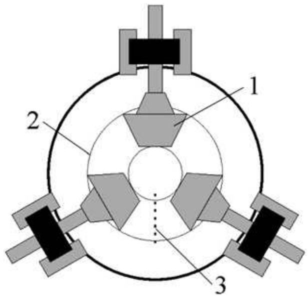

Fig. 3. Ultrasonic gauge movement track: 1—roller, 2—pile-up ring, 3—measurement track.

3. The research methodology

In the tests typical branded types of coal from Opole Power Plant were used, i.e. coal blend GWA and "Piast" coal containing 7.2 and 9.6%

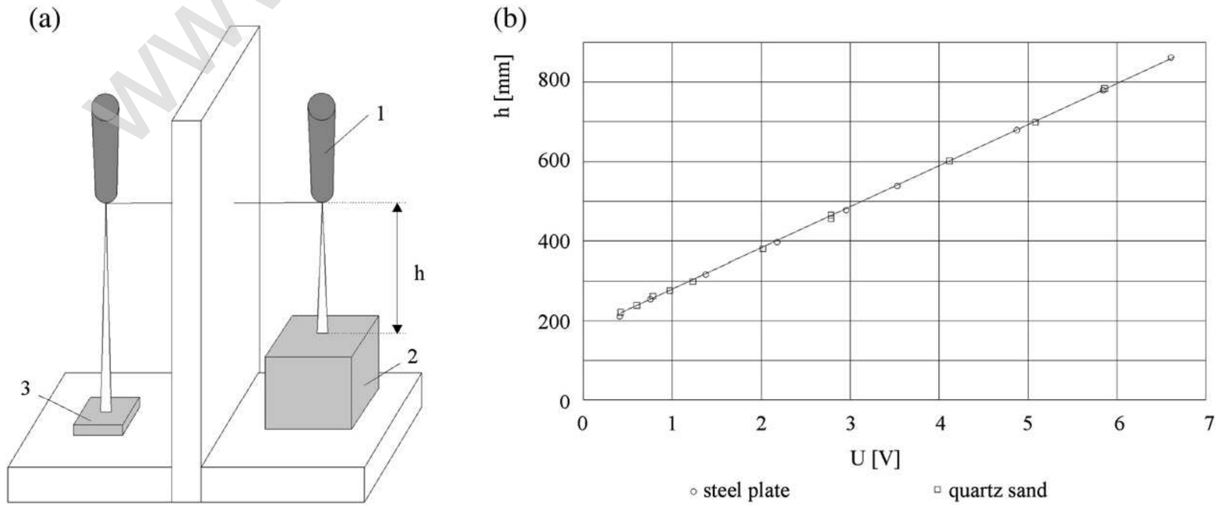

Fig. 2. (a) Test stand for calibrating the ultrasonic gauge. 1—gauge, 2—material vessel, 3—steel plate. (b) Gauge calibration characteristics for a steel plate and quartz sand.

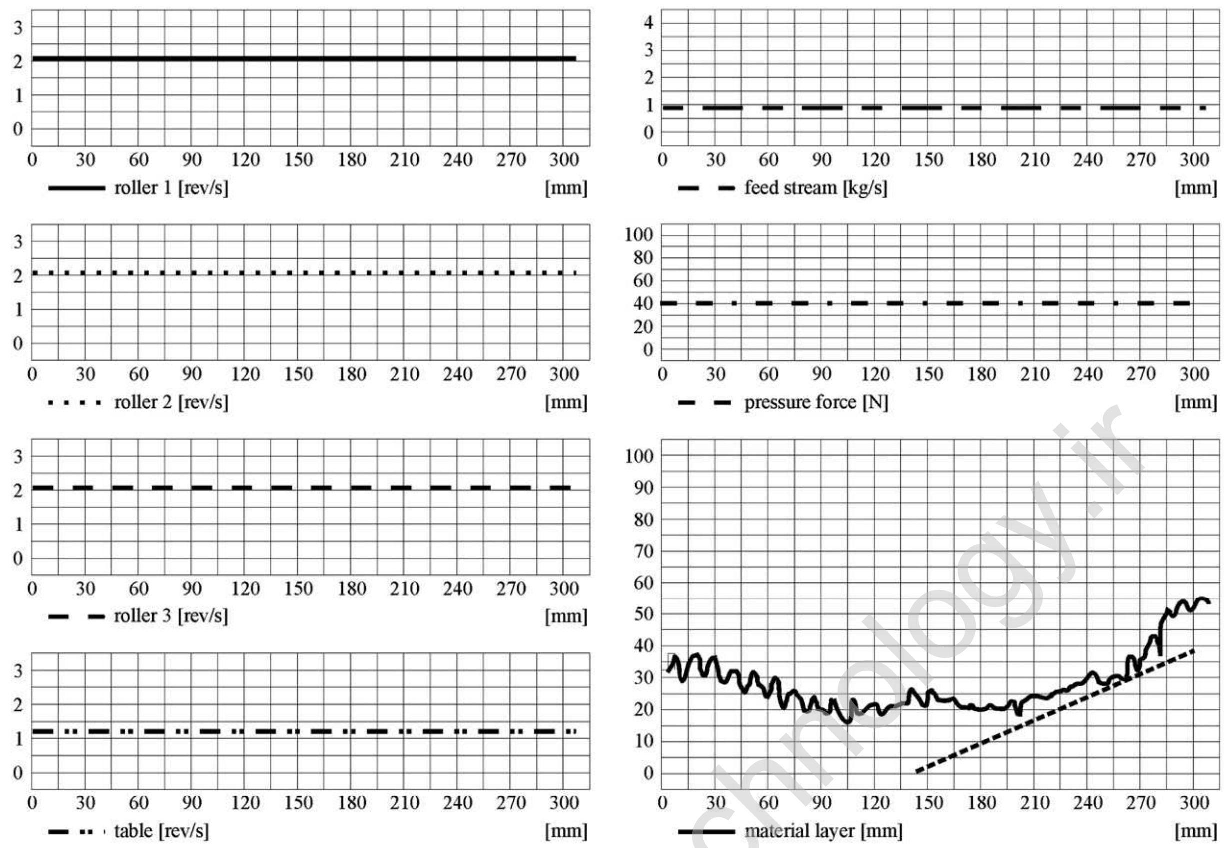

Fig. 4. Examples of measurement results.

of moisture, 23.3 and 24.4% of ash, with the calorific value of 20.2 and 22.1 MJ/kg, 21.1 and 29.3% of volatile matter volume, and 57 and 64 grindability in the Hardgrove index, respectively. After a granulometric analysis of the coal used in Opole Power Plant, and in order to stick to the conditions of an industrial milling system we used the material of maximum grain size below 6400 μm. The assumed size grade and the amount (12 Mg) were obtained by screening ca 40 Mg of coal on a special sieve.

While performing the tests in the model system, all the parameters subject to adjustment in industrial mills were experimentally changed. This is why the measurements were carried out for two different pile-up ring heights, two feed streams, two roller-table positions and five table rotary velocities. All the mentioned parameter changes were realized according to the scheme shown in Fig. 5. The limited number of tests performed for the given ranges of parameter changes resulted from the need to prepare large amounts of grinding material of defined granularity.

A single measurement for the defined rotary velocity was initiated when the table's motor started. On reaching the required rotary velocity of the table, the feeder was started and after less than a minute the feed stream stabilized. Next the measurements of the rotary velocities of the table and rollers, of the feed stream and of the rollers pressure were initiated. If the measured values did not change with time, a scanning system for the material layer on the table was

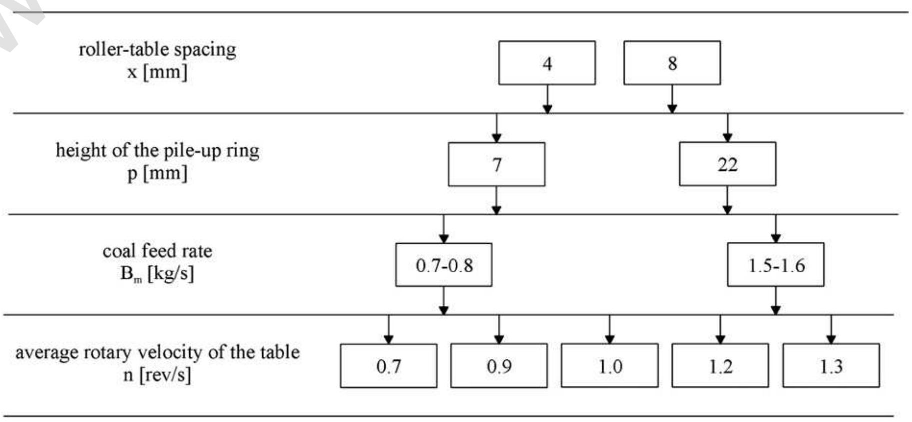

Fig. 5. Changes in test parameters (roller–table spacing, height of the pile-up ring, coal feed rate, average rotary velocity of the table).

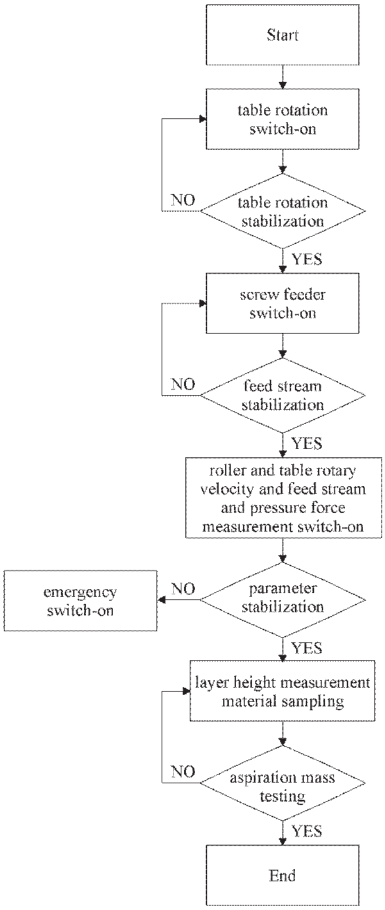

Fig. 6. Measurement algorithm.

switched on; simultaneously material samples were also taken. When fluctuations of the measured values occurred, the following actions were taken: stop the feed stream, stop the mill's motor, and stop the measuring system. A single measurement took about 3 min. During this time the material layer became stabilized with the defined feed stream and rotary velocity. Simultaneously, the table's radius was "scanned", samples were taken before and behind the milling area, and the mass of these samples was checked. Fig. 6 shows an algorithm of the performed experiments.

When the test run for five rotary velocities of the table was over, the milled coal bunker and feed coal bunker were emptied and the latter was filled with a portion of fresh coal.

4. Test results

Determined in the tests, selected values of the layer thickness of quartz sand and hard coal were set up and are shown in Figs. 7–10. In order to make the analysis easier, the rollers shapes are drawn in broken lines on the diagrams.

Execution of the tests for both the quartz sand and for hard coal resulted in the following: the operational examination of the coal mills often revealed a considerable accumulation in the amounts of ash matter (silica) on the table. Its ability to clear itself was difficult because of its bigger specific gravity. In comparison – and under the same conditions – bulks of sand and coal material enabled an assessment of this phenomenon's impact on the material bulk shape. The sand alone, being different from the coal bulk density and having different friction factors, made it possible to maximize the effect.

In comparison with the test results for quartz sand (Figs. 7 and 8) and with those for hard coal (Figs. 9–10) we can identify a considerable similarity in the bulk shapes formed under the same conditions. For both the low pile-up ring (p = 7 mm) as well as the high one (p = 22 mm) the bulks of sand are (at the same rotary velocity) slightly lower than those formed by coal. This results mainly from the coal's higher inner friction and sliding friction against the elements of the milling system i.e. table and rollers.

Here, these are the table rotary velocity and the piling impingement (action) of the rollers that have a crucial impact on the material bulk shape.

By analysing Figs. 7–10, it was observed that in low rotary velocity ranges n = 0.7–0.9 rev/s (upper lines in the charts), there was considerable coal and quartz sand swelling before the rollers, as well as on the flat part of the table (up to approx. r = 200 mm). An increase in the table rotary velocity over n = 1.0 rev/s results in a noticeable tendency for the coal and quartz sand layer to become thinner. For the velocities n = 1.0 to 1.3 rev/s and applying a pile-up ring of the height p = 7 mm, the thickness of the material layer on the table shows little tendency to change within the grinding track, reaching the value of about 15 mm.

Changing the height of the pile-up ring from p = 7 to p = 22 mm causes a considerable increase in the thickness of the layer on the grinding track. This is especially visible at the edge of the track, i.e. for r > 340 mm. In mid track (r = 230–340 mm), the material layer visibly decreases in thickness as a result of the kinematics of the process.

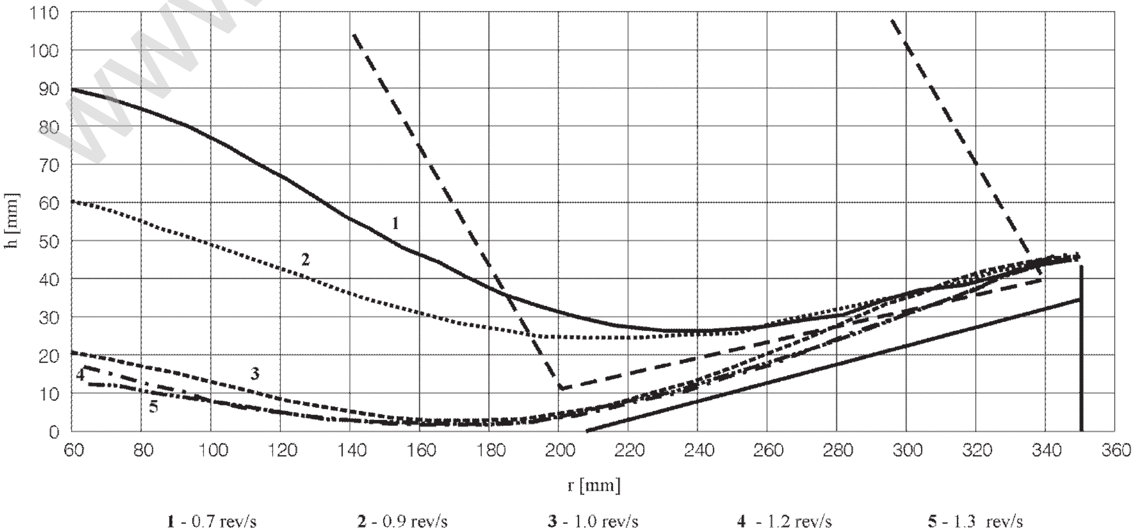

Fig. 7. Quartz sand bulk shape at rotary velocity of the table n as in the legend, pile-up ring height p = 7 mm, table–roller distance x = 8 mm and feed stream B_m = 0.8–0.9 kg/s.

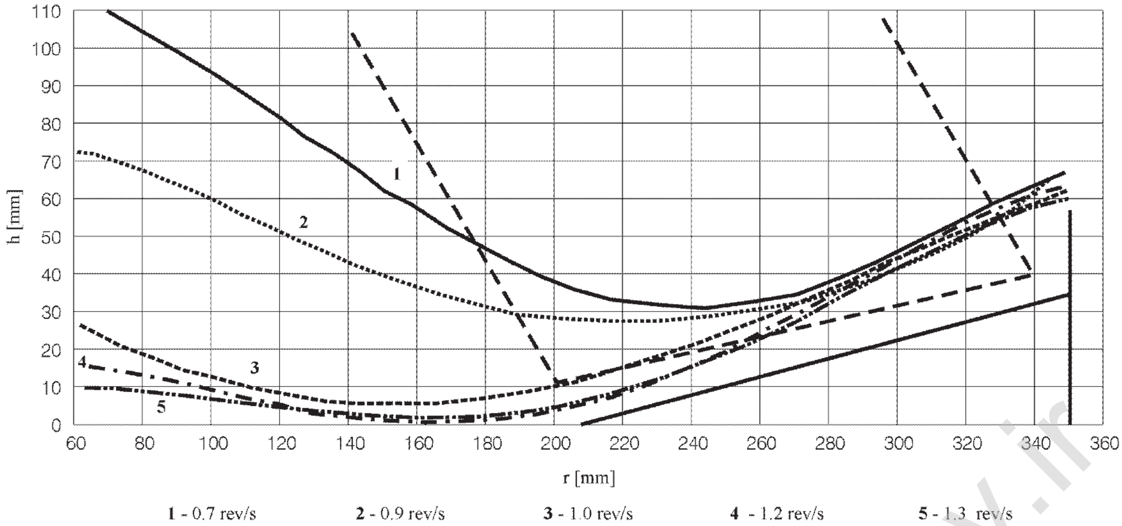

Fig. 8. Quartz sand bulk shape at rotary velocity of the table n as in the legend, pile-up ring height p=22 mm, table–roller distance x=8 mm and feed stream B_m=0.8–0.9 kg/s.

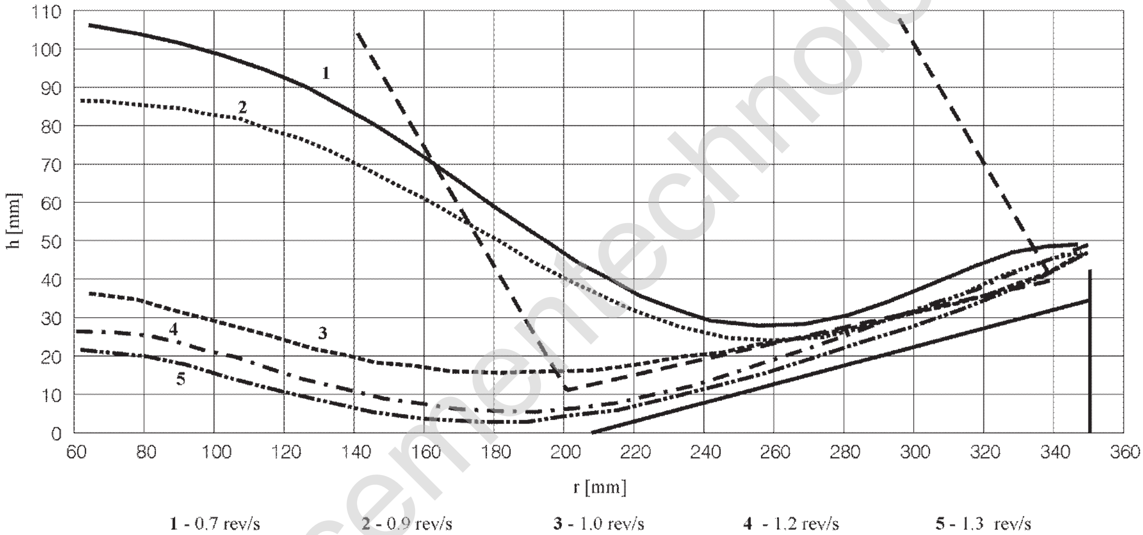

Fig. 9. Hard-coal bulk shape at rotary velocity of the table n as in the legend, pile-up ring height p=7 mm, table–roller distance x=8 mm and feed stream B_m=0.7–0.8 kg/s.

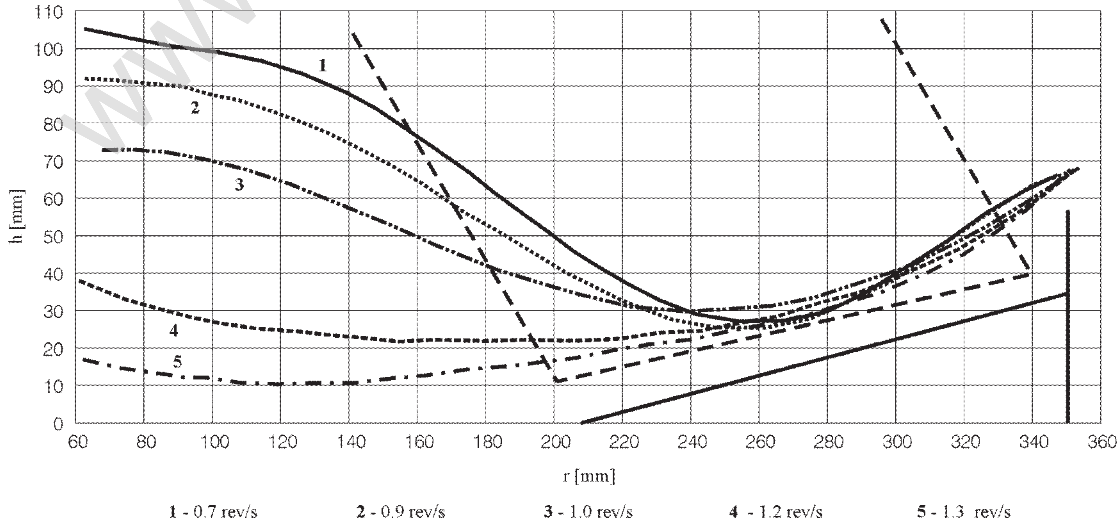

Fig. 10. Hard-coal bulk shape at rotary velocity of the table n as in the legend, pile-up ring height p=22 mm, table–roller distance x=8 mm and feed stream B_m=0.7–0.8 kg/s.

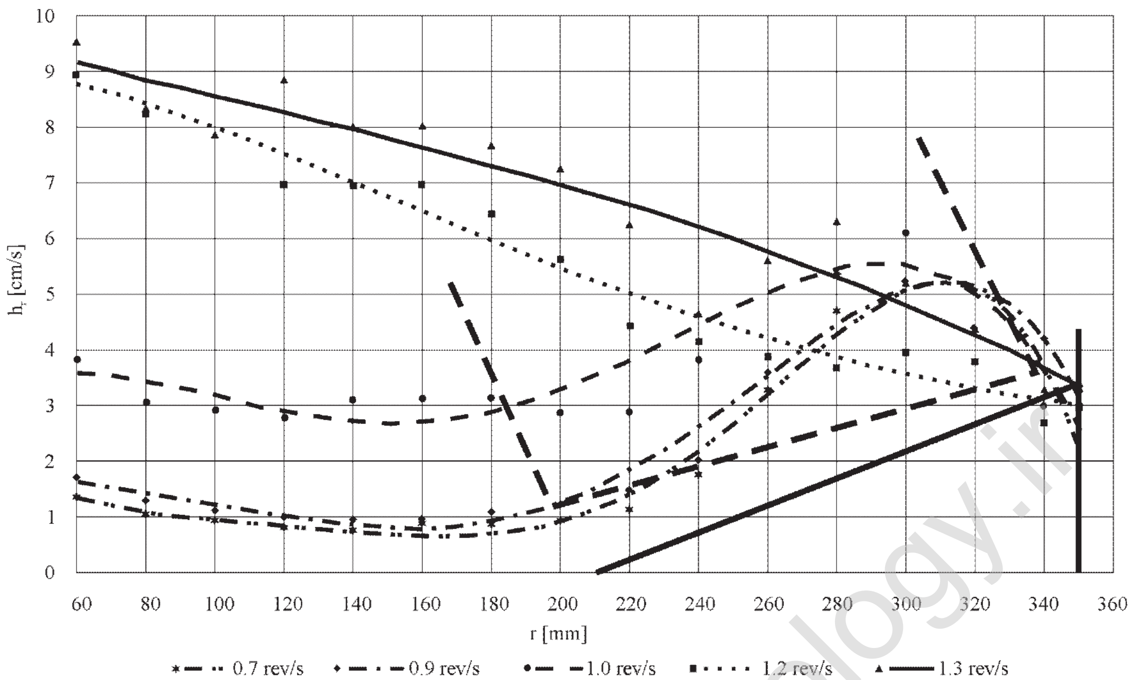

Fig. 11. Calculated average radial velocities v_r for different shapes of bulk coal; height of the pile-up ring $p=7$ mm, table–roller distance $x=4$ mm and feed rate $B_m=0.7–0.8$ kg/s.

On the basis of the determined bulk shapes on the table, average radial velocities of the material were calculated (Figs. 11 and 12). The following assumptions were made:

- the coal on the table is a body of revolution,
- the material density ρ is constant within the bulk, equal to that determined in static conditions,
- the bulk shape is defined by the function $h(r)$ resulting from the measurement of the coal layer thickness.

Taking into account the above assumptions, in order to determine average radial velocity the following equation (linking this velocity with the material stream B_m) was used:

$$B_m = v_r \cdot A \cdot \rho, \tag{1}$$

where A is the area of the bulk's vertical section the grind material moves through

$$A = (2 \cdot \pi \cdot r \cdot h(r) - S(r)), \tag{2}$$

in the above equation $S(r)$ is the area of the bulk's vertical section occupied by the rollers.

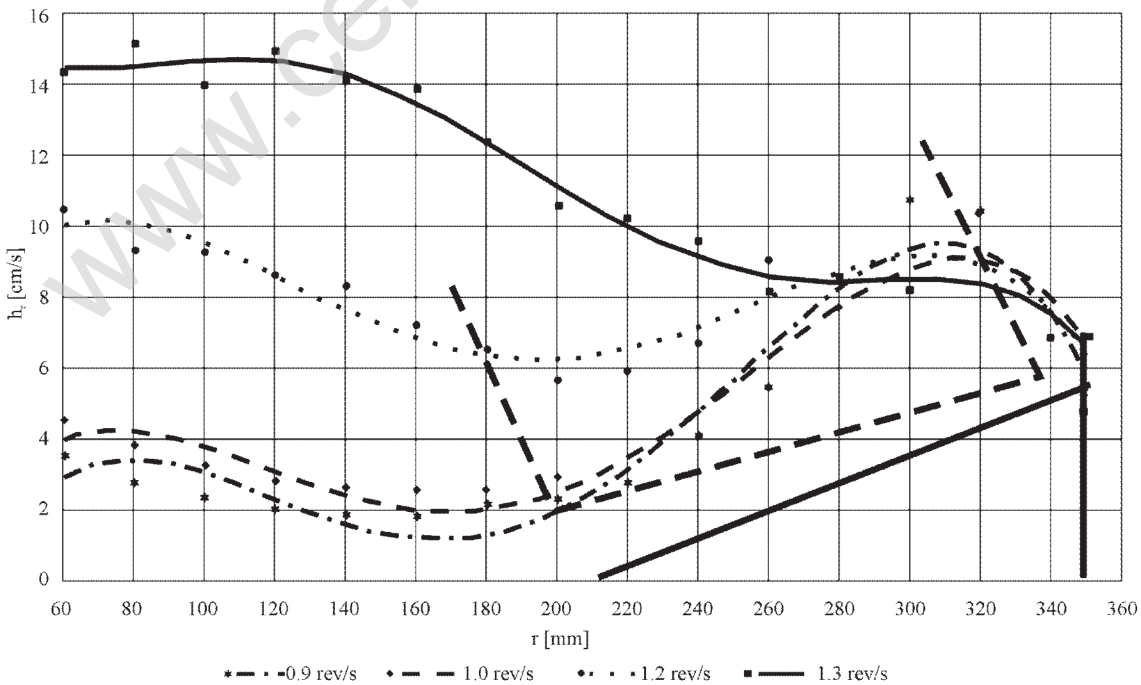

Fig. 12. Calculated average radial velocities v_r for different shapes of bulk coal; height of the pile-up ring $p=7$ mm, table–roller distance $x=4$ mm and feed rate $B_m=1.5–1.6$ kg/s.

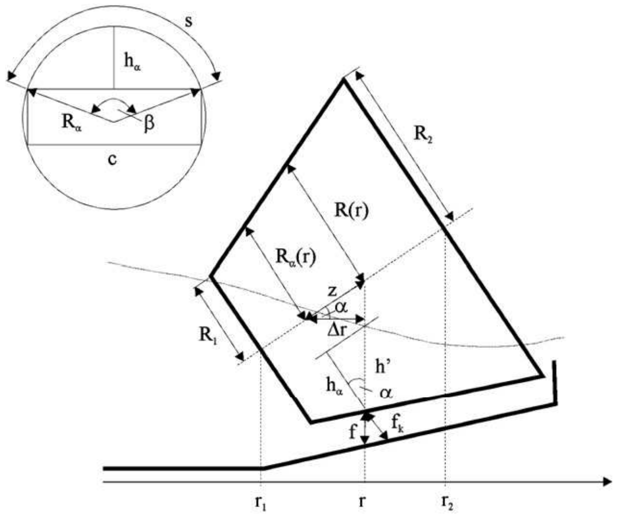

Fig. 13. Notation for roller 'immersed' in bulk material.

Determining the area $S(r)$ requires the introduction of an appropriate formula. Fig. 13) shows a roller "immersed" in the material bulk, and the assumed notation.

For the table's radius equal r_1 the roller's radius is R_1, and R_2 is for the table's radius r_2 respectively. Because of the linear dependence of the roller radius on the table radius we can write the following:

$$R(r) = a \cdot r + b \tag{3}$$

where a and b are coefficients. Using the above conditions, introducing them into Eq. (3) and determining a and b we obtain:

$$R(r) = \frac{R_2 - R_1}{r_2 - r_1} \cdot r + R_2 - \frac{R_2 - R_1}{r_2 - r_1} \cdot r_2, \tag{4}$$

In accordance with Fig. 11, α is an angle between the plain parallel to the roller front and the vertical plain, and is a structural (construction) feature of the table–roller system. Also, according to Fig. 11, the height of the grind material layer along the radius r equals:

$$h(r) = h' + f \tag{5}$$

The value f, with a good approximation, represents the size of a gap between the table and the roller. Thus we can write:

$$h(r) = \frac{h_\alpha}{\cos\alpha} + f \tag{6}$$

Having measured h, and knowing f and α, we can determine h_α.

According to the notation in Fig. 11, the following can be written:

$$\Delta r = R(r) \cdot \sin\alpha \tag{7}$$

and

$$R_\alpha = R(r - \Delta r). \tag{8}$$

The area of the circular sector corresponding to h_α can be expressed by

$$S_\alpha(r) = \frac{1}{2}(s \cdot R_\alpha - c(R_\alpha - h_\alpha)) \tag{9}$$

where:

$$c = 2R_\alpha \sin \arccos\left(\frac{R_\alpha - h_\alpha}{R_\alpha}\right) \tag{10}$$

and

$$s = 2R_\alpha \arccos\left(\frac{R_\alpha - h_\alpha}{R_\alpha}\right). \tag{11}$$

Then the area $S(r)$ in the area of the bulk's vertical section occupied by the three rollers is

$$S(r) = 3 \cdot S_\alpha(r) / \cos\alpha. \tag{12}$$

An analysis of average radial velocities of the coal on the milling track shows that they do not exceed $v_r = 15$ cm/s.

The average radial velocities v_r within the whole range of values of the table's radius r tend to diminish when the grinding material moves on the table having no contact with the rollers. This is shown in the results obtained for the table's rotary velocity $n > 1.0$ rev/s and the feed stream $B_m = 0.7–0.8$ kg/s. Getting the rollers harnessed to the system causes a considerable increase of the average radial velocity around the front of a roller.

Average radius wise velocities in the vertical section of the bulk may decrease also with the use of the high profile pile-up ring increasing the thickness of the layer. It is noteworthy that high-profile pile-up rings considerably reduce the average radial velocity of the material (even by several cm/s) at the edge of the table.

It can also be observed that the average radial velocity of the material is higher for larger feed streams. An explanation for this effect is that the thickness of the material layer increases in proportion to the feed stream volume.

Apart from the above, a visualization testing technique was also used here. This consisted in filming markers that moved over the material surface layers. The markers were white gravel grains 3–4 mm in diameter (Fig. 14). The markers were fed onto the table together with the coal through an opening in the feeder casing. The majority of the markers, as observed, got mixed with the coal, which considerably hindered the analysis. However, some frames with visible markers on them could be selected. The markers were then defined by their position coordinates (x, y) (see Fig. 15). The basis for determining all

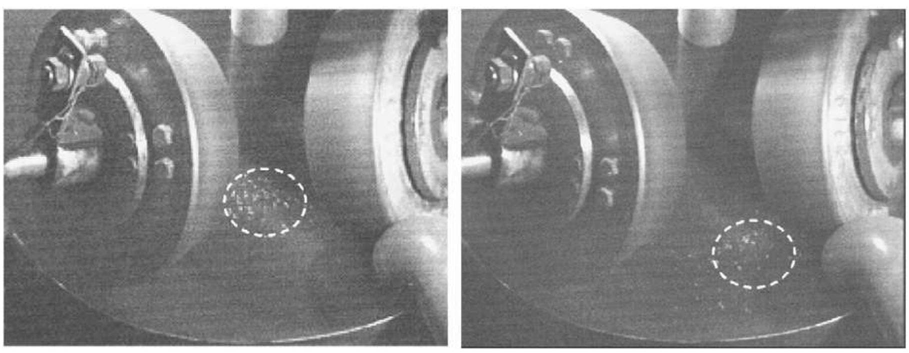

Fig. 14. Pictures of moving markers.

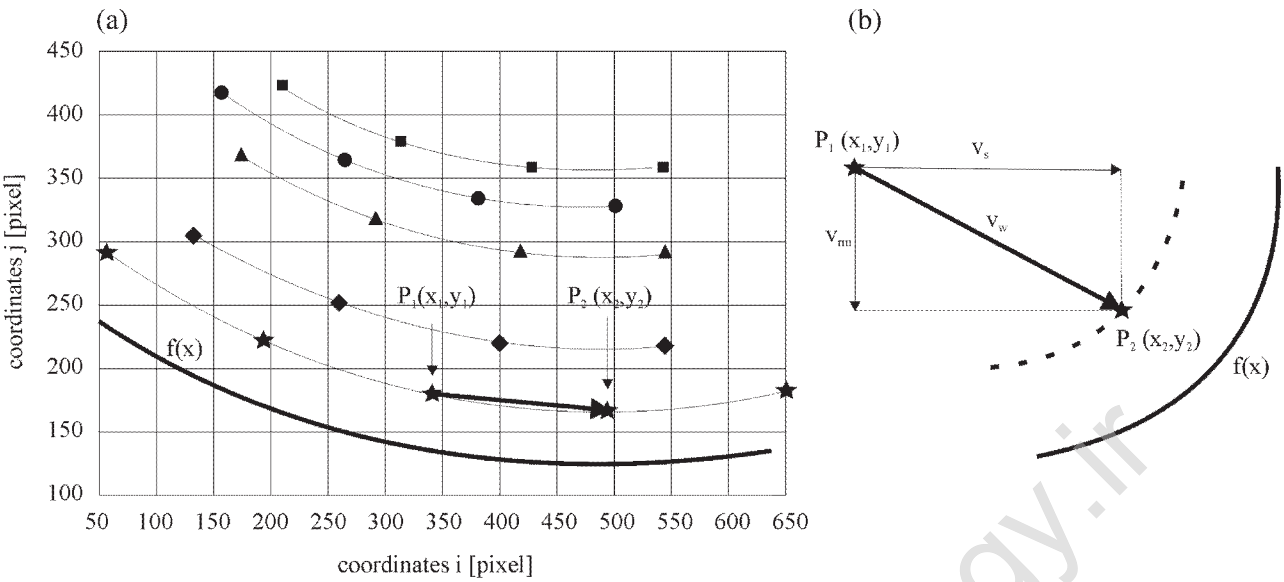

Fig. 15. (a) Marker movement trajectories. (b) Determination of velocity components v_s—tangential, v_{rm}—radial, v_{cr}—resultant, $f(x)$—pile-up ring approximating function.

the distances was the pile-up ring. Based on the markers' position coordinates and the function $f(x)$ approximating the pile-up ring shape, the least distances among the points Δr_{min} along the radius were determined by minimizing the functional

$$\Delta r_{min} = \left(\min\rightarrow\left(\sqrt{(x_n-i)^2+(y_n-f(i))^2}-\sqrt{(x_{n+1}-i)^2+(y_{n+1}-f(i))^2}\right)\right), \quad (13)$$

where $i=(0–700)$ and $n=(1, 2, 3, 4, 5,\dots)$.

In order to determine the radial component of the velocity of a marker on the bulk surface, the time Δt between individual frames was used:

$$v_{rm} = \frac{\Delta r_{min}\cdot e}{\Delta t} \quad (14)$$

where the coefficient e is responsible for the transformation of the coordinate system registered by the camera into the real one.

It was observed during the test that the milled coal layer was overlaid by the layer flowing round a roller. The radial velocity of the upper layer of coal reached about 66 cm/s as measured by the location of the markers.

Measuring the movement of the markers over the coal bulk surface (Fig. 16) indicates that the radial components of the velocity on the milling track tended to decrease for a radius exceeding $r=200$ mm, where the rollers gradually reduced their ability to cause the material to swell. For the rotary velocity of the table below $n=1.0$ rev/s and above the radius $r=260$ mm, the rotary velocities of the markers did not exceed $v_{rm}=10$ cm/s. At 60 mm away from the pile-up ring, it could be observed that the markers' radial velocities are similar to those (v_r) determined by measuring the thickness of the material bulk at a given table radial segment.

It can be stated that within the milling track there are big differences in radial velocities of the material as a function of its

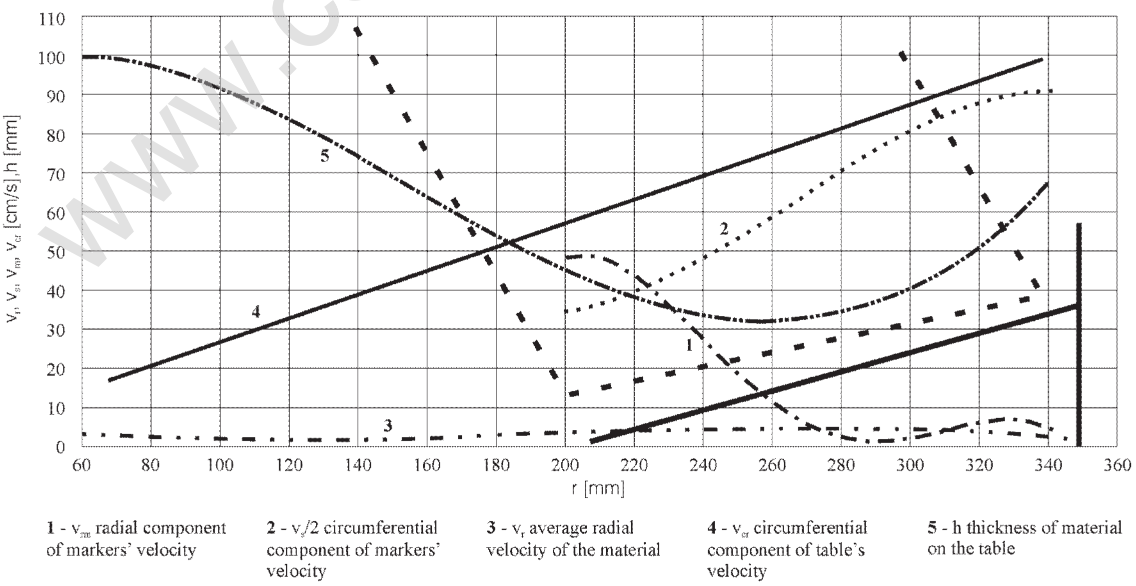

Fig. 16. Velocity values as in the legend (radial component of markers' velocity, circumferential component of markers' velocity, average radial velocity of the material, thickness of material on the table, circumferential component of table's velocity) for rotary velocity of the table $n=0.9$ rev/s, pile-up ring height $p=22$ mm, table-roller spacing $x=8$ mm and feed stream $B_m=1.5–1.6$ kg/s.

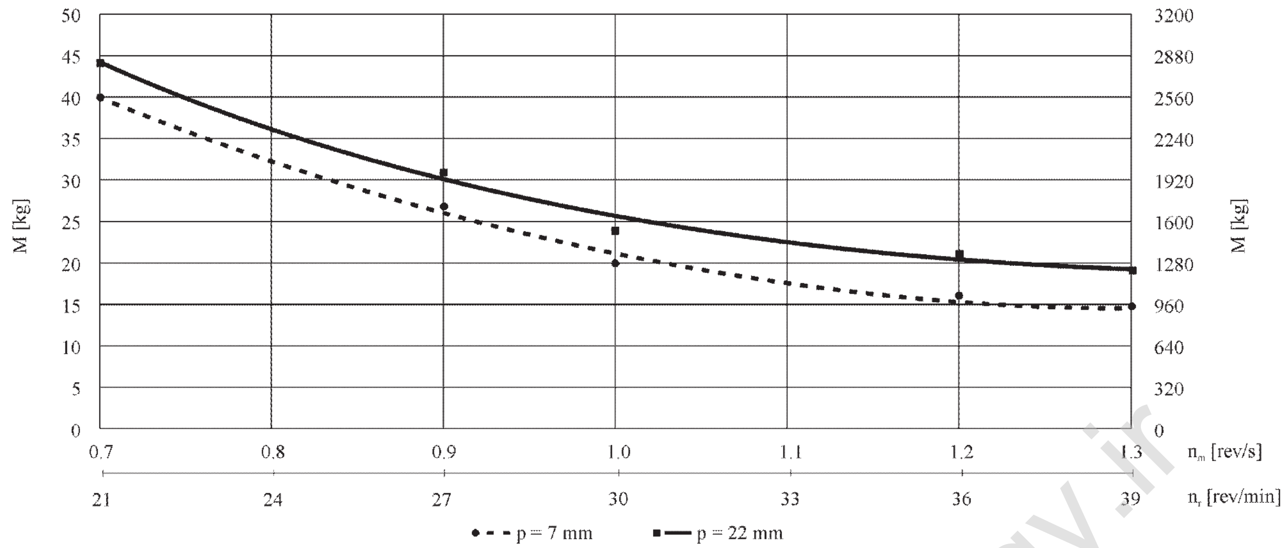

Fig. 17. Coal mass *M* on the mill table at rotary velocity of the table *n*, pile-up ring height *p* as in the legend, table–roller spacing $x=8$ mm and coal feed stream $B_m=1.5–1.6$ kg/s.

thickness. This mainly results from the tendency of the rollers to pile up the material. This can be confirmed not only by the differences between the radial velocities of the material surface layer and its average radial velocity, but also by the surface layer-table sliding. The closer to the table's rim, the smaller are the differences. This confirms that assuming a constant, static material bulk density is justifiable within a considerable part of the analysed system. Basic differences in the test results obtained with different methods confirm the conclusion that the movement of the material in the direct vicinity of a roller's front shows considerable differentiation in its radial velocity within the bulk. This is a key area in the functioning of a mill and thus demands special attention.

The last stage of the material movement testing was determining the mass *M* of coal on the mill's table. At the table rotary velocities $n>1.0$ rev/s the thickness of the coal and the quartz sand layers tends to decrease. The change means that there is less material accumulated on the table. In order to determine the material mass, a similar assumption as for average radial velocity calculations was received. Having determined from the measurements the function $h=f(r, n, B_m)$, it was possible to determine numerically the bulk volume taking into consideration that part of this volume is occupied by the rollers.

The measurements confirmed that the material mass *M* on the table depends not only on the table rotary velocity n and the feed stream B_m, but also on the pile-up ring height (Fig. 17). It is obvious that within the whole range of the table rotary velocity, the material volume is bigger for a higher pile-up ring $p=22$ mm than for a ring with $p=7$ mm. A change of the rotary velocity causes accumulation or release of a certain amount of the material. For example, for hard coal, a change within the range $n=1.0$ to 1.3 rev/s results in the release of about 8 kg. In a real industrial mill, this corresponds to $M=512$ kg.

5. Summary

This research was aimed at analyzing bulk shapes of quartz sand and hard coal as the grind material on the table of a ring-roller mill. It was observed that the height of sand layers, in the same conditions, is slightly smaller than of the ones formed by coal. However, the dominant impact on the bulk shape is that of the table's rotary velocity and the rollers piling impingement (action) on the grind material. The height of the pile-up ring is of importance, too.

On the basis of the measured coal layer's height on the table we calculated average radial velocities of the material. The calculations were made for two coal feed streams and two different heights of the pile-up rings. In each case the results were taken at five different rotary velocities of the table. The test showed that the average radial velocity, in the bulk's cross section, does not exceed 15 cm/s. At higher table's rotary velocities the radial velocity is inversely proportional to the length of the radius *r*. At lower velocities of ca 0.7–0.9 rev/s it is noticeably smaller but only within the rollers area. This is connected mainly with an increase in the grind material layer's height together with the roller-generated limitation of the vertical surface area which the feed stream flows through.

The results were then supplemented with tests based on the movement of markers over the surface layer of the coal bulk. These tests enabled to determine the material's average radial and tangential velocities in the surface layer. It was found out that across the width of the milling track there is considerable differentiation of the material's velocity along the radius in the function of the layer height. This is mainly due to the piling impingement of the rollers. The closer to the table's edge the smaller the differences are.

A change in the table's rotary velocity results in accumulation or release of a considerable part of the material. Thus, the rotary velocity may be a useful parameter in the mill control system. This is why the tests also concerned the mass volume of the material accumulated on the table.

It was also observed that for a specific mill charge and table-roller gap, there is a range of rotary velocities where the surface layer, within the milling track, is parallel to the table's surface, and its thickness should allow effective milling to take place. Simultaneous tests on milling effects [11] confirm that the optimal rotary velocity for the considered milling system is about 1 rev/s.

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