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Simulational and experimental determination of the exploitation parameters of a screw conveyor

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Highlights

- The influence of the DEM model parameters on the results of the simulations is significant.
- DEM study and experimental test results of the screw conveyor are in a great agreement.
- Determination of the conveyor's exploitation parameters using DEM method is possible.

Abstract

The paper discusses the designing process of screw conveyors, with regard to the determination of the exploitation parameters of such devices with the use of the Discrete Element Method (DEM). The influence of the chosen model input parameters on the results of the simulations was examined. The key parameters which determine the exploitation characteristics of a screw conveyor were identified as follows: the size of a DEM particle, coefficients of internal and external friction. Experimental measurements of the laboratory screw conveyor provided the actual exploitation characteristics of a device used for the transportation of a limestone powder. The comparison of the results of the simulations and experiments gave satisfactory results. For this reason, DEM simulations were identified as an effective tool for determining and optimization of the construction and exploitation parameters of the screw conveyors.

Keywords

screw conveyor, Discrete Element Method, bulk material, exploitation characteristics.

1. Introduction

Screw conveyors can be used either as independent conveyor systems or as a part of a production line, for example in lime, cement, energy, food, or agricultural industry plants. Screw conveyors have two key advantages: a simple construction and easy adjustment of their efficiency for a given application. However, the behavior of bulk materials during the transportation by a screw conveyor is a very complicated process, dependent on a number of factors, such as rotational speed of the screw, filling rate, or physical properties of the transported material. Up-to-date methods of designing screw conveyors are based on the algorithm which takes into consideration characteristic dimensions of a screw, rotational speed of a shaft, bulk density, and empirical coefficients characteristic for a given bulk material [15, 19]. In the case of standard bulk materials, such as limestone or cement, these methods allow the design of fully-functioning conveyors; however, in the case of, for example, highly abrasive, fragile or strongly cohesive materials, traditional methods of designing do not give satisfactory results. As a consequence, the devices are usually oversized and face difficulties in reaching the required performance. This is why, the identification of physical properties of the transported material is vital while designing this kind of devices. What is more, as it was demonstrated in [18], the efficiency of a screw conveyor is strongly correlated with the properties of the transported bulk material. For this reason, the designs of screw conveyors are very frequently based on the past experience in designing and exploitation of the designers [2].

Currently, the designers are able to choose geometrical and exploitation parameters of the screw conveyors with the use of the simulation tools, which allow the examination of the behavior of a bulk material during the transportation by a screw conveyor. Usually, the behavior of bulk materials is simulated with the use of the Discrete Element Method (DEM). It allows the determination of a conveyor's operating parameters, such as the mass efficiency and the power demand. However, in order to reflect the behavior of a bulk material during the transportation by a screw conveyor and, as a result, obtain reliable results of the simulation, it is inevitable to determine precisely the material parameters which describe the DEM model, based on actual physical properties of the transported bulk material.

Since many years, screw conveyors have been a subject of simulation studies with the use of DEM method. Numerous studies discussed the verification of the computational model with regard to the efficiency of the conveyor. The authors of [11] showed a good agreement between the results of mass efficiency determined in the DEM simulation and in the experimental study of an "OLDS" elevator (a special case of a screw conveyor, in which the trough rotates around the fixed screw, causing axial movement of the material). In the paper [13] the authors present the results of laboratory tests, computer simulations, and theoretical calculations of the mass efficiency of a screw conveyor in relation to its rotational speed and the angle of inclination. It was proven that DEM analyses provide a good agree-

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ment with reality in the case of conveyors which transport materials horizontally and vertically. In the case of the in-between angles of inclination, DEM simulations underestimate the mass efficiency of the conveyors in relation to the reality. Simulation studies described in [10] showed that the increase of the filling rate and rotational speed of the screw caused the increase of the conveyor's efficiency. The authors of [14] simulated a few different versions of a screw conveyor (a screw with a constant external diameter of the shaft and flights and constant pitch, a screw of a varying pitch, a screw on a shaft of variable external diameter). Simulations and experiments showed a very good agreement between the results of mass efficiency for all the considered versions, apart from the case with the screw of a varying pitch, for which the simulated mass efficiency was underestimated by 24%. This discrepancy was justified with the use of too large DEM particles in the simulation in comparison with the screw pitch. Simulation studies were also conducted in order to analyze the influence of DEM model input parameters on the results of the simulation. In [11], the influence of external friction and restitution coefficients on the results of the DEM simulations was examined, with regard to the conveyor's mass efficiency and the power demand. The studies showed that the increase of the friction coefficient caused the decrease of the mass efficiency and the increase of the power demand. The influence of the coefficient of restitution on the simulation results was minimal. A similar relation between the values of the friction coefficient and the mass efficiency of the conveyor was observed in [10]. The influence of the radius of a DEM particle on the simulation results was analyzed in [14]. It was observed that the conveyor's efficiency decreases with the increase of the particle radius. On the other hand, for the radius smaller than 0.8 mm, the observed mass efficiency was independent of the DEM particle's size.

Studies to date have shown that DEM simulations of the transportation of bulk material by a screw conveyor provide reliable results. However, very little attention has been given to the estimation of the screw conveyor's power demand. The correct determination of the power and efficiency allows the determination of exploitation characteristics of a conveyor, which in turn facilitates the choice of the device's exploitation parameters, with regard to the energy consumption and effective transportation of the material.

The authors of the above studies have also noticed reasonably that the results of the simulation depend strongly on the DEM model input parameters, such as the radius of a particle or the coefficient of external friction. However, there is a lack of knowledge on the importance of the remaining parameters describing the model, such as the coefficient of internal friction or the coefficient of rolling resistance, for the results of the simulation. Since the conveyors can be working at different rotational speeds and for different filling rates, it seems reasoned to verify the influence of these remaining DEM parameters on the simulation results.

The following paper discusses comprehensively the influence of the DEM model input parameters on the results of the exploitation parameters of a screw conveyor, depending on the filling rate and rotational speed of the screw. The results of the analysis provide information on the qualitative and quantitative influence of the particular DEM model parameters on the results of the simulation, with regard to the mass efficiency and the power demand. This allows a correct definition of a numerical DEM model of the transportation of a bulk material, which can be used for the determination of geometrical and exploitation parameters of a screw conveyer. This approach can be used for designing effective conveyors with minimized power demand, reduced mass, and decreased wear of the screw flights. The paper also describes a comparison of the exploitation characteristics of a screw conveyor obtained by simulations and in an experiment.

2. Description of DEM simulations

A constant development of Computer Aided Engineering (CAE) has made computer simulation methods a significant tool used both for scientific research purposes and as a support in design and construction works. High computational powers of computers and a common use of computer programs with developed numerical methods implemented facilitate modeling of complicated physical phenomena with great accuracy with regard to the reality. This is why, with the help of computer simulations, a quick verification and comparison of numerous ideas is possible, without the need of building and testing expensive prototypes. In the case of continuum mechanics, a Finite Element Method (FEM) is successfully used [3, 12], and in the field of fluid dynamics – Computational Fluid Dynamics (CFD) [21]. For the granular materials, a Discrete Element Method (DEM) has been developed [17]. The theoretical basis for this method is the assumption that the modeled material is treated as a group of distinct particles interacting with each other repeatedly. The algorithm is based on contact mechanics; with the use of different contact models, the forces acting upon the particles are determined.

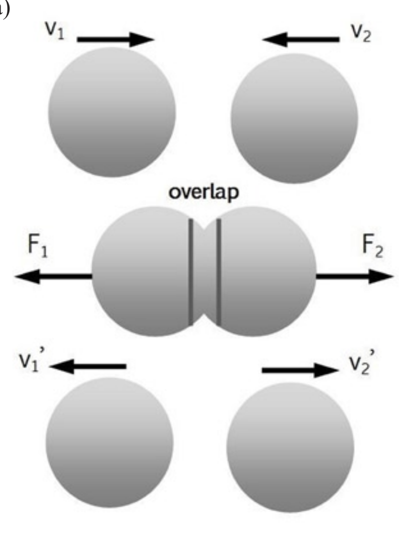
Based on the Newton's laws of motion, the accelerations of the particles are calculated; then, the velocities and coordinates of the DEM particles at a certain time are determined through the integration of the equations [22]. It is assumed that the modeled objects (particles) are solids; however, DEM algorithm assumes the deformation of the particles during the collisions. The depths of the reciprocal overlaps are calculated under the assumption that the shapes of the objects remain unchanged (Fig. 1a).

The contact model connects the depth of the overlap (calculated at normal and tangent directions to the direction of the movement of the colliding particles) and the value of the contact force.

Fig. 1b) shows a contact model of two particles during the collision. A variety of developed contact models gives possibilities of modeling various interactions between the particles, such as the model of interaction with friction but without cohesion, or the model of tension resistant interaction (with cohesion).

The behavior of a bulk domain consisting of a great number of DEM particles is influenced by the parameters of the individual particles (size, shape, density), as well as by the contact parameters (coefficients of friction, rolling resistance, coefficient of restitution) [1, 4, 6]. A basic shape of a DEM particle is a sphere; however, actual grains or chunks of a ma-

a)



b)

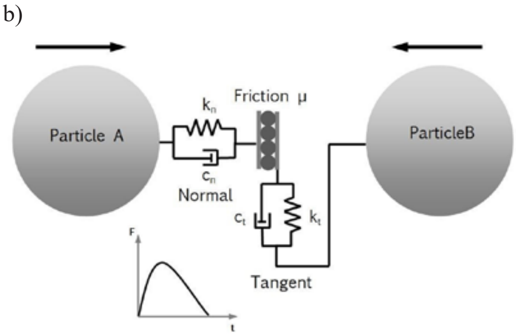


Fig. 1. a) The collision of rigid particles, where: v_1, v_2 – velocities of the particles before the collision, F_1,F_2 – forces resulting from the collision, v_1', v_2' – velocities of the particles after the collision;

b) a contact model of two particles during the collision, where: k_n – stiffness modulus, normal to the surface of the contact, k_t - stiffness modulus, tangent to the surface of the contact, c_n – viscous damping coefficient, normal to the surface of the contact, c_t – viscous damping coefficient, tangent to the surface of the contact, μ – Coulomb coefficient of friction terial hardly ever are of a perfect spherical shape. This is why, DEM simulations allow building complicated shapes, resulting from permanent merging of spherical particles into undividable objects (clumps). However, it causes a significant increase of the computational time. Therefore, it is crucial to find a compromise between the actual and the modeled size and shape of the particles [16]. In order to reflect the real behavior of the material in DEM simulations, the model input parameters (friction coefficients, density, etc.) must be calibrated based on the actual properties of the bulk material [4, 6, 9].

3. The influence of DEM model input parameters on the exploitation parameters of a screw conveyor

The adopted values of DEM model input parameters, i.e., sizes of the particles, coefficients of internal and external friction, the coefficient of restitution, or the rolling resistance define the behavior of the bulk material, as it was shown in a number of papers [5,7,8,20]. This is why, a correct definition of a material DEM model is crucial in the simulation of the transportation of a bulk material by a screw conveyor. In an engineering practice, it is often the case that the data on the physical properties of the material is incomplete. This is why, a commonly used approach is to arbitrarily adopt the missing values.

The paper presents an analysis of the influence of the chosen DEM model input parameters on the values of the mass efficiency and the power demand of a screw conveyor. A part of a screw conveyor of the following parameters was modeled: the external diameter of the flight D_{out}= 160 mm, the shaft diameter d_{in}= 70 mm, the screw pitch s = 75 mm. The total length of the model was l = 150 mm, which corresponded to the double of the screw pitch. In order to ensure a constant flow of the material, a periodic boundary condition was used in the model (Fig. 2).

For the need of the performed simulation studies, two filling rates were adopted: 50% and 95%. DEM particles were spherical and of a uniform size. The simulations of the transportation of the material were carried out for three different rotational speeds of the screw shaft, i.e., 10, 40, and 80 rpm. The simulation time was chosen individually for each rotational speed, so as to allow at least three full revolutions of the shaft. This ensured the stabilization of the transported material. A commercial software EDEM 2019 was used.

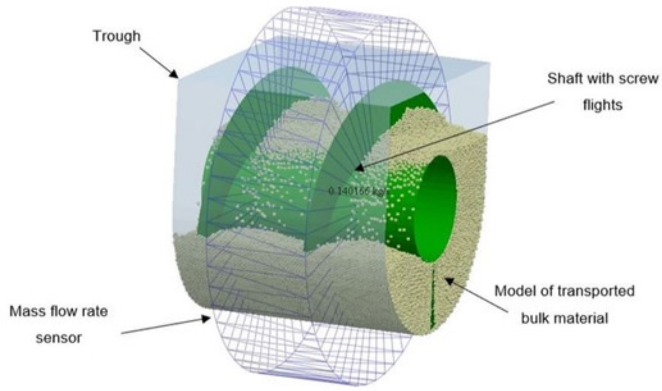


Fig. 2. A view of the modeled part of the screw conveyor.

Figs. 3 and 4 show the results of the analysis of the influence of the chosen DEM model input parameters on the mass efficiency and the power demand of the screw conveyor. In order to facilitate the interpretation of the differences between the results, normalized values were used.

Fig. 3 shows the influence of the particular DEM model input parameters on the results of the mass efficiency of a screw conveyor. Fig. 3a) shows the influence of the particle size on the results of the simulation. It can be noted that the mass efficiency decreases with the increase of the particle radius in the whole range of the considered rotational speeds. This trend is particularly noticeable for the high fill-

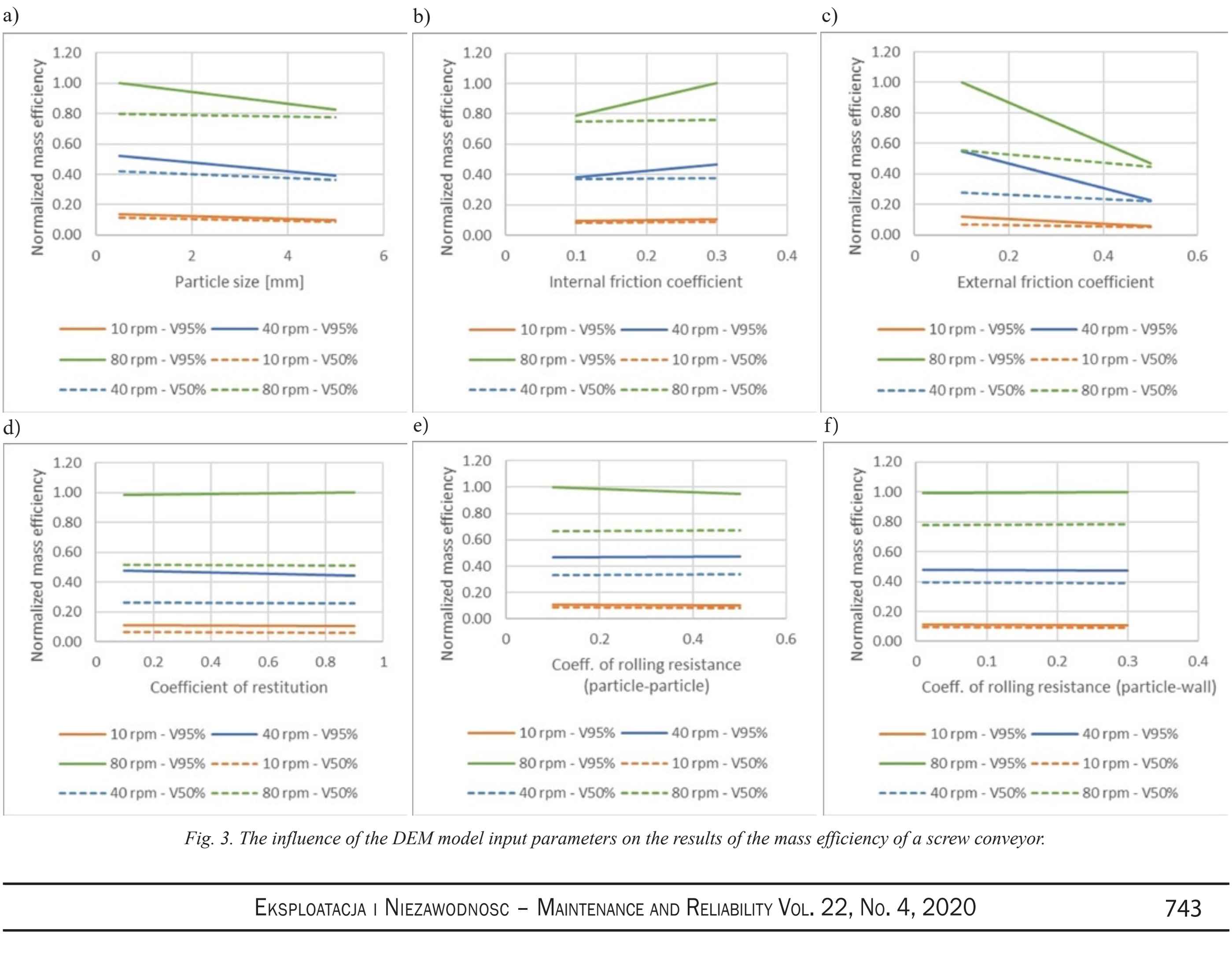


Fig. 3. The influence of the DEM model input parameters on the results of the mass efficiency of a screw conveyor.

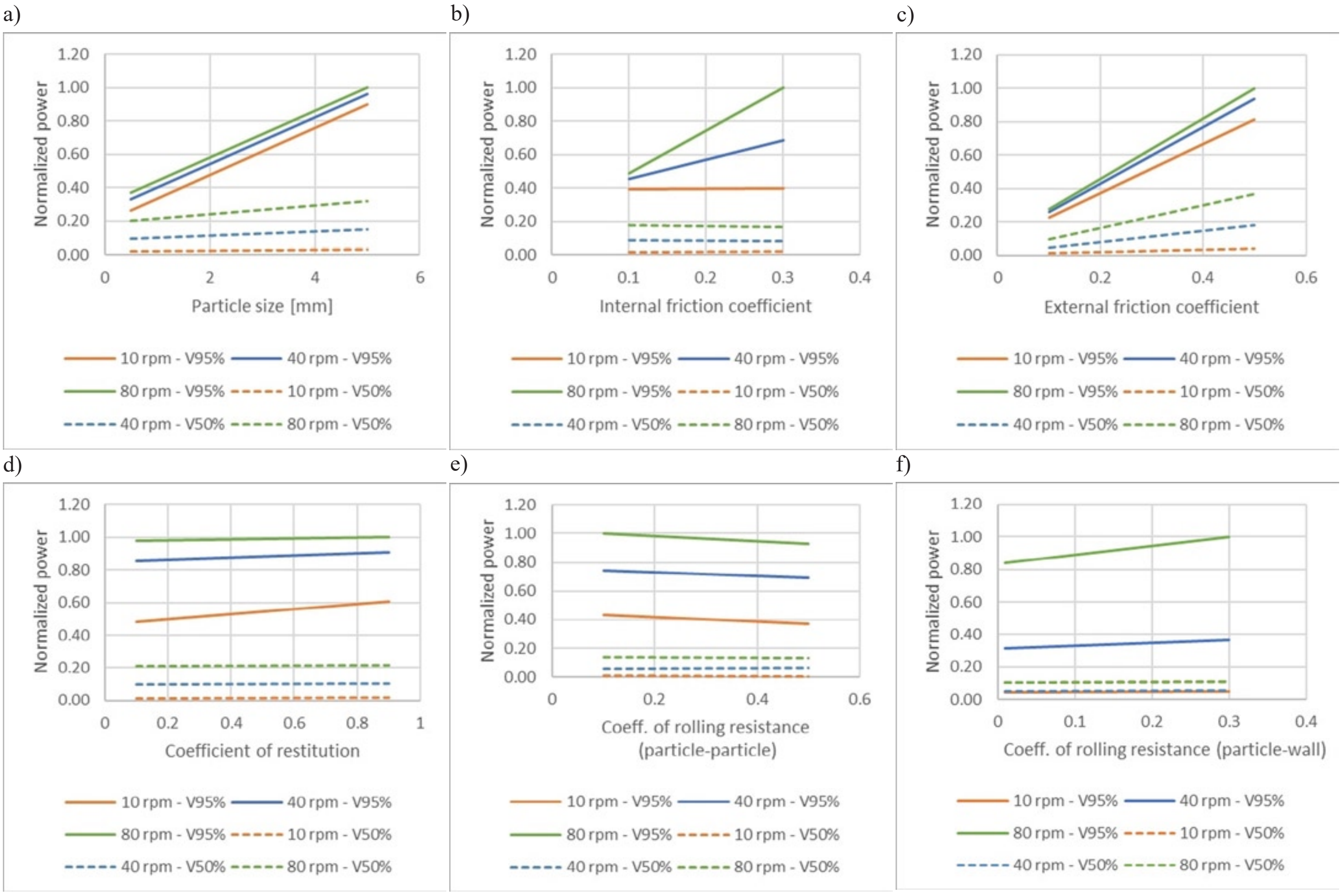


Fig. 4. The influence of the DEM model input parameters on the results of the power demand of a screw conveyor

ing rate. In the case of 50% filling rate, the drop of the mass efficiency is less visible. The increase of the internal friction coefficient of a bulk material caused the increase of the mass efficiency in the case of the high filling rate for all the rotational speeds of the shaft. In the case of a partial filling rate, the results of the simulation are barely dependent on the value of the coefficient of internal friction, which is shown in Fig. 3b). The increase of the coefficient of external friction caused a significant drop of the efficiency in the whole range of rotational speeds, especially for the high filling rate, which is shown in Fig. 3c). Figs. 3d)-f) provide information on the influence of the coefficient of restitution and rolling resistance values on the simulated mass efficiency of the screw conveyor. The above figures show that these coefficients hardly change the results.

Fig. 4 shows the influence of DEM model input parameters on the results of the power demand required for the transportation of a bulk material by a screw conveyor.

The results of the performed analysis show that the enlargement of a DEM particle increases the power demand, in particular for the high filling rate, which is illustrated by Fig. 4a). A similar effect can be observed in the case of the increase of the coefficient of internal friction. For the high filling rate, the lower was the rotational speed, the smaller was the increase of the power demand caused by the increase of the friction coefficient. For the 50% of filling rate the increase of the friction coefficient had an insignificant influence on the change of the power demand, which is shown in Fig. 4b). In the case of the increase of the coefficient of external friction, the power demand required for the transportation of the material increased significantly, in particular for the 95% filling rate. In the case of 50% filling rate, the increase of the friction coefficient caused less intensive increase of the power demand, especially for the lower values of the rotational speed, which is shown in Fig. 4c). The value of the restitution coefficient did not change the results of the simulations significantly with regard to the power demand, which is shown in Fig. 4d). Only in the case of the rotational speed equal to 10 rpm and 95% of filling rate the increase of the power demand could be observed together with the increase of the restitution coefficient. The increase of the rolling resistance between the DEM particles showed a slight decrease of the power demand (Fig. 4e)). In the case of the friction coefficient defined between DEM particles and the surface of the conveyor's elements, the increase of the friction coefficient caused a slight increase of the power demand, which is shown in Fig. 4f).

Figs. 5-7 show the influence of the DEM model input parameters, such as the size of the particles and coefficients of external and internal friction, on the results of the exploitation characteristics of a screw conveyor.

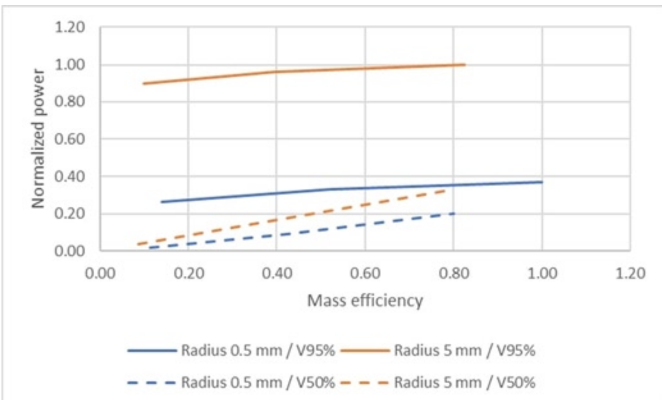


Fig. 5. The influence of the size of a DEM particle on the exploitation characteristics of a screw conveyor.

Fig. 5 shows the influence of the size of a DEM particle on the exploitation characteristics of a screw conveyor. It can be noted that the radius of the DEM particle has a significant influence on the results determining the exploitation parameters of the conveyor. For larger radii, higher values of the power demand were required for the transportation of the material with the same efficiency. This effect is particularly visible for the high filling rate (95%).

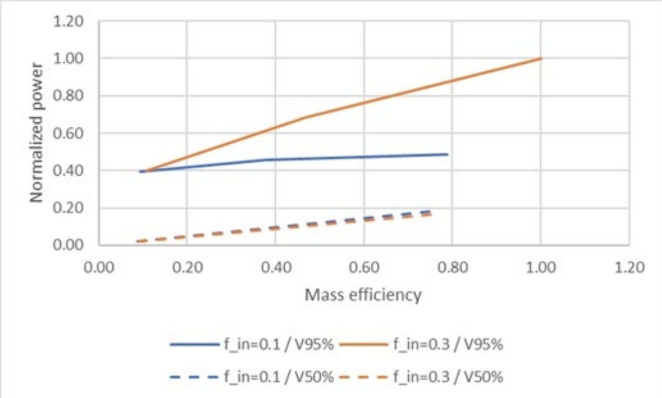


Fig. 6. The influence of the coefficient of internal friction on the exploitation characteristics of a screw conveyor

Fig. 6 shows the influence of the coefficient of internal friction on the exploitation characteristics of a screw conveyor. The performed simulations has indicated that for the high filling rate, the value of the internal friction coefficient strongly determines the exploitation parameters of the screw conveyor. It was also observed that for the higher values of coefficient of internal friction, higher values of the power demand are required for the transportation of the bulk material with the same efficiency. In the case of the 50% filling rate, the influence of the value of the coefficient of internal friction was insignificant.

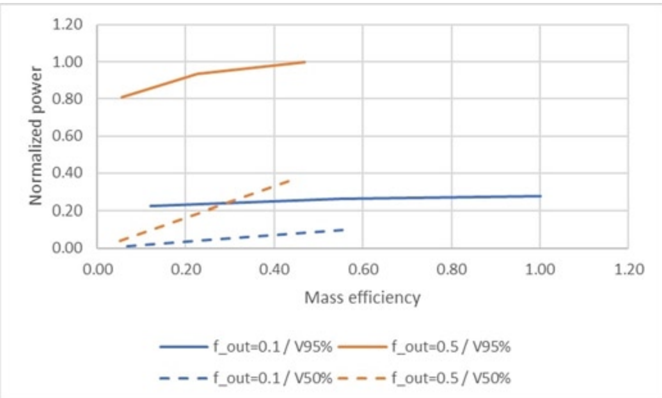


Fig. 7. The influence of the coefficient of external friction on the exploitation characteristics of a screw conveyor

The value of the coefficient of external friction influences the results of the exploitation characteristics significantly, which is shown in Fig. 7. The increase of the coefficient of internal friction from 0.1 to 0.5 caused a significant increase of the power demand for the same mass efficiency, both for the 50% and 95% of the filling rates.

4. Laboratory and simulation studies of the exploitation parameters of a screw conveyor

Because of the significant influence of some of the DEM model input parameters on the simulation results, a pilot study of the transportation of a bulk material by a screw conveyor was performed. Fig. 8 shows a scheme of the proposed research setup.

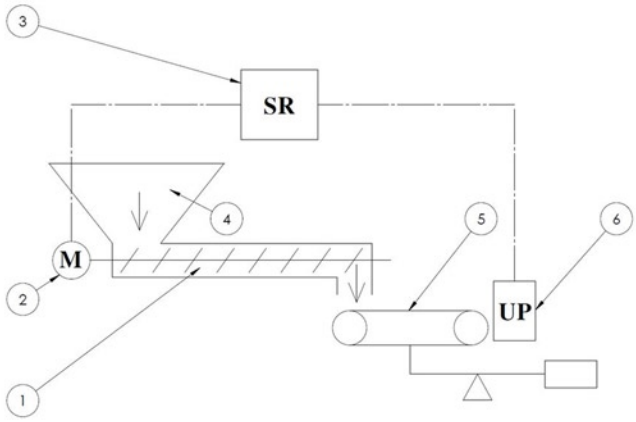


Fig. 8. A scheme of the laboratory test setup.

The proposed laboratory test setup consisted of the following elements:

1 – screw conveyor under study,

2 – conveyor's drive (M), consisting of a 4 kW helical gear unit, rotational speed of the screw shaft regulated by the use of a frequency converter,

3 – results acquisition unit (SR), based on a FBs 60MCR2 controller,

4 – hopper of a 4 m^3 volume,

5 – belt conveyor scale WMTP B-650,

6 – weighting unit (UR), maximum efficiency Q_{max} = 10 Mg/h, accuracy 0.5 % (from 5 to 100% Q_{max}), accuracy class 1 (from 5 to 100% Q_{max}).

The aim of this experiment was to determine the efficiency and the power demand of an actual screw conveyor working under the industrial conditions. The obtained laboratory results were used for the verification of the adopted DEM model input parameters and for the determination of the exploitation characteristics of the device. A screw conveyor transporting limestone powder was studied. The dimensions of the device under study were: the total length of the conveyor – 4000 mm, the external diameter of the screw flights 160 mm, the shaft diameter 70 mm, the screw flights pitch 75 mm. The measurements were taken for the rotational speed within the range of 20-70 rpm. Table 1 shows the calibrated material model parameters of the limestone powder used in the DEM simulation.

DEM parameters were calibrated based on the results of the laboratory tests of the physical properties of the limestone powder, according to the methodology described in [9]. In order to reduce the computational time, a homogenous size of the DEM particles of 3 mm was adopted.

Table 1. Physical properties and calibrated DEM parameters of the limestone powder

Physical properties				Calibrated DEM parameters			
Angle of repose,°	Coefficient of external friction, -	Bulk density, kg/m^3	Granulation, µm	Coefficient of internal friction, -	Coefficient of external friction, -	DEM solid density, kg/m^3	Radius of a DEM particle, mm
36.4	0.44	1170	1-20	0.24	0.44	1980	3

Fig. 9 shows an image from the DEM simulations with the distribution of material's velocity inside the trough during the transportation of the limestone powder.

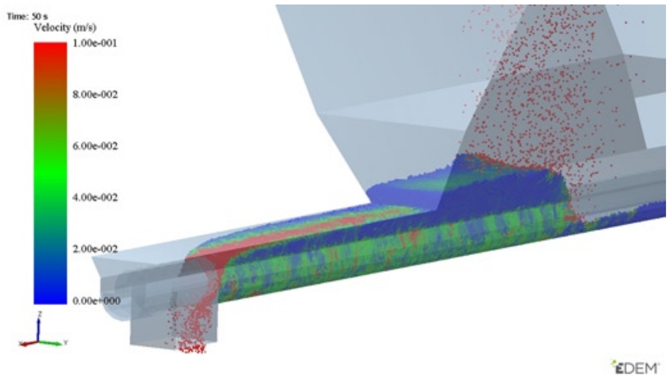


Fig. 9. Velocity distribution inside the trough of the modeled screw conveyor

Fig. 10 shows the results of the study on the mass efficiency as a function of the rotational speed obtained for an actual screw conveyor and in the DEM simulation.

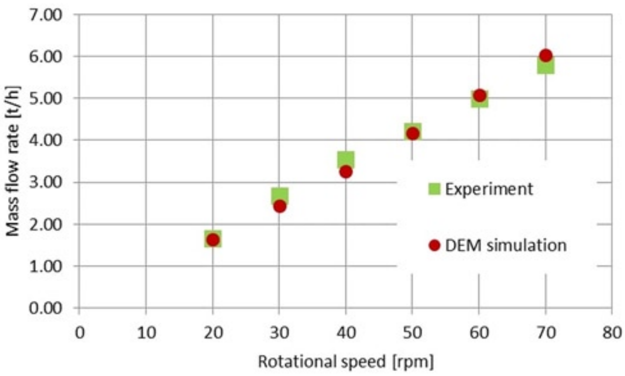


Fig. 10. The values of the mass efficiency of the screw conveyor obtained experimentally and in the simulation as a function of the rotational speed.

Fig. 10 shows a very good agreement between the results of the simulation and the measurements of the actual screw conveyor in terms of the mass efficiency. The discrepancies between these two sets of results were less than 1%.

Fig. 11 shows analogous results of the power demand of a screw conveyor as a function of the rotational speed of the shaft.

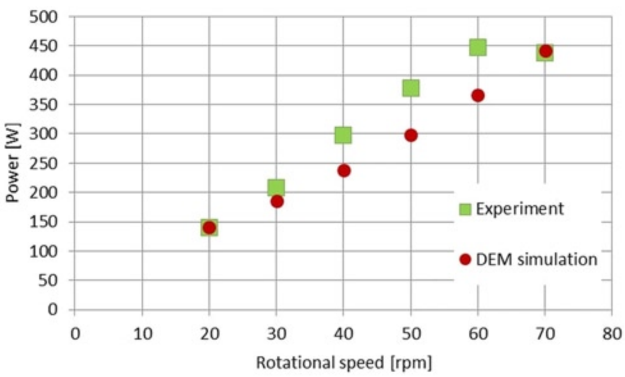


Fig. 11. The values of the power demand of the screw conveyor obtained experimentally and in the simulation as a function of the rotational speed.

DEM simulations underestimated the power demand of the tested screw conveyor. Based on the sensitivity analysis of the DEM model, the values of the external friction coefficient should be increased in the first place; however, the increase of the friction coefficient will probably result in the decrease of the mass efficiency.

Fig. 12 shows the actual and the simulated exploitation characteristics of the tested screw conveyor.

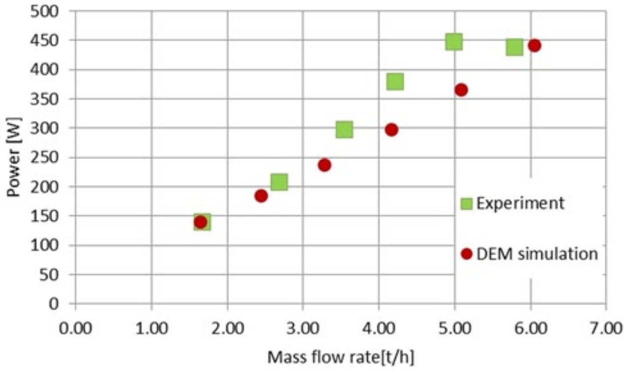


Fig. 12. Experimental and simulated exploitation characteristics of the tested screw conveyor.

The results of the simulation are consistent in terms of the obtained exploitation characteristics of the screw conveyor. For the efficiencies up to three tones per hour the results of the experiment and the simulation are in agreement. For the higher efficiencies, the simulation underestimates the results in relation to the reality.

5. Conclusions

The performed analysis has shown which of the DEM model input parameters influence the results of the simulation of the transportation of a bulk material by a screw conveyor and to what extent, with regard to the determination of the exploitation parameters of the device. As it was shown, the key parameters of the material model which determine the results of the simulation are: the size of the DEM particles and the values of the coefficients of internal and external friction. It was also noticed that for a higher filling rate, the results of the simulations are more sensitive to the model input parameters. This is why the physical properties of the bulk materials should be precisely identified in laboratory tests and used for the calibration of the material DEM model. With a precisely defined material model, the simulations of the transportation of a bulk material by a screw conveyor can be done in order to define the exploitation characteristics of the device. With arbitrarily adopted model parameters, DEM simulations can provide false results of the mass efficiency and the power demand. As it was shown in the simulations, the exploitation characteristics may be very different depending on the model input parameters. As a result, the construction of the conveyor may be significantly under- or overestimated. Hence, in order to obtain the required efficiency, the device will have to work at extremely high or low rotational speed of the screw shaft. Improperly chosen drive will be working outside the nominal range of the power characteristics. According to the described simulations of the transportation of the limestone powder by a screw conveyor, with an accurately defined DEM model we can obtain a very good agreement between the numerical simulations and laboratory measurement results in terms of the mass efficiency and the power demand of the conveyor. The results of the DEM analysis not only deliver the exploitation characteristics of the device, but also provide information on the behavior of the material during the transportation by the conveyor. With the use of DEM simulations, the optimization process of the transportation of the bulk material by a screw conveyor can be done. The right choice of the construction and exploitation parameters of the device would ensure that the transportation is realized with the required efficiency and with a minimized use of power, construction materials, or the wear of the screw flights. Shaping of the chute and the feeding zone will also be possible. The methodology of designing with the use of numerical DEM simulations may be an effective tool supporting the design process of the devices with strictly defined exploitation requirements.

Further experimental and numerical studies will be focused on the screw conveyors of varied construction dimensions, i.e., different screw flight pitches, different external diameters of the screw, transporting both dry and cohesive materials of a different granulation.

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