

Use of DEM in the Determination of Friction Parameters on a Physical Comparative Model of a Vertical Screw Conveyor

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This article deals with the use of DEM in the application of a screw conveyor for bulk materials. Utilisation of DEM anticipates input parameters which can be obtained only by experimental and laboratory activity in the area of the transport and properties of bulk materials. These concern mainly friction parameters describing flow properties on the transport equipment. Without this knowledge, the use of DEM is limited. With knowledge of the mechanical and physical properties of bulk materials and contact geometries, the use of DEM applies to the simulation of the real behaviour of the conveyed material. This state can only be achieved by verification of the concordance of the simulation and real state, alternatively by calibration. Calibration must be performed on the basis of ranges of input values ascertained in the laboratory environment. After that, it is necessary to obtain the output parameters by an experiment from the DEM-simulation such as particle velocity during transport on the vertical screw conveyor. The same method is used when it is necessary to obtain values from the actual equipment by the PIV method on the basis of which the DEM model will be optimized.

Key words

discrete element method, particle image velocimetry, vertical screw conveyor, validation of DEM, calibration of DEM

Introduction

Theoretical description of the function of vertical and inclined screw conveyors is described in the article by Roberts.¹ Owen² used the DEM to compare the efficiency of transport between horizontal and vertical screw conveyor. This comparison clarifies the issue of the area of the vertical screw conveyors. DEM is used to study the optimizing of screw conveyors or feeder currently.^{3–5}

In practice, designs of conveyor systems with the use of DEM are based on knowledge of the input parameters.^{6–8} The main requirements are the values of the transport quantity completed in time^{9,10} with the lowest economic demands.¹¹ The key input parameter for such systems is knowledge of the mechanical-physical properties of the materials to be conveyed.¹² Theoretical conveyor design is realized by using idealized models and empirical calculations. The measured properties of transported materials are an important input for the design of conveyors.

Companies use their company standards for specific applications of specialized equipment but these procedures may not always be sufficient in case of unconventional conveyors. Nowadays, re-

quirements for accuracy, development speed, lower economic demands and reliability are increasingly greater. The trend is represented by computer support of the design and optimization of the equipment design^{13,14} in a short time. In the processes of bulk material transport, the scientific activity is directed at studying the behaviour of particulate substances and their mechanical and physical properties.^{15–20} DEM helps in the simulation of the behaviour of bulk material composed of particles in relation to the equipment geometry with which it is in contact. These observed properties of behaviour must be applied to DEM and also calibrated. The calibration process means achieving such a situation where the computer DEM model of the particulate substance approaches the real bulk material behaviour.^{21–24} The range of parameters of the mechanical and physical properties of the real bulk material detected in the laboratory are optimized in DEM until similarity is achieved between the output data obtained from DEM and PIV.²⁵

Methods

Validation of DEM and real model

Verification of the DEM model by the real model (Fig. 1) was performed by a high-speed cam-

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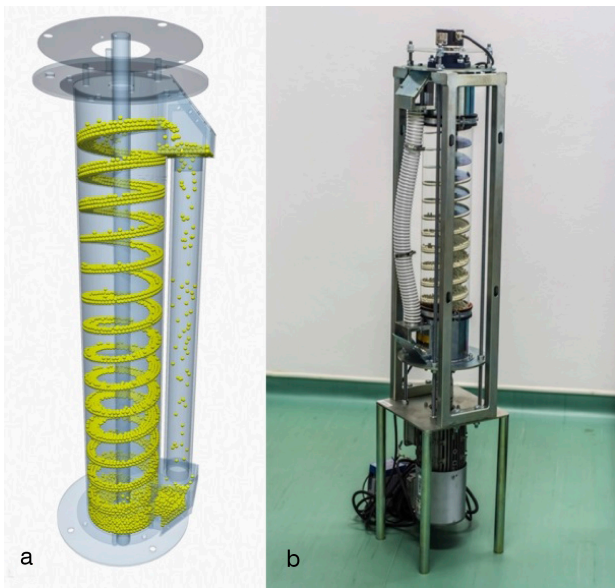


Fig. 1 – DEM model (a) and the real model (b) of the vertical screw conveyor

era with the relevant DaVis software from the LaVision Company. For this verification, the PIV system was used.

Particle Image Velocimetry (PIV) is an optical method for visualizing flow. It measures particle velocity in a medium such as water, air and particulate material. These media must, however, be sufficiently illuminated. The light intensity is related to the frame rate of the camera. The higher the frame rate of the camera, the more light is needed. The field of view is balanced by the ratio of sensor size and lens focal length of the camera. Used for the recording of images is a CCD camera, which is connected to the PC. This connection is for live viewing, camera focus and calibration of pixels to millimetres. When recording, the camera should be directed normal to the plane of the recording area. The recording data from the camera go through a high-speed controller into the PC. For PIV analysis, at least two exposures are needed. The speed of the recorded motion of particles is set by timing of exposure. For rapid movement, a short time between the two exposures is used. For slow movement, a longer exposure time is used. The two images between themselves must represent a small difference of particle motion in time. This will ensure a more accurate auto- or cross-correlation analysis for the evaluation of the vector field. Creation of a vector field takes place on the PC with software from Davis LaVision. The result of PIV analysis is a two-dimensional vector field. It is possible to obtain average-speed particle motion from a specific area captured.

In the physical model of the screw conveyor, it was difficult to take an image due to the casing's circular cross-section that did not make a fully suited 2D plane on which to focus the objective of the high-speed camera. The captured images showed distortion when using a lens with a focal length of 50 mm. This deformation was partially reduced by using a lens with a focal length of 85 mm. The camera imaging frequency ranged from 200 to 600 Hz, where the higher values were used for higher revolutions of the auger. The DEM and PIV verification method for the vertical screw conveyor focused on determining the vertical component of particle velocity during transport by the auger. This component in the capacity calculations represents the particle transport velocity.

The high-speed camera is limited to approx. 3,600 images. The camera memory can be enlarged by reducing the resolution of individual images at the expense of resolution capacity for subsequent post-processing. If the imaging frequency was considered at 600 frames per second, the duration of the entire record was 3,600/600, which means 6 seconds. Basic processing of 3,600 frames took about five hours of calculation. The PIV software thus has large requirements for data storage and backup. Consequently, the DEM/PIV validation was limited to one second of activity recording.

The computer model of screw conveyor for DEM was created in a 3D CAD system. EDEM Academic supports files such as *.IGS or *.STEP. It is necessary to import a 3D CAD model into the DEM. The DEM creates a geometrical mesh of the 3D model and assigns the physical properties. The CAD model, however, has the ideal shape and does not contain real inequality such as welds and deviations of the shape of the screw. The screw and construction of the conveyor are made of steel. The casing of the screw conveyor consists of transparent glass. The bottom of the screw conveyor is formed by a hopper. The material emerges from the conveyor in its upper portion. The lower and upper parts are connected by a hose, and here are the Plexiglas windows. The hose connection is for circulation of material in the conveyor.

The 3D model was created with the following parameters: screw diameter of 0.14 m, pitch 0.05 m, pitch angle 6.49° and thickness of the blade of 2 mm. The inner diameter of the glass casing is 0.143 m, wall thickness 3 mm, height of glass casing 0.5 m and overall transport elevation 0.68 m.

Prior to the experiment, the transported material was inserted through a hose into the conveyor.

This material moved along the screw upwards after running the conveyor. The high-speed camera recorded the movement of the material through the glass casing.

Validation without DEM calibration

The conformity of DEM model with the results of the PIV is feasible providing measurement of friction and mechanical-physical parameters of the transported material. The input parameters for DEM (Table 1 and Table 2) are the prerequisite. The DEM input parameters given in Table 1 are necessary for detecting and measuring the forces. Although this article does not focus on this measurement, the values are stated in the table for information purposes. The values given in Table 2 were detected in the laboratory for plastic spherical particles with a diameter of 6 mm. These are ammunition for airsoft weapons.

Table 1 – *Input parameters for measuring forces in EDEM Academic*

Contact material	Steel	Glass	Plastic	Plastic glass
Poisson’s ratio μ [-]	0.3	0.19	0.39	0.48
Shear modulus G [Pa]	$8.077 \cdot 10^{10}$	$2.857 \cdot 10^{10}$	$8.993 \cdot 10^8$	$8.74 \cdot 10^8$
Density ρ [kg m ⁻³]	7850	2180	1780	1180

The DEM validation by PIV was performed on the vertical screw conveyor by filming the v_y . For filming, one area on the casing was chosen which was approximately identical to both the DEM model and the real model (Fig. 2).

Table 2 – *Input parameters detected by laboratory measurement for EDEM Academic*

Interaction with plastic particles	Steel	Glass	Plastic	Plastic glass
Coefficient of restitution	0.82	0.93	0.48	0.85
Coefficient of static friction	0.44	0.32	0.35	0.41
Coefficient of rolling friction	0.013	0.004	0.014	0.006

From the point of view of file data volume and the high number of tests, the time of filming of V DEM/PIV was limited to 100 values in a period of one second. The v_y thus obtained were averaged and their course is recorded in the chart (Fig. 3).

The auger speed was set for PIV/DEM at 148 rpm and the number of particles used in the conveyor was approximately 6.645. To achieve accurate auger revolutions, the real model was equipped with a frequency converter and incremental sensor. The results of the averages of the v_y for the DEM and PIV simulation of measurement are very similar. This first validation was performed without calibration.

Overview of the standard deviation of the measured v_y for DEM and PIV is presented in Table 3.

Table 3 – *PIV and DEM results of variance and v_y fluctuation for measurements of screw speed 148 rpm*

Screw velocity 148 [rpm]	Average v_y [m s ⁻¹]	Standard deviation [m s ⁻¹]	Coefficient of variation	Speed fluctuation [%]
DEM	0.0290	$3.2130 \cdot 10^{-3}$	0.1108	11.1
PIV	0.0287	$2.4683 \cdot 10^{-3}$	0.0860	8.6

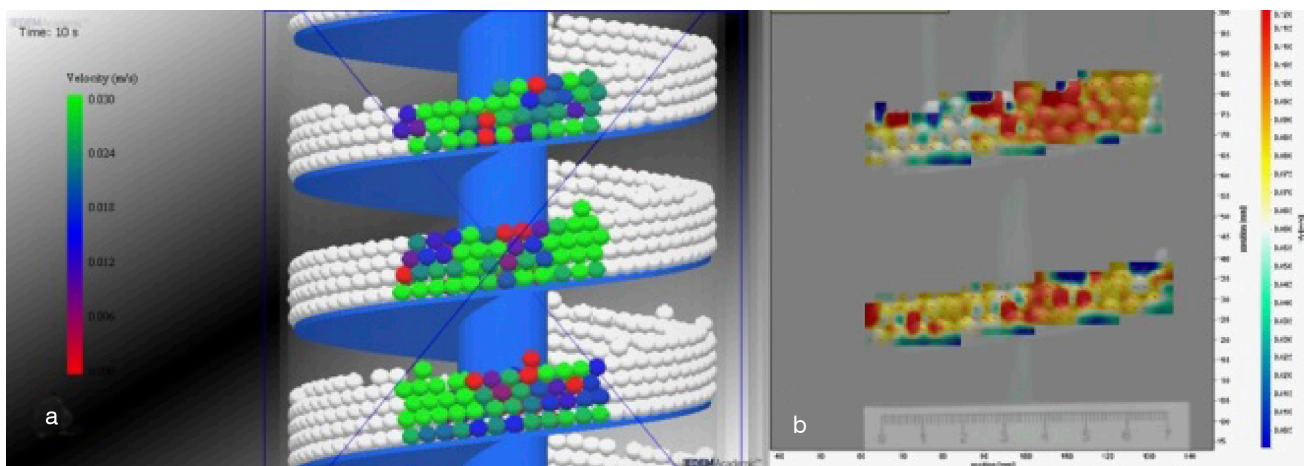


Fig. 2 – *Detection of v_y of DEM (a) and PIV (b)*

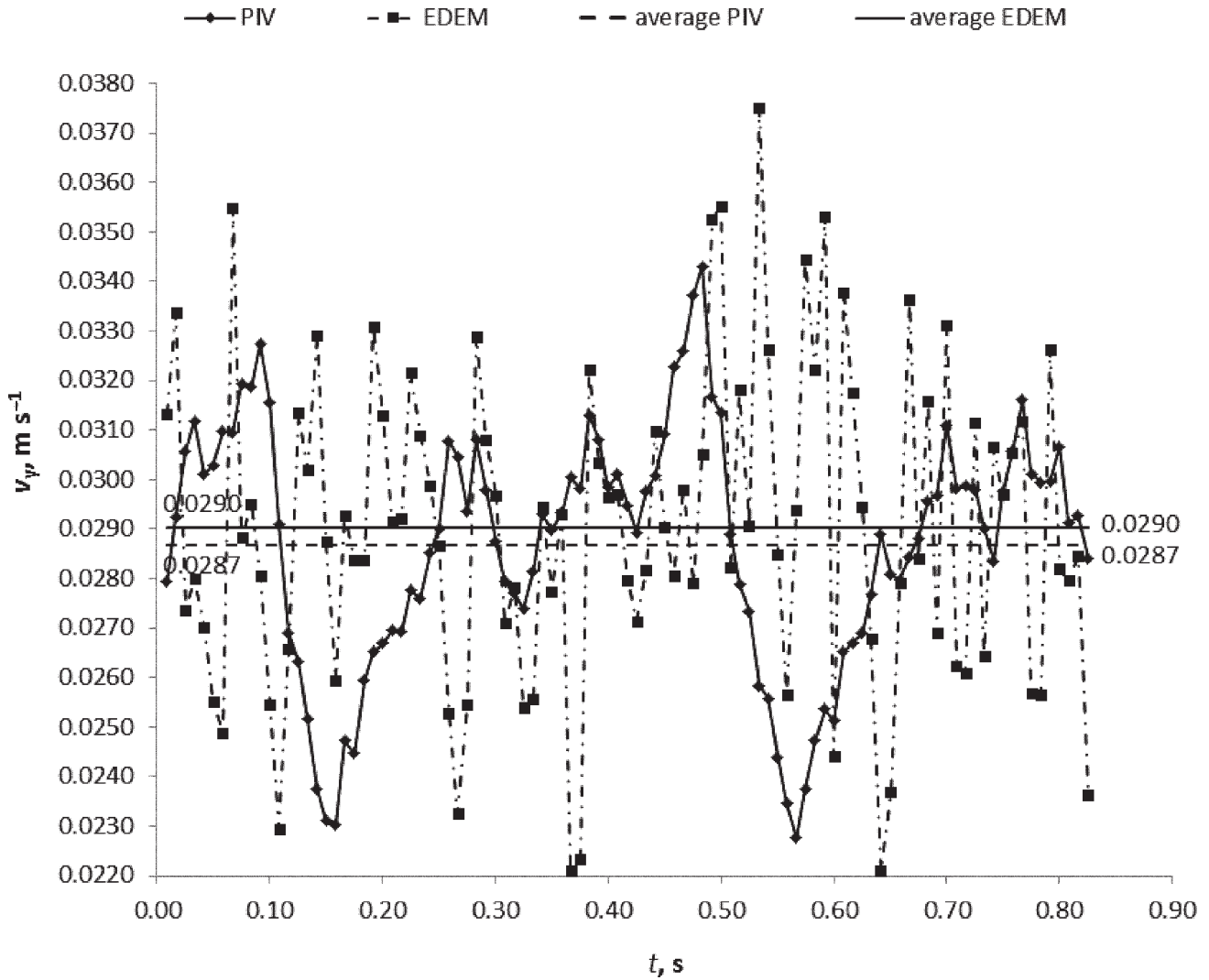


Fig. 3 – Average values of v_y from the measured area

Validation with DEM calibration

After one year of using the real model in different promotional actions, another series of measurement took place. The assumption was finding the same state as in the case of validation without calibration. After several measuring series, it was concluded that this state cannot be achieved. Screw blade wear was ascertained during thorough inspection (Fig. 4).

Wear of the active surface of the screw was found by observation. The surface roughness changed only at the edge of the blade of the screw. This part is most frequently in contact with the particles. This is due to centrifugal force, which pushes the particles into the outside part of the screw. The remaining blade surface is smooth. White plastic particles were black after prolonged use and metal dust was found at the bottom of the screw conveyor.

This wear changed the whole approach to the PIV and DEM validation. It was necessary to calibrate the simulated model so that outputs of the v_y from DEM corresponded to the results from PIV measuring.

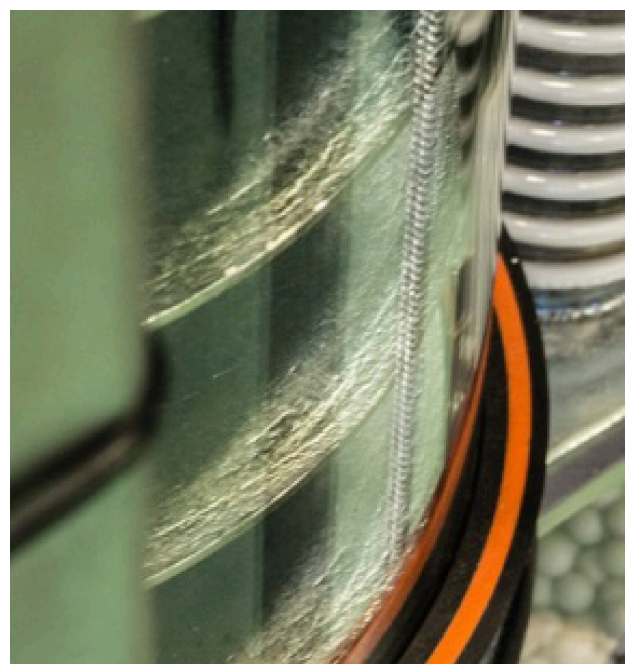


Fig. 4 – Auger blade wear found on the real model

Results and discussion

Fig. 5 presents the results of a similar measurement shown in Fig. 3. The difference was in the speed of the screw. Instead of 148 rpm, used was 141 rpm. The average speed between DEM and PIV at 141 rpm differed by about 0.0059 m s^{-1} , as shown in Fig. 5.

The average measured value of v_y from PIV was 0.0206 m s^{-1} and from EDEM Academic 0.0265 m s^{-1} with the use of the values in Table 1 and Table 2.

Calibration was realized by a change in the static friction coefficient between the transported spherical particles and the auger blade. Since methodical measurement of static friction directly on the auger was not possible, the approach was performed through a series of experiments in the EDEM Academic application. Measurement of the real model by PIV was carried out with speed of the auger of 141 rpm and number of particles of about 6,645. The friction value had to be increased gradually compared to the friction value 0.44 from Table 2 up to a value of 0.88. An increase in the auger friction resulted in a reduction in the v_y size.

Figure 6 shows the achieved result of the v_y of 0.0210 m s^{-1} after calibration of friction in DEM. The friction itself took place in the bottom part of the glass casing (in the area of the first third of its height). It happened due to the highest geometric inaccuracy of the helix shown at its end in the upper part just before the discharge. Unlike the DEM model, the real model also has seams left behind after welding of individual components of the auger. The double value of friction between the auger blade and the transported particles was used for other experiments that are meant to verify the correct choice of the new static friction coefficient of 0.88.

Overview of the standard deviation of the measured v_y for speed of screw 141 rpm is shown in Table 4.

Furthermore, a comparison was carried out of DEM/PIV for screw speed 80 rpm and 170 rpm. There were also differences in comparison of DEM/PIV, as shown in Fig. 7 and Fig. 9. These differences were resolved by calibrations of DEM, as shown in Fig. 8 and Fig. 10.

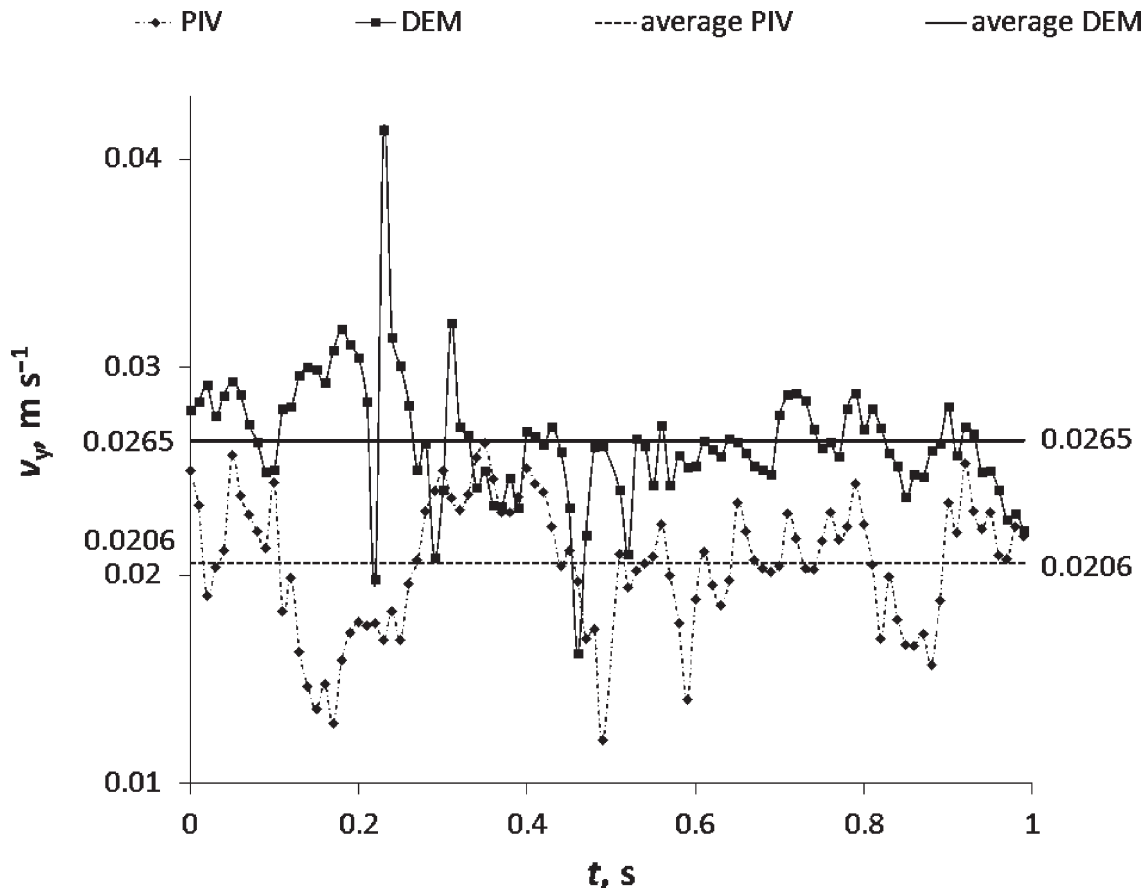


Fig. 5 – Average v_y of DEM/PIV for screw speed 141 rpm before calibration

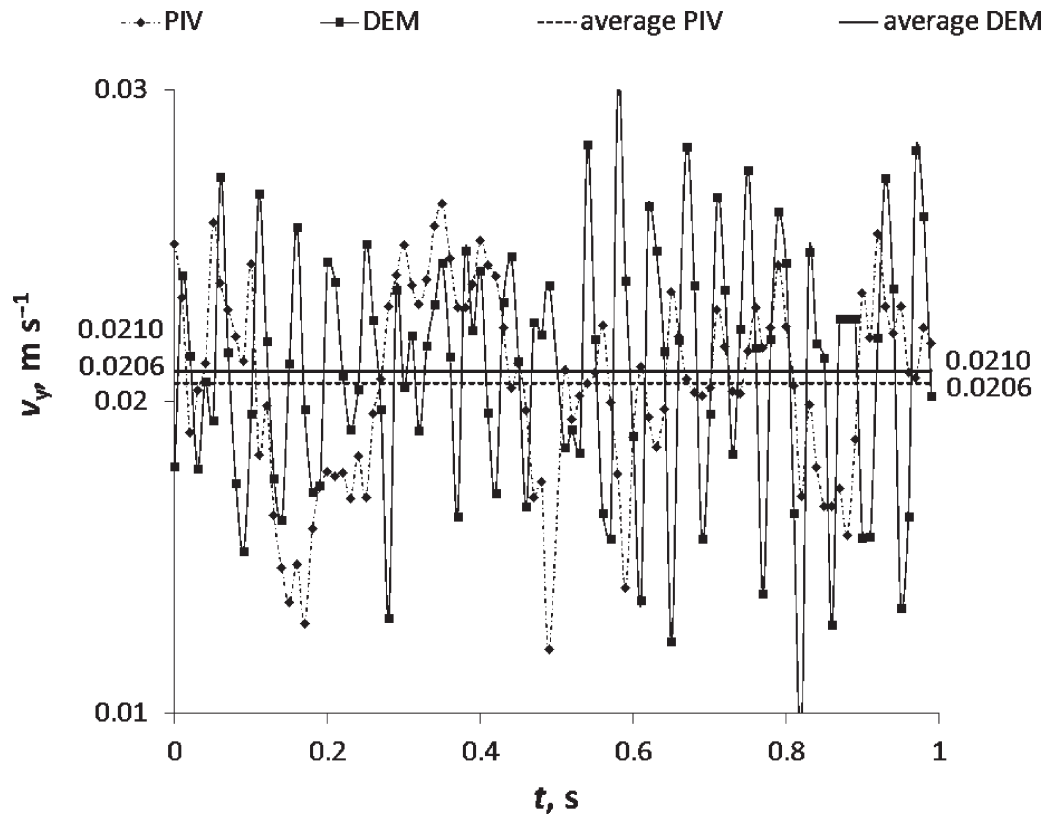


Fig. 6 – Average v_y of DEM/PIV for screw speed 141 rpm after calibration

Table 4 – PIV and DEM results of variance and v_y fluctuation for measurements of screw speed 141 rpm before and after friction change in DEM

Screw velocity 141 [rpm]	Average v_y [m s ⁻¹]	Standard deviation [m s ⁻¹]	Coefficient of variation	Speed fluctuation [%]
DEM before friction change	0.0265	$3.0066 \cdot 10^{-3}$	0.1135	11.4
DEM after friction change	0.0210	$4.1139 \cdot 10^{-3}$	0.1961	19.6
PIV	0.0206	$3.1160 \cdot 10^{-3}$	0.1513	15.1

The difference between the average velocities of the particles was 0.003 m s^{-1} for a screw speed of 80 rpm before calibration, as shown in Fig. 7. This difference was 0.0011 m s^{-1} after calibration, as shown in Fig. 8.

It is thus possible to retrospectively determine by DEM calibration the value of friction between the transported material and the part of the structure of the transport equipment with which it is in contact, if not known, only if the available initial measured values were validated on the real model and the DEM model of the equipment. If the model of DEM and the results of the PIV are not in agree-

ment, it is not possible to declare the value of friction as correct.

Overview of the standard deviation of the measured v_y for speed of screw 80 rpm is given in Table 5.

Table 5 – PIV and DEM results of variance and v_y fluctuation for measurements of screw speed 80 rpm before and after friction change in DEM

Screw velocity 80 [rpm]	Average v_y [m s ⁻¹]	Standard deviation [m s ⁻¹]	Coefficient of variation	Speed fluctuation [%]
DEM before friction change	0.0132	$8.2834 \cdot 10^{-3}$	0.6256	62.6
DEM after friction change	0.0091	$7.3536 \cdot 10^{-3}$	0.8063	80.6
PIV	0.0102	$1.4432 \cdot 10^{-3}$	0.1419	14.2

The course of the output data of the v_y for auger speed of 80 rpm is shown in Fig. 6. Data from DEM showed a scattering of values around the line of the v_y average value higher than with data from PIV, as shown in Table 5. The material in the equipment circulated and individual peaks could be caused by particle acceleration. The particles

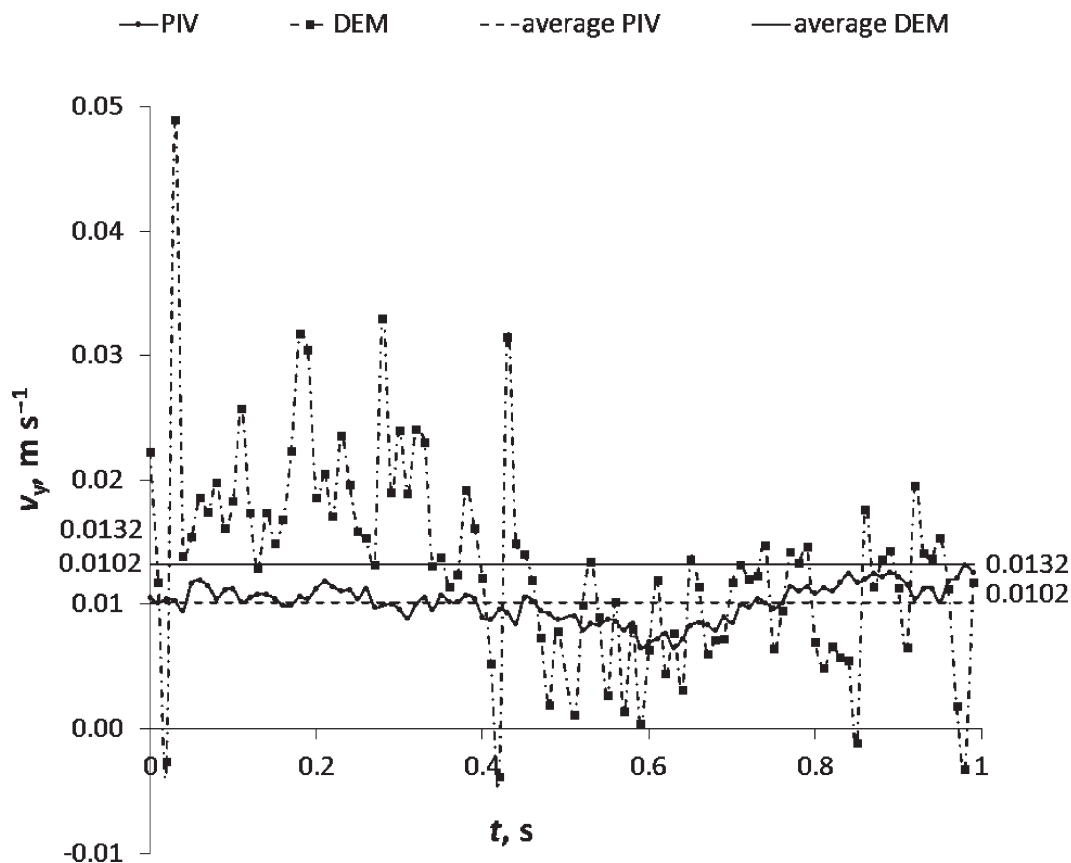


Fig. 7 – Average particle v_y of DEM/PIV for screw speed 80 rpm before calibration

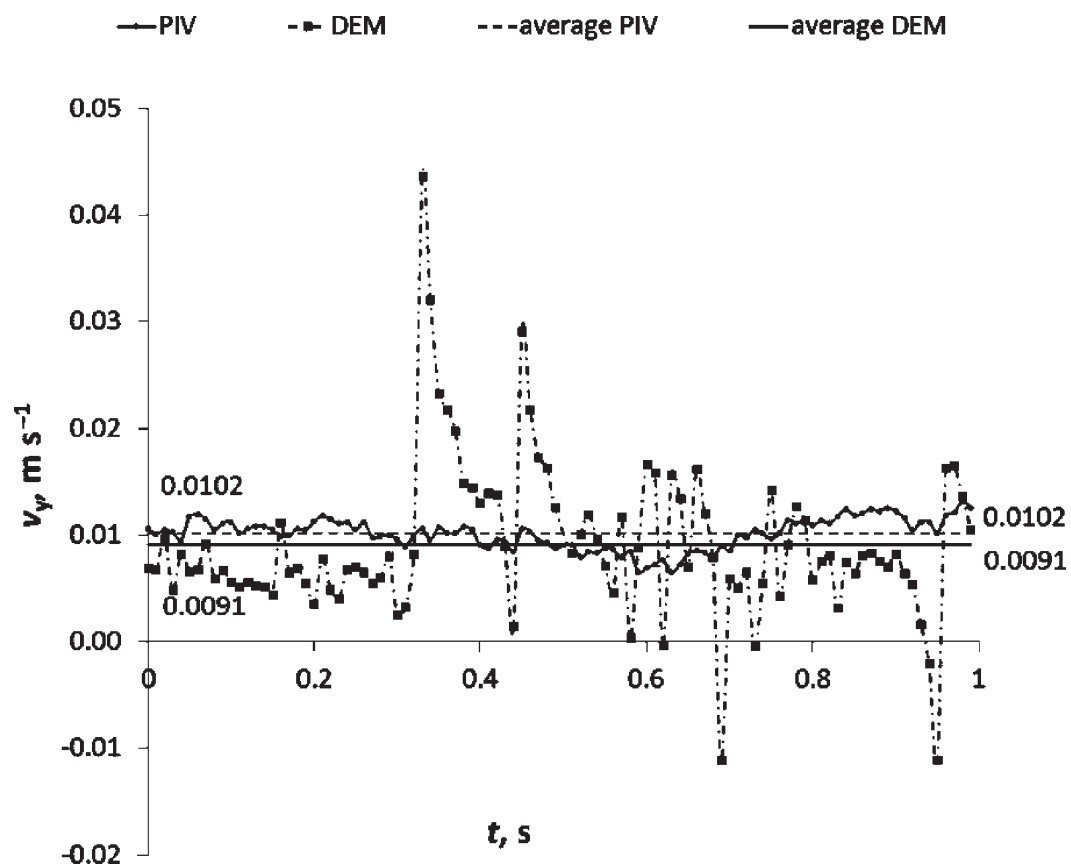


Fig. 8 – Average particle v_y of DEM/PIV for screw speed 80 rpm after calibration

occurring in the highest part of the conveyor returned immediately to the hopper. The fast change in material quantity in the hopper could also cause a change in pressure force at the auger input. The frequency of the peaks is probably related to the setting of the auger speed. However, the regular occurrence of these peaks for DEM and PIV was not recorded. The indication of periodic occurrence of peaks for data from PIV was recorded in Figs. 6 and 10.

Data collection with regard to recording duration was limited by storage, camera memory and time expenditure on processing. To go through one cycle on the conveyor, the particle had to overcome a vertical distance of about 700 mm upwards via the auger, and finally downwards by free-fall from the discharging hopper back to the hopper via the connecting pipe. The entire process of one circulation lasted a minimum of 70 seconds when setting the auger speed at 80 rpm. For auger speed 170 rpm it lasted a minimum of 26 seconds.

The difference between the average velocities of the particles was 0.0049 m s^{-1} for a screw speed of 170 rpm before calibration, as shown Fig. 9. This difference was 0.0007 m s^{-1} after calibration, as shown Fig. 10.

Overview of the standard deviation of the measured velocity for speed of screw 170 rpm is given in Table 6. Fluctuations in particle velocities were the smallest compared to other experiments at the screw speed of 170 rpm.

Table 6 – PIV and DEM results of variance and v_y fluctuation for measurements of screw speed 170 rpm before and after friction change in DEM

Screw velocity 170 [rpm]	Average v_y [m s^{-1}]	Standard deviation [m s^{-1}]	Coefficient of variation	Speed fluctuation [%]
DEM before friction change	0.0327	$1.4017 \cdot 10^{-3}$	0.0429	4.3
DEM after friction change	0.0271	$3.4117 \cdot 10^{-3}$	0.1259	12.6
PIV	0.0278	$5.6221 \cdot 10^{-3}$	0.2022	20.2

Conclusions

DEM validation was performed using PIV on a real model of the vertical screw conveyor. By validation, a difference in the average speed of particles of 0.0003 m s^{-1} was found between PIV and DEM.

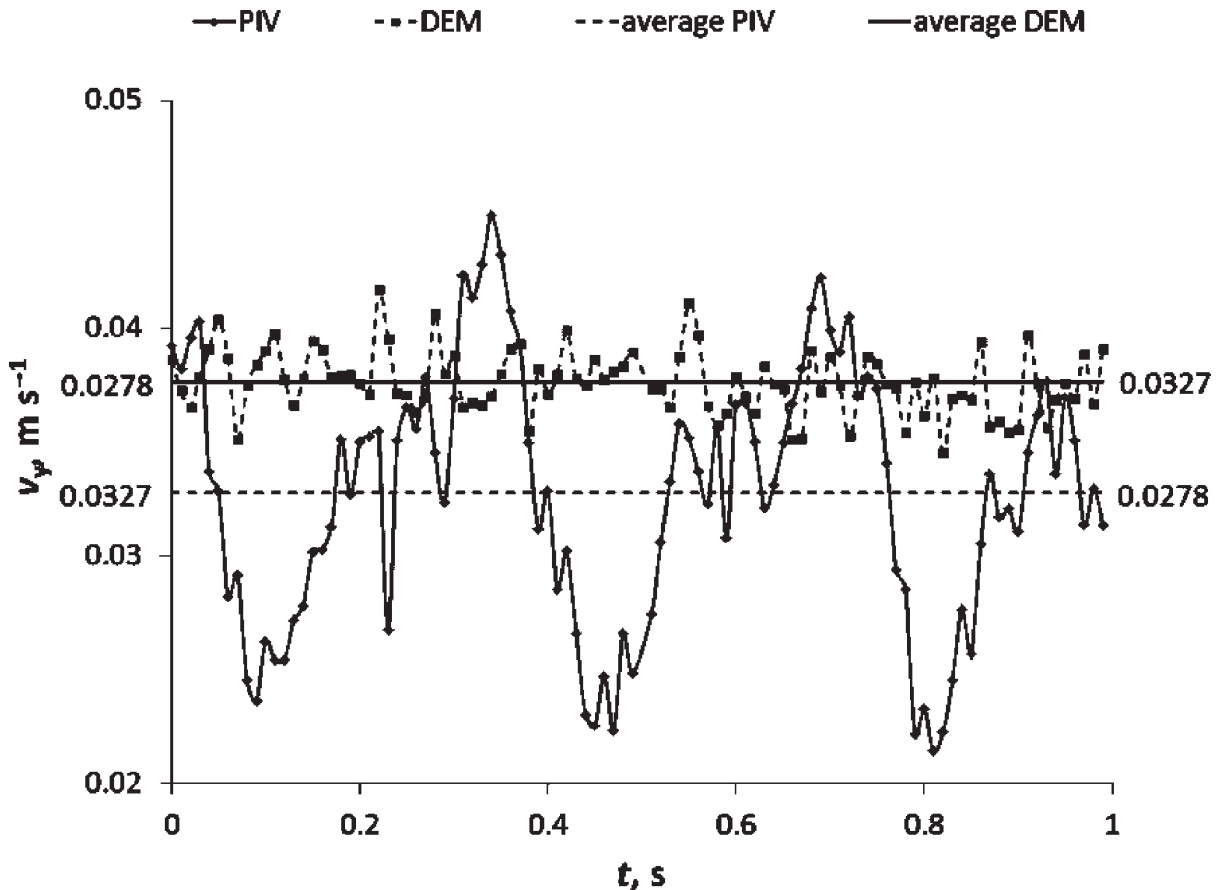


Fig. 9 – Average particle v_y of DEM/PIV for screw speed 170 rpm before calibration

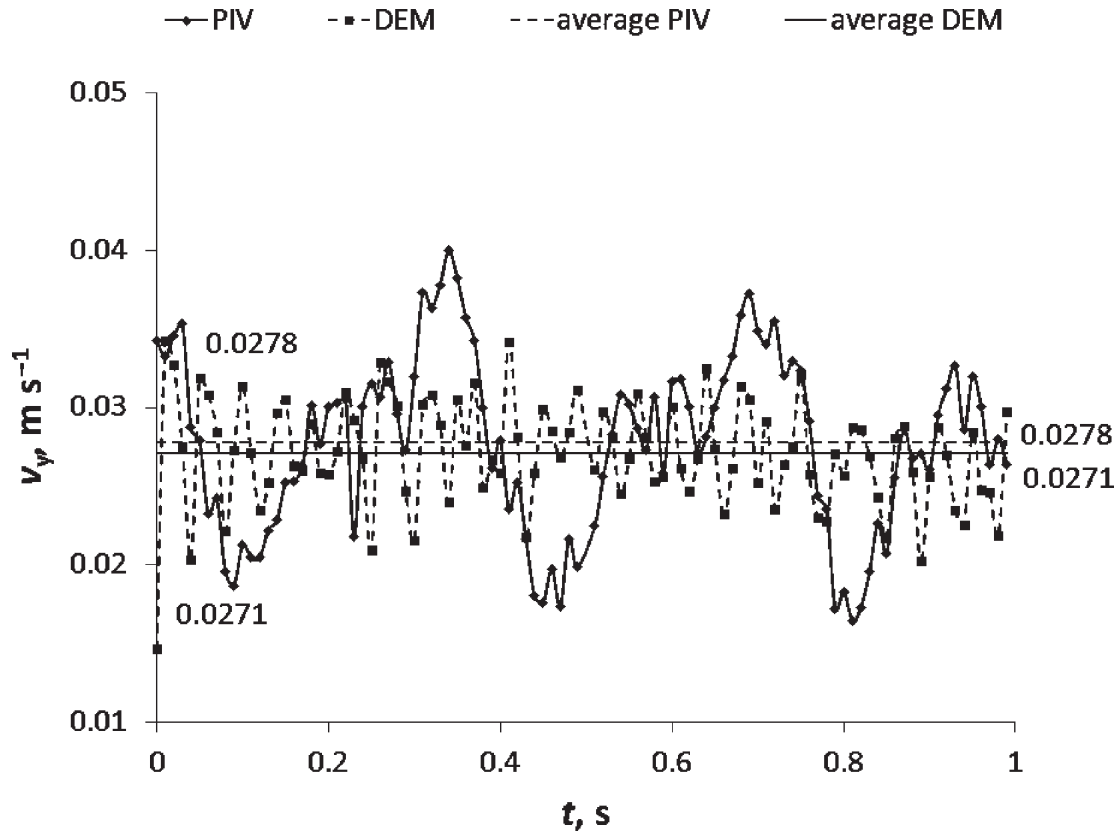


Fig. 10 – Average v_y of DEM/PIV for screw speed 170 rpm after calibration

The mechanical screw blade wear of the real model was traced after one year of use for publicity purposes. The new DEM validation was performed using other screw speeds and with the initial input data for the DEM. The DEM calibration of the model was performed on the basis of the observed variable particle velocities in DEM and PIV. Calibration represented parameter change of friction between the conveyed material and the screw blade in the DEM. The friction increased from 0.44 to 0.88. The result was a reduction in average v_y of 20.8 % for the screw speed of 141 rpm. The value 31.1 % was for the screw speed of 80 rpm, and the value 17.1 % was for the screw speed of 170 rpm. Changing the speed of the particle by friction was performed to get closer to outputs from PIV measurements.

The difference between the average speeds of DEM and PIV was 0.0004 m s^{-1} for the screw speed 141 rpm after the change of friction. It was 0.0011 m s^{-1} for the screw speed of 80 rpm and 0.0007 m s^{-1} for the screw speed 170 rpm. Found were v_y fluctuations for PIV and DEM measurement. The lowest fluctuation of v_y was 14.2 % for the screw speed of 80 rpm in the PIV measurements. The value 15.1 % was for 141 rpm and 20.2 % for 170 rpm. DEM measurement revealed the lowest v_y fluctuations for screw speed of 170 rpm, and the highest for screw speed of 80 rpm, both before and after calibration.

In terms of difference in fluctuations between the PIV and DEM measurement of v_y , the best measurement was obtained with screw speed of 141 rpm.

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List of symbols and acronyms

- v_y – particle velocity vertical components, m s^{-1}
- t – time, s
- DEM– Discrete element method
- PIV – Particle image velocimetry

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