Introduction

Theoretical description of the function of vertical and inclined screw conveyors is described in the article by Roberts.1 Owen used the DEM to compare the efficiency of transport between horizontal and vertical screw conveyor. This comparison clarifies the issue of the area of 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.5–8 The main requirements are the values of the transport quantity completed in time9,10 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, requirements 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 design13,14 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-
era with the relevant DaVis software from the LaVi-
sion 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 particu-
late material. These media must, however, be suffi-
ciently 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 ex-
posure. For rapid movement, a short time between
the two exposures is used. For slow movement, a
longer exposure time is used. The two images be-
tween 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 Da-
vis LaVision. The result of PIV analysis is a two-di-
imensional vector field. It is possible to obtain aver-
age-speed particle motion from a specific area
captured.

In the physical model of the screw convey-
or, 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 val-
ues were used for higher revolutions of the auger.
The DEM and PIV verification method for the verti-
cal screw conveyor focused on determining the
vertical component of particle velocity during
transport by the auger. This component in the ca-
pacity calculations represents the particle transport
velocity.

The high-speed camera is limited to approx.
3,600 images. The camera memory can be en-
larged by reducing the resolution of individual
images at the expense of resolution capacity for
subsequent post-processing. If the imaging frequen-
cy 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 re-
cording.

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 prop-
ties. 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 materi-
als emerges from the conveyor in its upper por-
tion. 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 con-
veyor.

The 3D model was created with the follow-
ing 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 materi-
also 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>
<thead>
<tr>
<th>Table 1 – Input parameters for measuring forces in EDEM Academic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact material</td>
</tr>
<tr>
<td>Poisson’s ratio $\mu$ [-]</td>
</tr>
<tr>
<td>Shear modulus $G$ [Pa]</td>
</tr>
<tr>
<td>Density $\rho$ [kg m$^{-3}$]</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Table 2 – Input parameters detected by laboratory measurement for EDEM Academic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction with plastic particles</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Table 3 – PIV and DEM results of variance and $v_y$ fluctuation for measurements of screw speed 148 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw velocity 148 [rpm]</td>
</tr>
<tr>
<td>DEM</td>
</tr>
<tr>
<td>PIV</td>
</tr>
</tbody>
</table>

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

![Figure 5](image_url)

*Fig. 5 – Average \( v_y \) of DEM/PIV for screw speed 141 rpm before 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

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

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 agreement, 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

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

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>
<thead>
<tr>
<th>Screw velocity 170 [rpm]</th>
<th>Average (v_y) [m s(^{-1})]</th>
<th>Standard deviation [m s(^{-1})]</th>
<th>Coefficient of variation</th>
<th>Speed fluctuation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM before friction change</td>
<td>0.0327</td>
<td>1.4017 \times 10^{-3}</td>
<td>0.0429</td>
<td>4.3</td>
</tr>
<tr>
<td>DEM after friction change</td>
<td>0.0271</td>
<td>3.4117 \times 10^{-3}</td>
<td>0.1259</td>
<td>12.6</td>
</tr>
<tr>
<td>PIV</td>
<td>0.0278</td>
<td>5.6221 \times 10^{-3}</td>
<td>0.2022</td>
<td>20.2</td>
</tr>
</tbody>
</table>

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.

![Average particle \(v_y\) of DEM/PIV for screw speed 170 rpm before calibration](image-url)
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
References


