Discrete element modelling of screw conveyor-mixers

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Abstract

Screw conveyors are used extensively in food, plastics, mineral processing, agriculture and processing industries for elevating and/or transporting bulk materials over short to medium distances. Despite their apparent simplicity in design, the transportation action is very complex for design and constructors have tended to rely heavily on empirical performance data. Screw conveyor performance is affected by its operating conditions (such as: the rotational speed of the screw, the inclination of the screw conveyor and its volumetric fill level). In this paper, horizontal, several single-pitch screw conveyors with some geometry variations in screw blade were investigated for mixing action during transport, using Discrete Element Method (DEM). The influence of geometry modifications on the performance of screw conveyor was examined, different screw designs were compared, and the effects of geometrical variations on mixing performances during transport were explored. During the transport, the particle tumbles down from the top of the helix to the next free surface and that segment of the path was used for auxiliary mixing action. The particle path is dramatically increased with the addition of three complementary helices oriented in the same direction as screw blades (1458.2 mm compared to 397.6 mm in case of single flight screw conveyor). Transport route enlarges to 1764.4 mm, when installing helices oriented in the opposite direction from screw blades. By addition of straight line blade to single flight screw conveyor, the longest particle path is being reached: 2061.6 mm.

Keywords: DEM, modified screw conveyor, premixing, optimization.

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Screw conveyors are widely used for transporting and/or elevating particulates at controlled and steady rates. They are used in many bulk materials' applications in industries ranging from industrial minerals, agriculture (grains), pharmaceuticals, chemicals, pigments, plastics, cement, sand, salt and food processing. Screw conveyors can be designed with the same or variable pitch, cone-shaped screw conveyors are also used, with constant or variable pitch. If not designed properly for the transported material, the experienced problems include: surging and unsteady flow rates, inaccurate metering and dosing, inhomogeneity of the product, product degradation, excessive power draw, high start-up torques, high equipment wear and variable residence time and segregation. In case of hygroscopic material transport, it is possible that material is being pasted to the screw blade and/or to the casing, reducing the gap size between them. This affects the screw transporting capacity, increasing energy consumption.

The segregation of powder materials should be attributed to the specific shape of particles and the differences in weights, but also to the length of the screw transporter. It is very difficult to design and manufacture screw transporter with increased length, particularly due to deformation of long screw shaft, in which case additional support(s) are required between the initial and final bearings case. A summary of current design methods and problems experienced for screw conveyors can be found in Bortolamasi and Fottner (2001) [1]. The description of the theoretical behavior of screw conveyors can be found in articles by Yu and Arnold (1997) [2] and Roberts (1999) [3].

Discrete element modeling (DEM), of particulate flow in a screw conveyor was first reported by Shimizu and Cundall (2001) [4]. They examined the performance of horizontal and vertical screw conveyors and compared their results with previous work and empirical equations. Owen *et al*. (2003) [5], introduced the use of a periodic slice model to explore the performance of a long screw conveyor. Cleary (2004) [6] used DEM to study draw down patterns from a hopper by a 45° inclined screw conveyor. This work was extended by Cleary (2007) [7] to examine the effect of particle shape on the draw down flow from the hopper and on the transport characteristics of the screw conveyor.

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Screw conveyors are also used for metering (measuring the flow rate) from storage bins and adding small controlled amounts of trace materials (dosing) such as pigments to granular materials or powders [8–10]. Dosing feeders are often constructed by adding frequency converters for speed change and fine dosing to the desired value. In this case it is very important to properly choose the geometry of the screw transporter. Changes in screw geometry, with several additional elements welded on screw blade can significantly increase the homogeneity and reduce the segregation of materials by particle size.

Screw transporters are frequently used to remove powder or grain material from silos, and transport it to the mixer. It is very important to mix thoroughly all individual components (for instance in animal food industry), in order to obtain the homogeneous product. Before the mixing process is performed, it is often practice that some premixing action is done, using some type of the auxiliary mixer. There are many mixer types, used for this action, mostly counter-screw types, and more recently specially profiled blade mixers, utilized in the industry.

The leading idea in this article was to analyze transport action of screw conveyor and to utilize the screw blade with changed geometry as continuous premixing agent, before material enters the mixer. The volumetric fill level of the screw transporter depends on many processing parameters, but is never equal to one, and the possibility of welding additional elements to screw coil geometry exists. It was intended to improve mixing by inserting additional helix or helical strips, in the same or opposite direction of material flow, on the periphery of the spiral screw trajectory. The transport of specific particles depend on the rotational speed of screw conveyor, but also on the geometry of the helix, and the transporting path can be greatly prolonged by inserting these element to the screw coil. In this case, particle velocity is significantly increased, and the probability of mixing is also enhanced, in respect to distance traveled is much longer.

The main aim of this paper is to consider the possibility of prolonging particle transport path from the moment of entering to the moment of leaving the screw conveyor, with addition of new elements welded on the helix of screw conveyor, in order to increase the effect of auxiliary mixing along with the transport of particles. In this way a screw transporter could be considered as transporter and also the continous premixer. Discrete Element Method (DEM) was used to explore the modifications in screw geometry and the influence on transport path, during the transport of just one particle, with the intention to keep the material flow unspoiled.

MATERIALS AND METHODS

DEM simulation involves following the motion of every particle involved in the model definition, and modeling of each collision: inter-particle and between the particles and their environment (*e.g.*, the internal surface of the screw casing and the surface of the rotating screw). The boundary geometry is built using a CAD package and imported as a small sized triangular surfaces mesh into the DEM package. This provides unlimited flexibility in specifying the three dimensional geometries with which the particles interact. Here the particles are modeled as spheres (also imported as small sized triangular surfaces).

The modeling technique is based on the assumption that the particle is soft (soft particle method), and that particles are allowed to overlap. The amount of overlap is labeled as Δx, and the normal and tangential relative velocities determine the collisional forces (F_n and F_t). Figure 1 illustrates the collisional force as the result of normal and tangential forces. The normal force F_n is considered as the repulsive force that pushes the particles apart (or particle from bounding geometry), depicted as the action of the spring, and also dissipation action, resulting in an effective coefficient of restitution, shown as dashpot action. Tangential component is considered as an incrementing spring action and dashpot action that is subjected to frictional limit.

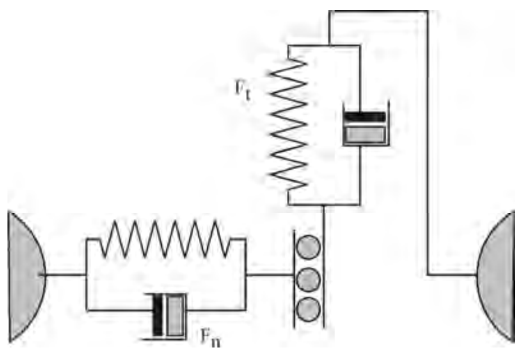

Figure 1. The contact force model.

In this article, DEM analysis was used to investigate the path of single particle, during transport, considering the differences in helix of the screw conveyor. Here applied DEM analysis can be summarized as follows: neighboring interaction list is based on the used grid (defined by used triangular surface mesh), and the boundary objects (also defined by triangular surface mesh), which are treated as virtual, non-moving particles. The collisional forces on the specific particle and boundaries are efficiently evaluated using the neighboring list and the spring-dashpot interaction model (Fig. 1) [12]. All the forces on the boundary objects and specific particles are summed and the resulting equations of motion are integrated using DEM package. The particle velocities and their axial and tangential (swirl) components were invariant to changes of particle–wall friction.

RESULTS AND DISCUSSION

In this work the influence of helix geometry on single spherical particle trajectory is investigated. Applied DEM analysis, the mutual influence of different configuration of helix geometry and observed particle, is focused to inspect the possibility of prolonging single particle path during transport. The analysis of particle trajectory was intended to start in the moment when spherical particle enters the screw conveyor and stop in the moment when particle leaves the transporter. However, it was noticed that the segment of particle trajectory repeats each time the helix makes one revolution, concluding that it is possible to draw conclusions on prolonging the path, during transport, by observing only one segment of the particle trajectory. This conclusion was employed to shorten the process simulation, and also to reduce computer's central processing unit (CPU) calculation time. One of the key factors that the modeler should be aware in DEM analysis is shortening the CPU time and also the reduction of other computer resources (such as amount of RAM memory, motherboard performances, multiprocessors support, etc.), by making these basic assumptions.

The basic screw conveyor used in this study was a standard pitch, single flight screw conveyor with no additional helices, which is commonly used in processing industry. The pitch of the screw is defined as the length, along the drive shaft, of one turn of the helical blade, as shown in Figure 2. A standard pitch screw has its pitch equal to the outer diameter of the helical blade. The DEM model was simplified (and the CPU time is significantly reduced) by applying periodic boundary conditions to a single pitch of the screw as shown in Figure 2. The pitch of the screw was 50 mm, the diameter of the screw shaft was 15 mm, and the blade thickness was approximately 1 mm. The internal diameter for tubular case was 47 mm, giving a gap of about 1.5 mm between the outer edge of screw blade and the internal surface of the casing. Screw conveyor length was 400 mm. All simulations used the same rotational speed of 20 rpm.

DEM particles are modeled as spheres in three dimensions. Small-sized triangular surfaces mesh was used for geometrical modeling of seed, (grain that is very close to spherical shape), and for the DEM calculation, and the size of the particles used was 4.0 mm, with a density of 500 kg/m^3. The particle–boundary frictions used for the DEM (base case) simulations were 0.3, and particle–boundary coefficients of restitution were 0.3. The maximum overlap between particle and boundary is determined by the normal spring stiffness. Typically, average overlaps of 0.1–0.5% are desirable, requiring a spring constant of 1000 N/m for this type of simulation.

A series of DEM simulations was performed for various screw conveyor-mixer geometry. Standard pitch, single flight screw conveyor's transporting action was used in comparison to other modified screw conveyors with additional flights welded on the periphery of the spiral helix in order to improve mixing. Examined modified screw conveyor-mixers used in this article were:

1. Screw conveyor-mixer with three additional helices oriented in the same direction as screw transporting helix, welded on the periphery of the helix, Fig. 3a,

2. Screw conveyor-mixer with three additional helices oriented in the opposite direction from transporting helix, welded on the periphery of the helix, Fig. 3b,

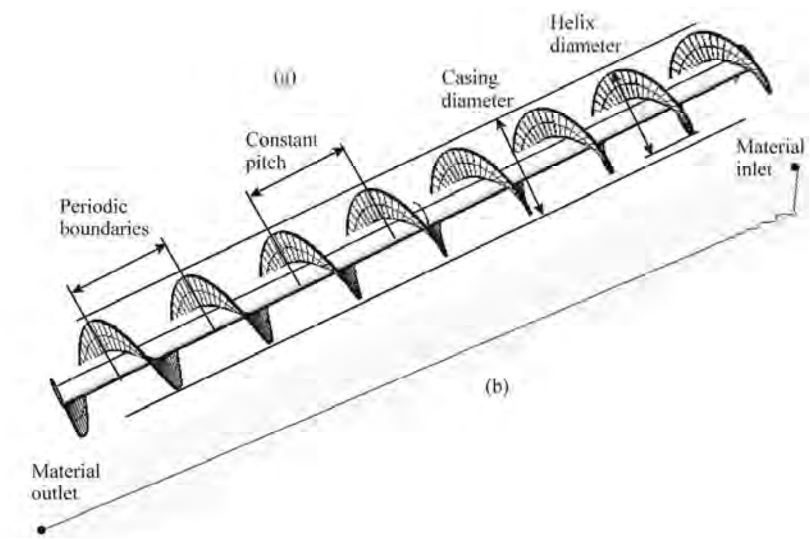

Figure 2. a) Standard pitch, single flight screw conveyor; b) particle path.

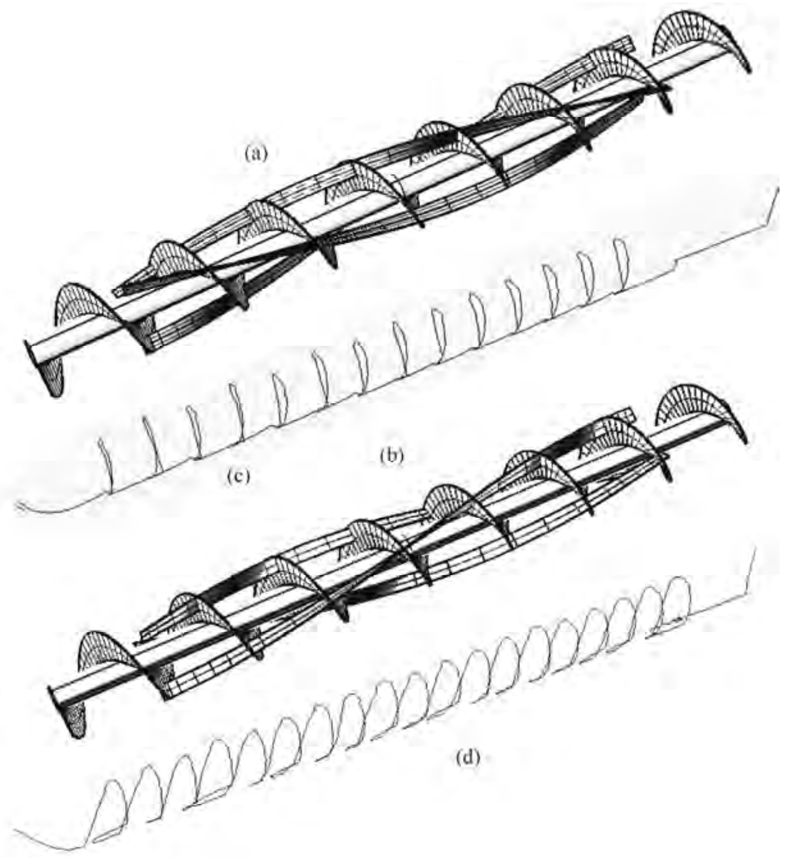

Figure 3. a) Screw conveyor-mixer with three additional helices oriented in the same direction as screw blades, b) screw conveyor-mixer with three additional helices oriented in the opposite direction from screw blades, c) particle path and d) particle path.

3. Screw conveyor-mixer with three truncated additional helices oriented in the opposite direction as transporting helix, welded on the periphery of the helix, Fig. 4a and

4. Screw conveyor-mixer with additional straight line blades, welded on the periphery of the helix, Fig. 4b.

The movement of granular particles, modeled as spheres in DEM simulation, was observed from the initial moment, the entering in screw transporter-mixer to the moment of leaving the external tube, and the motion path was analyzed. The full length of obtained path, during the simulation, and also the retention time were recorded.

The purpose of this analysis is to improve the geometry of the standard screw transporter with additional elements, welded on the perifery of the helix that enables prolonging of particle path within the screw conveyer. Also, the velocity increase of the single particle could be expected.

It is well known, that the screw conveyor fill level should be less than 50%, *i.e*., much of the volume above the helix blade is empty during transport, and this volume can be used for additional mixing action during transport. During the transport in classical screw transporter, the particles generally travel in the straight line, along the transporter length.

Using DEM simulation of the particle trajectories, single particle coordinates $x = f(t)$, $y = f(t)$ and $z = f(t)$ have been obtained, and the spatial curve showing the trajectory of that particle is plotted (Figs. 2b, 3c and d and 4c and d), from the moment of entering until the moment of leaving the screw conveyor.

The effect of single path prolonging leads to enhance the interferences between observed particles and increase probability of particles being mixed during the transport (in case that screw conveyor is transporting several different components and/or different particle sizes). The movement of just one single particle has been observed in order to show possible solutions that would increase the particle path by adding elements to the screw conveyor, not changing the basic dimensions of the screw conveyor.

In the first case, when the screw transporter works only as a conveyor, the particle path is almost a straight line (Fig. 2b), while in all other cases the particle is moving on a much longer path which was particularly evident in the case of screw conveyor-mixer with additional straight line blade (Fig. 4d).

In case of single flight screw conveyor (Fig. 2a), the total particle path is only 397.6 mm, according to DEM

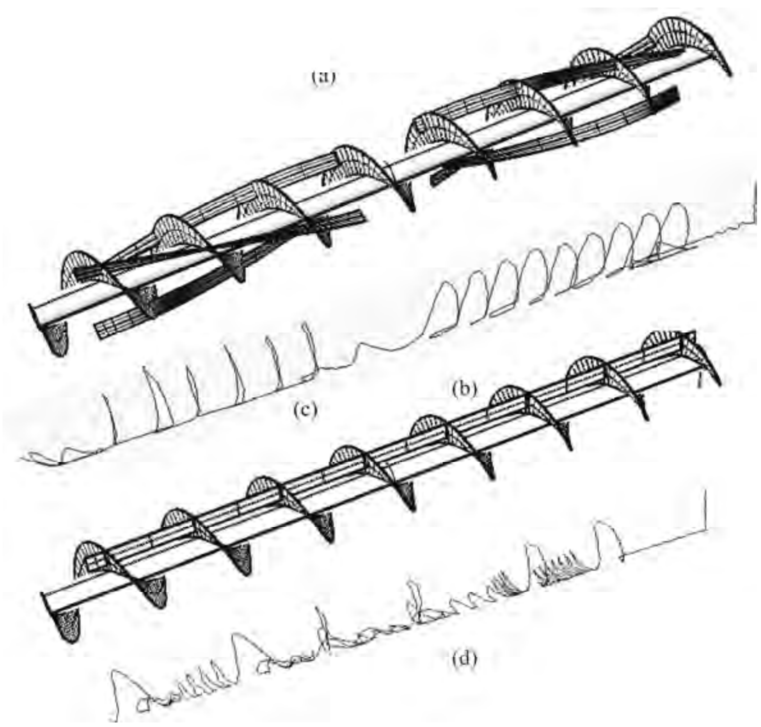

Figure 4. a) Screw conveyor-mixer with three truncated additional helices oriented in the opposite direction as screw blades, b) Screw conveyor-mixer with additional straight line blade, c) particle path and d) particle path.

simulation. Initial small perturbation was observed, and afterward straight lined path, caused by screw conveyor transporting action.

Screw conveyor-mixer with three additional helices oriented in the same direction as screw blades (Fig. 3a), strongly enlarges the total particle path, calculating more than a three times longer trajectory of 1458.2 mm, for equal transport time of 23.5 s. After reaching the top of the screw the particle tumbles down from the top of the helix. The particle tumbling down to the next free surface on the heap and that segment of path can be used for auxiliary mixing action.

When using screw conveyor-mixer with three additional helices oriented in the opposite direction from screw blades (Fig. 3b) for transporting and auxiliary mixing action, transporting path enlarges even more, to 1764.4 mm, which was expected, because opposite oriented helices return the single particle a bit backward, as can be seen from Fig. 3d.

By truncated additional helices oriented in the same direction as screw blades (Fig. 4a), particle path is being shortened (due to broken helices at the middle of screw conveyor). In this case, total path is 1728.8 mm.

Screw conveyor-mixer with additional straight line blade exerts the longest single particle path in this simulation (Fig. 4b): 2061.6 mm, which is a less more than five times compared with single flight screw conveyor.

CONCLUSION

Modified geometry screw conveyor and its utilization in mixing action were analyzed. The main idea was to improve mixing action by inserting additional helix or helical strips, on the periphery of the helix, in the same or opposite direction of material flow. The transport action of single particle depends on the geometry of the helix, and the transporting path can be significantly prolonged by inserting these elements to the helix of screw transporter. Particle retention time remains constant, but the velocity is significantly increased, and the probability of mixing of two or more particles is also enhanced, in respect to traveled distance is much longer.

Discrete Element Method (DEM) was used for an investigation of the effects of differences in screw geometry and the influence on transport path, during the transport of just one particle, with an intention to use a screw conveyor as transporter, but also as the continous pre-mixer.

The particle path is being extended by addition of complementary helices oriented in the same direction as screw blades (particle path is enlarged more then three times), or in the opposite direction of screw blades (when particle path is endured extended more then four times).

The longest path result obtained in DEM simulation was with the screw conveyor with additional straight line blade, which is a less more than five times compared with single flight screw conveyor.

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IZVOD

KORIŠĆENJE METODE DISKRETNIH ELEMENATA NA MODELOVANJE PUŽNIH TRANSPORTERA-MIKSERA

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(Naučni rad)

Pužni transporteri se veoma intenzivno koriste u industriji za proizvodnju i preradu hrane, plastike, mineralnih sirovina, u poljoprivrednoj proizvodnji kao i u prerađivačkoj industriji za podizanje i/ili transport rasutih materijala na kratkim i srednjim rastojanjima. Uprkos njihovoj očiglednoj konstrukcionoj jednostavnosti, sam čin transporta je veoma složen za razumevanje i konstruktori se često oslanjaju na iskustvene podatke pri konstruisanju i izradi. Osobine pužnih transportera su određene radnim uslovima (kao što su: brzinu rotacije vratila puža, ugao pod kojim je nagnut pužni transporter, nivo zapreminskog punjenja puža, itd.). U ovom radu je opisano nekoliko horizontalnih puževa, konstantne dužine koraka, pri čemu su geometrije pužnih spirala neznatno izmenjene radi ispitivanja procesa mešanja tokom transporta, korišćenjem metode diskretnih elemenata (*Discrete Element Method* – DEM). Ispitivani su uticaji geometrijskih izmena na osobine pužnog transportera, različita konstrukciona rešenja pužne spirale su međusobno poređena, kao i efekti geometrijskih izmena na mešanje u toku transporta. Tokom transporta u pužnom transporteru, čestice padaju sa vrha pužne spirale na prvu sledeću slobodnu površinu pužne spirale i taj segment putanje čestice može da bude iskorišćen za dopunsko mešanje materijala tokom transporta. Putanja čestice se drastično povećava ugradnjom tri dodatne zavojne površine usmerene u istom pravcu kao i pužna spirala (1458,2 mm u poređenju sa 397,6 mm u slučaju pužnog transportera sa jednom spiralom). Skraćivanjem dodatnih zavojnica, koje su usmerene u istom smeru kao i pužna spirala, unekoliko se smanjuje putanja čestice, na dužinu od 1728,8 mm (usled prekidanja zavojnice na sredini pužnog transportera). Putanja čestice se produžava na 1764.4 mm, kada se ugrade dodatne zavojne površine koje su usmerene u suprotnom pravcu od pravca pužne spirale. Ugradnjom tri dodatna pravolinijske letve, dobijena je najduža putanja čestice: 2061,6 mm.

Ključne reči: DEM • Modifikovani pužni transporter • Predmešanje • Optimizacija