Conveyor belt trajectories - comparing predicted to experimental results

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Conveyor Belt Trajectories – Comparing Predicted to Experimental Results

D.B. Hastie, and P.W. Wypych

A conveyor transfer research facility has been commissioned at the University of Wollongong to investigate particle flow mechanisms through conveyor transfers. As part of this research, investigations into conveyor trajectories have been undertaken at varying belt speeds and using two granular free-flowing materials. Numerous numerical methods exist to predict the material trajectory from the head of a belt conveyor. Each method uses varying combinations of particle and bulk properties as well as the conveyor geometry. These have been used to predict the experimentally measured trajectories. The discrete element method (DEM) has also been utilized to produce further trajectory predictions. A 3D CAD model of the experimental test facility has been generated and combined with the particle and bulk properties of the test materials. DEM simulations have been produced to compare to the other two methods. The results of experimental testing are compared directly with numerical methods and DEM simulations to ascertain whether any of these models can be relied on to accurately predict conveyor trajectories.

Key Words: conveyor trajectories, belt conveying

1 Introduction

Belt conveyors are widely used in industry to transport material from one point to another. Many configurations are possible, from a single conveyor forming a stockpile, to many interconnected belt conveyors, which then rely on well designed transfers to deliver material further through the system. The path the material takes to the next step in the process is dictated by the way the material leaves the head of a conveyor. There are installations which run successfully, having systems which have operated for many years, however, not all have been ‘engineered’, instead relying on a rule-of-thumb approach by experienced and long serving staff.

The research presented in this paper focuses on the material trajectory as it leaves the head pulley of a belt conveyor from an experimental perspective, predictions made by applying a variety of numerical trajectory models, and the use of the discrete element method (DEM). Comparisons will be made between these three methods to establish whether the numerical models or the DEM simulations can successfully predict the experimental particle trajectories.

2 Experimental Setup

An experimental conveyor transfer research facility has been commissioned at the University of Wollongong, allowing detailed velocity based particle flow analysis through hood and spoon style conveyor transfers and conveyor trajectories. The facility consists of three 300 mm wide Aerobelt conveyors arranged to allow continuous re-circulation of material. A 1 m³ feed bin supplies material to the first conveyor (L = 4.5 m), inclined at 5° with a smooth belt, while the other two conveyors are inclined at 23°, both having crescent belts (L = 6.7 m and L = 11.4 m). Variable speed drives control the three conveyors independently and a maximum belt speed of 7 m/s can be achieved.

The conveyor transfer facility has been used to measure a series of trajectories by removing the hood and spoon and supporting framework to allow the material stream uninterrupted flow to the second conveyor.

Two materials have been selected for the experimental trials, polyethylene pellets (ρ₁ = 919 kg/m³, ρ₂ = 514 kg/m³) and corn (ρ₁ = 1362 kg/m³, ρ₂ = 691 kg/m³). These materials were selected due to being granular free-flowing, their robust nature and relatively uniform particle size. The corn was also chosen for its different particle shape.

Preliminary experimental testing was contained within an acrylic enclosure with the conveyor transfer removed. Trajectories were recorded ranging from 0.5 to 2.25 m/s at 0.25 m/s increments. The upper belt speed limit was due to potential impact with the enclosure. The flow was captured with a standard digital video camera as well as a still digital SLR camera, however,

Fig. 1: Polyethylene pellet trajectory for a belt speed of Vₜ = 4 m/s and material feed rate of mᵢ = 37.8 t/h.
analysis proved difficult due to parallax errors and subsequently no data was taken from these tests. A new arrangement was then produced, incorporating the addition of a 100 mm square grid behind the trajectory stream and an interception hopper, designed to manually slide along the receiving conveyor, allowing capture of the trajectory stream and smooth delivery of material onto the receiving conveyor. This trajectory hopper also allowed higher belt speeds to be tested, now ranging between 1 and 7 m/s in 1 m/s increments. Any framework obstructing a clear view of the trajectory stream was removed and the final arrangement can be seen in Fig. 1. Conveying of material was at full capacity for the installed belts, based on edge distance calculations provided by CEMA in 2005 [1]. This allowed both upper and lower trajectory boundaries to be measured.

Table 1 summarises the range of experimental tests performed for polyethylene pellets and corn. Limitations with the feeding arrangement resulted in a maximum feed rate of 37.8 t/h to be achieved for polyethylene pellets. This meant that full capacity conveying was not achievable for some of the higher belt speed tests.

Each test performed was videoed in the same way as the preliminary tests although not used for analysis. The tests were also photographed, not by capturing the overall trajectory, but as a series of successive small sections to minimise any potential parallax error. These sections were then analysed and the data combined to produce overall trajectories. The results of the experimental trajectory analyses are presented in Figs. 2 and 3.

The trajectory plots for the polyethylene pellets showed an interesting occurrence for the high belt speeds. The trajectory profiles for the three highest belt speeds (i.e. $V_b = 5$, $6$ and $7$ m/s) were very similar and in fact overlapped each other whereas the lower belt speed trajectories were distinctly separate. Two possible reasons for this were tabulated, firstly, the particles may have been reaching their terminal velocity at or close to the point of discharge from the head pulley of the conveyor or, secondly, material is slipping while on the conveyor belt, thus causing the particles to have a reduced discharge velocity. Of the two options, the latter was believed to be the most likely cause. To verify this, the Redlake high-speed digital video camera was positioned perpendicular to the flow stream to capture the particles at the point of discharge from the conveyor for each belt speed tested. The subsequent analysis of each particle stream was broken up into the lower and upper halves to determine if there was any relative motion within the material travelling on the conveyor as well as slip between the particles and the belt.

The complete results are presented in Fig. 4. As can be seen, there is very good agreement when comparing the belt speed to the particle discharge velocity up to and including $V_b = 5$ m/s for the lower and upper halves of the material stream. However, there is a substantial drop in particle discharge velocity for belt speeds of $V_b = 6$ m/s and above. For these higher belt speeds, it is also evident that there is a velocity differential between the lower and upper halves of the material stream. These findings indicate that material slip is in fact occurring and, as a result, the decision was made to only compare trajectories for belt speeds

<table>
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<tr>
<th>Belt Speed (m/s)</th>
<th>Polyethylene pellets (m/s)</th>
<th>Corn (m/s)</th>
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<tr>
<td>1</td>
<td>19</td>
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<td>2</td>
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<td>33.2</td>
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<td>7</td>
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<td>1</td>
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<td>2</td>
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<td>7</td>
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Table 1: Experimental trajectory setup.
up to and including $V_b = 5 \text{ m/s}$, where material slippage does not seem to be an issue. Additionally, the belt speed was checked with a laser tachometer for the full range of belt speeds tested and found to be accurate.

The most likely cause of this particle slippage is due to the distance between the feed point and conveyor discharge being too short for the higher belt speeds to allow material to achieve steady state. The particle characteristics specific to the polyethylene pellets most likely contributed to this slippage occurring, such as: relatively round shape, low density, moderately high coefficient of restitution and low friction. Other more angular materials with higher densities may not be affected by particle slippage.

The decision was then made that a maximum belt speed of $V_b = 5 \text{ m/s}$ would be tested for the experimental corn trajectories to avoid any potential issues similar to that seen with the polyethylene pellets.

As with the polyethylene pellet testing, the possibility of particle slip was investigated. Reviewing the previously used method, there was no way to directly measure the belt speed from the high-speed video footage. Instead, having to rely on the setting of the variable speed drives at the beginning of each test.

The Redlake high-speed digital video camera was mounted vertically above the discharge point of the conveyor as shown in Fig. 5 (left). The camera was aligned so as to capture the flow of one side of the particle stream to allow sufficient resolution to obtain accurate results as shown in Fig. 5 (right). Divisions of 50 mm were drawn along the entire length of the conveyor belt to provide both the scaling factor and a marker to track the speed of the belt and although hard to see, are visible in Fig. 5 (right).

The results of the discharge velocity analysis are shown in Fig. 6 and indicate a perfect match for belt speed and particle discharge velocity. The test for a belt speed of $V_b = 5 \text{ m/s}$ is in fact approximately 4.8 m/s which is most likely due to the variable speed drive not being adjusted to the exact setting. Regardless of this, for this belt speed, the particles are discharging at the same speed as the belt. From these results, it can be concluded that the trajectory profiles presented in Fig. 3 are accurate for the five belt speeds tested.

A significant finding from the experimental trajectory testing is that the underside of the trajectory stream does not keep the flat profile which is present at the point of discharge. As product moves along the conveyor through the troughed section, the material is forced into a curved geometry, however, once the transition zone is reached, the profile of the material changes from a troughed to flat profile when material reaches the head pulley and discharges. This flattening of the material through the transition zone causes a degree of lateral downward velocity to some of the material which continues after discharge, forming what has been termed “wings”.

Fig. 1 shows an example of these wings. The material present in this region of the trajectory stream is not as densely packed as the main body of the trajectory and as such the influence of air drag effects is more pronounced and particles separate quite freely from the main stream.

### 3 Numerical Trajectory Models

Conveyor trajectories have been the subject of predictive models as far back as the early 1900s. There is a wide ranging variation in the level of complexity in those models which do exist. Seven methods can be found in the literature: CEMA 2005 [1], MHEA [2], Booth [3], Golka et al. [4], Korzen [5], Dunlop [6] and Goodyear [7]. For all methods, there are two main conditions which are addressed: low-speed conveying conditions, where material wraps around the head pulley to an angular position before discharge, and high-speed conveying, where material leaves the conveyor at the point of tangency between the belt and head pulley. The specifics of these models have been detailed previously by Hastie and Wypych [8] and Hastie et al. [9] and will not be repeated here.

Considering the observations noted in Fig. 4, the decision was made to only produce numerical based trajectories up to and including a belt speed of $V_b = 5 \text{ m/s}$ for both polyethylene pellets and corn. The parameters for the experimental geometry as well as the particle characteristics for polyethylene pellets and corn have been applied to the seven trajectory methods listed above.

Some minor adjustments have been made to these methods such as the material height at discharge, $h$, and centroid height, $a_v$, which are used in the CEMA 2005 [1] and MHEA [2] methods and which have been determined directly from experimental measurements. The generated conveyor profiles for the numerical trajectory methods and three belt speeds are presented in Fig. 7 for polyethylene pellets and Fig. 8 for corn.
Reviewing the trajectory streams for each belt speed investigated, the following common observations have been made for polyethylene pellets and corn:

- For a belt speed of \( V_b = 1 \) m/s, low-speed conveying conditions apply and each of the trajectory methods generates a separate trajectory profile for the lower and upper boundaries.
- For a belt speed of \( V_b = 2 \) m/s, high-speed conveying conditions have been reached.
- For a belt speed of \( V_b = 2 \) m/s, the CEMA 2005 [1] and Goodyear [7] methods produce identical profiles.
- For a belt speed of \( V_b = 2 \) m/s, the Golka [4] method without divergent coefficients and the Korzen [5] method without air drag, produce identical profiles.
- For a belt speed of \( V_b = 2 \) m/s, the CEMA 1966; 1979; 1994, and 1997 [10-13] and MHEA [2] methods clearly produce the largest trajectory and continue to do so for the higher belt speeds.
- For all belt speeds exhibiting high-speed conditions, the Golka [4] method without divergent coefficients falls symmetrically inside the CEMA 2005 [1] method, while the Golka method with divergent coefficients falls symmetrically outside the CEMA method.

- As belt speed increases, there is a noticeable merging of several trajectory methods.
- For a belt speed of \( V_b = 3 \) m/s, the same trajectory method groupings exist as for the \( V_b = 2 \) m/s case.
- For belt speeds of \( V_b = 4 \) m/s and \( V_b = 5 \) m/s, the same trajectory method groupings apply and exhibit the same trends for both.

It has also been observed that there are some differences between the numerical prediction of conveyor trajectories when comparing polyethylene pellets and corn:

- For polyethylene pellets conveyed at a belt speed of \( V_b = 3 \) m/s, the Korzen [5] method incorporating air drag is beginning to diverge from the other trajectory methods and is falling closer to the conveyor head pulley, this is also somewhat true for corn but to a lesser extent.
- For polyethylene pellets at belt speeds of \( V_b = 4 \) m/s and \( V_b = 5 \) m/s, the Korzen [5] method incorporating air drag is now more noticeably falling closer to the conveyor head pulley than any of the other methods, this is also somewhat true for corn but to a lesser extent.

It is also important to point out that all of these trajectory methods are two dimensional models and as a result, can only produce trajectory profiles corresponding to the central longitudinal axis of the conveyor from which they emanate. This has implications when comparisons are to be made between the various methods of determining conveyor trajectories as will be explained in Section 5.
4 Discrete Element Modelling

Discrete element modelling (DEM) is becoming more widely used as a design tool and is ideal for generating conveyor trajectories. The simulations performed as part of this research have been achieved using the commercial software package, EDEM, by DEM Solutions. Particles are not just able to be simulated as spheres but also as clusters of spheres to generate more complex shapes. This has added an extra degree to the trajectory comparisons, by allowing investigation of the effect clustered particles have over spherical representations. The polyethylene pellets used experimentally have been modelled as spherical particles with an equivalent volume diameter of 4.75 mm and also as clustered particles consisting of two spheres of 4.3 mm diameter and merged to have a total length of 4.75 mm as shown in Fig. 9. The corn used experimentally have been modelled as spherical particles with an equivalent volume diameter of 8.75 mm and also as clustered particles consisting of 6 spheres and also as clustered particles consisting of 12 spheres, which both represented an averaged particle shape from 20 measured particles, see Fig. 10. Initially it was thought that the bumpy surface of the 6-sphere cluster would not be representative of the actually particles so the smoother 12-cluster particle was generated. Subsequent simulations found that there was very little difference in output between the two and so the 6-sphere cluster was subsequently used to save on computational time.

Table 2: Results of rolling friction sensitivity simulations.

<table>
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<tr>
<th>Number</th>
<th>Equivalent Diameter</th>
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<th>10°</th>
<th>15°</th>
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</table>
Calibration of the material feed rate was achieved by simulating the filling of a bin with a known number of both spherical and clustered particles in a given time. This process was repeated for various quantities of particles. The mass of particles in the bin at the end of each simulation was noted and a relationship graphed. This was found to be linear and an equation was generated which could output the number of particles required to generate any given material feed rate.

The initial setup of parameters necessitated the inclusion of the coefficient of rolling friction, which is in itself hard to measure. Kondic [14] suggests this value is in the order of two magnitudes smaller than both the static and kinetic friction and can be ignored. Others use a value of 1 per cent of the sliding (kinetic) friction [15] and others similar [16, 17]. As EDEM uses the coefficient of static friction, a coefficient of rolling friction equal to 1 per cent of this value was established for these simulations. It was subsequently found that this coefficient of rolling friction was too low as material was not discharging from the head of the conveyor at the same speed as the belt, instead slipping on the belt causing a reduced velocity producing inaccurate trajectories for later comparison.

A sensitivity analysis was then performed to determine what value of coefficient of rolling friction would achieve a particle discharge velocity equal to the belt speed. Six values were chosen ranging from 0.05 to 0.30 in 0.05 increments. These were performed for spherical and clustered particles and at a belt speed of \(V_b = 5\) m/s. As expected, the results for the clustered particles showed a better result than the spherical equivalents as the particle packing on the belt is better for clusters and less rolling occurs, as shown in Table 2. The results for the 6-sphere clusters for corn showed an even better result than the spherical polyethylene pellet representation, most likely due to the particle shape being noticeably flatter and somewhat rectangular. The particle velocity as a percentage of belt speed was reviewed for each of the coefficients of rolling friction values used and it was decided that a more representative value for polyethylene pellets was 0.30. For corn, the coefficient of rolling friction for the spherical particles was taken as 0.25 and for the 6-sphere clustered particles was taken as 0.15. These values are markedly higher than what has been previously proposed in the literature but in this application provided a near perfect agreement with respect to particle velocity versus belt speed. Further sensitivity analyses were then performed for the lower belt speeds using these coefficients of rolling friction and the results are also included in Table 2. The results for a belt speed of \(V_b = 1\) m/s show slightly elevated results but for the other belt speeds the comparisons are very near perfect. These results verified that the chosen coefficients of rolling friction should be used for polyethylene pellets and corn respectively.

DEM simulations were performed to reproduce the full capacity conveying measured experimentally using belt speeds from \(V_b = 1\) m/s to \(V_b = 5\) m/s. The particle data extracted consisted of the x and y coordinates of the complete three dimensional particle stream and plotted to produce trajectory profiles. Fig. 11 displays the results of the polyethylene pellet DEM simulations for both spherical and clustered particles (with experimental trajectories super-imposed) and Fig. 12 displays the results of the corn DEM simulations for both spherical and clustered particles (with experimental trajectories super-imposed). In both figures the spherical particles are represented by the blue points while the clustered particles are represented in grey. The results for both products show negligible difference between the spherical and clustered particles most likely due to there being no external influences on the particles once they discharge from the conveyor. It can also be seen that as the belt speed increases, there is deterioration of the underside of the trajectory stream. This is most evident for the 5 m/s belt speed simulations where there is a noticeable loss of integrity of the flow stream. This was also observed during the experimental testing.

5 Trajectory Comparisons

A lateral velocity component is introduced as material passes through the transition zone on the conveyor belt. Experimentally, it has been shown that due to this 'wings' develop at the
lateral extremities of the trajectory stream for the higher capacity feed rates due to. Experimental comparisons with the trajectory models could not be achieved directly as the numerical models provide a two dimensional representation of the trajectory stream, hence there is no way to account for the wings. This has led to the following sets of direct comparisons being made for both polyethylene pellets and corn:

- the experimental upper trajectory boundary versus the upper trajectory boundary predicted from the numerical models,
- experimental trajectories versus full stream EDEM simulations, and
- trajectory models versus EDEM simulations (thin slice only along the conveyor centreline).

Review of the plots produced for the experimental upper trajectory boundary versus the upper trajectory boundary predicted from the numerical models showed nearly identical results for polyethylene pellets and corn for the range of belt speeds and for this reason one graph is shown below in Fig. 13.

It can be seen that for \( V_b = 1 \) m/s, the experimental trajectory closely follows the Booth method. For belt speeds of \( V_b = 2 \) m/s, \( 3 \) m/s, \( 4 \) m/s and \( 5 \) m/s, the experimental trajectory follows the trajectory model grouping of CEMA 2005, Goodyear, Korzen (no air drag), Golka (no divergent coefficients) and Booth. The common numerical method in these comparisons is the Booth method. There are still some minor variations between these experimental and numerical trajectory curves which are most likely as a result of the analysis method used in the experimental testing.

The three dimensional EDEM trajectory simulations showed the 'wings' observed experimentally, indicating that the simulations were able to predict the dynamics of the material flow well, mimicking that occurring in reality. Fig. 11 and 12 provide comparison graphs of the experimentally generated upper and lower trajectory boundaries (vis. Table 1) and the corresponding EDEM simulations. In all cases, the upper experimental trajectory boundaries have a good fit with the EDEM outputs. There are more noticeable differences with the comparisons between the lower trajectory boundaries which may be as a result of air drag effects present in the experimental results but which could not be accounted for in the EDEM 'only' simulations.

EDEM produces three dimensional outputs which do not allow direct comparison with the two dimensional numerical trajectory models. To remedy this, during post processing of EDEM data, there is the ability to select regions of interest within the particle data (called binning). A 40 mm slice was taken along the length of the conveyor and down the centre of the trajectory stream which was then extracted for comparison with the trajectory models. Fig. 14 and 15 show the comparisons for polyethylene pellets and corn respectively for the five belt speeds tested experimentally. Each figure also includes an inset image, focussing on the bottom of the \( V_b = 1 \) m/s conveying condition to highlight which of the numerical models best fits the EDEM simulation data. For the \( V_b = 1 \) m/s case, the Booth method provides the best agreement with the simulation data although the stream is slightly wider. For high-speed conveying conditions, \( V_b = 2 \) m/s to \( V_b = 5 \) m/s, several numerical trajectory model curves predict the same path so have been merged to produce one curve only. For this comparison, the simulation data fits extremely well with the trajectory models for CEMA 2005, Goodyear, Korzen (no air
drag). Golka (no divergent coefficients) and Booth. In all cases, there is one numerical model which is accurately comparing to the EDEM simulation data, that being the Booth method.

6 Conclusions

Findings from the experimental test program have shown that material slip can be an issue when predicting conveyor trajectories, especially for high belt speeds. If material is fed onto a conveyor too close to the discharge point, there is a possibility that the material will not have achieved steady state at the point of discharge, thus particles may not be leaving the conveyor at the same speed as the belt is travelling. This has the potential to have serious consequences in relation to positioning of stockpiles or the design and positioning of conveyor transfers. Of course this can also be product dependent, based on such parameters as particle shape, friction and weight.

The numerical trajectory models are wide ranging in complexity and it has been shown that the predictions from these can vary substantially from experimentally determined trajectories. This research has shown that the Booth method provides a very good prediction of the experimental trajectories for both polyethylene pellets and corn under a wide range of belt speeds [3]. The Booth method also provides a very good agreement with the EDEM simulation outputs generated for the two test products over the full range of belt speeds considered.

The influence of particle shape in the EDEM simulations does not appear to have much of an effect on the final trajectory. The coefficient of rolling friction is one parameter which has been shown to have a noticeable influence on the way particles behave in this application. It is advisable that the sensitivity of this parameter be checked before the commencement of any DEM simulations.

Finally, further experimental testing will continue with different products, to produce an increasing database of information for which more detailed comparisons can be completed to determine whether the Booth (1934) method continues to accurately predict both experimental and EDEM simulations.

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References


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