COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED CONVEYOR BELT TRAJECTORIES

David B. Hastie and Peter W. Wypych

INTRODUCTION

Belt conveyors are commonly used in a multitude of industries to transport material from one location to another. Belt conveyors can be configured in many ways, from a single run which might form a stockpile, to many interconnected belt conveyors, necessitating the use of transfers to successfully deliver material through the system. Whichever method applies, the way in which material leaves the head of a conveyor will dictate the path the flow of material takes to the next step in the process. Many installations run successfully with systems that have been in operation 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.

EXPERIMENTAL

An experimental conveyor transfer research facility was designed and commissioned at the University of Wollongong to allow detailed velocity based particle flow analysis through hood and spoon style conveyor transfers (Figure 1). The facility consists of three Aerobelt™ conveyors arranged to allow continuous re-circulation of material. The feed bin is approximately 1 m^3 in volume and supplies material to the first conveyor (L = 4.5 m), inclined at 5º with a smooth belt, while the other two conveyors are inclined at 23º, 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 ms^{-1} can be achieved.

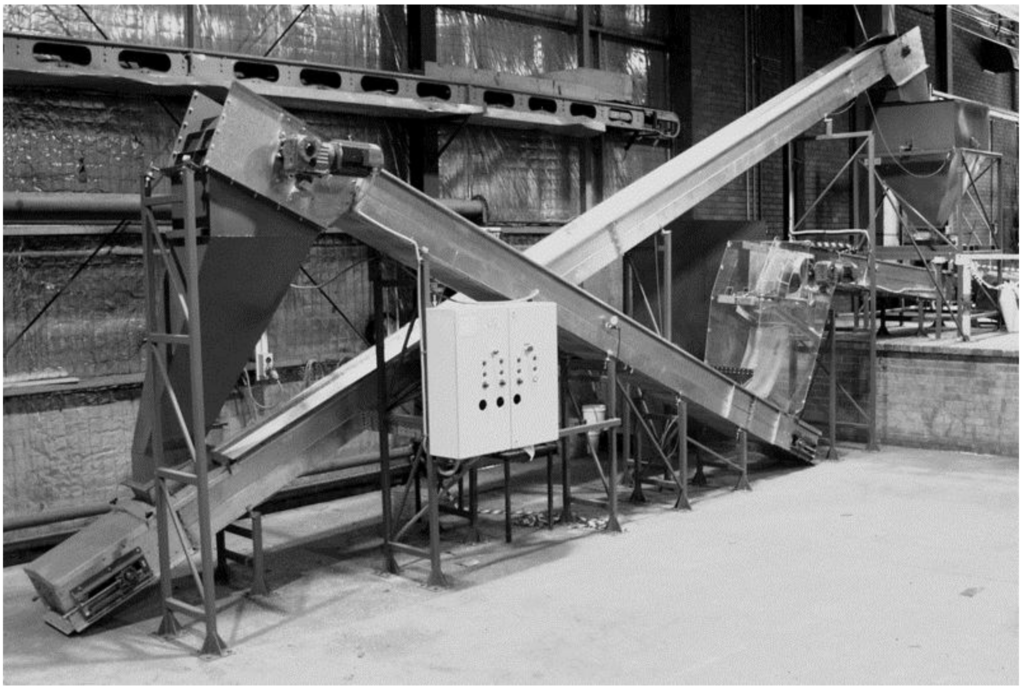

Figure 1: Conveyor transfer research facility

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.

Polyethylene pellets (ρ_s = 919 kg m^{-3}, ρ_b = 514 kg m^{-3}) were selected as the test material due to their robust nature and uniform particle size.

Preliminary experimental testing relied upon the acrylic cover containing the trajectory flow, (Figure 2). Tests were limited to belt speeds between 0.5 ms^{-1} and 2.25 ms^{-1} at 0.25 ms^{-1} increments. This upper belt speed limit was due to the trajectory stream falling in close proximity to the end acrylic cover containing the material. An example of the captured trajectory stream can be seen in Figure 2. The flow was captured with a standard digital video camera as well as a still digital SLR camera. However analysis proved difficult due to parallax errors. The results from these tests lacked accuracy and as a result have not been taken further.

Another method of profiling the conveyor trajectory was trialled with equipment from Bluescope Research being tested by an undergraduate mechanical engineering thesis student [1]. An optical laser connected to an X-Y frame was positioned above the head pulley of the discharge conveyor. The laser moved via stepper motors, controlling linear slides and was connected to a laptop via a data acquisition card to record the electrical signals. The size of the X-Y frame and linear slides meant that this arrangement was not ideal for obtaining the trajectory profile of the upper surface as not enough of the trajectory could be recorded. Profiling of the lower trajectory stream could not be approached in the same way. Instead of using the X-Y frame, the laser was fixed to an existing cross-brace and a stepper motor was used to rotate the laser to scan the lower trajectory profile. The lasers used had an operating focal length of 0.5 m to 6 m and had a limitation that if the trajectory stream fell too close to the laser, i.e. within 0.5 m, the laser could not detect the profile.

The decision was made that the laser scanning method was not feasible with the lasers available and as such was disregarded as a suitable method of determining the lower and upper trajectory profiles.

Figure 2: Trajectory, V_b = 1.5 ms^{-1}, m_s = 24 tph

An enhancement of the preliminary trajectory setup was then produced, including the addition of a 100 mm square grid behind the trajectory stream. Also included in this phase of the testing was the addition of 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, beyond the limiting 2.25 ms^{-1} of the preliminary trajectory testing. All extraneous framework was removed to give the most uninterrupted view of the trajectory possible and the final arrangement can be seen in Figure 3.

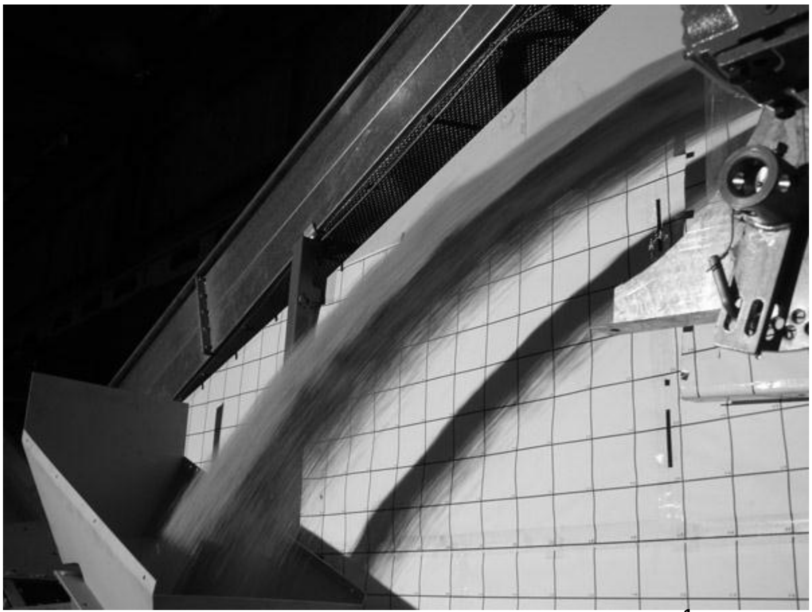

Figure 3: Trajectory for a belt speed of V_b = 4 ms^{-1} and material feed rate of m_s = 37.8 tph

The addition of the trajectory hopper allowed tests to be performed using belt speeds ranging from 1 ms^{-1} to 7 ms^{-1} in 1 ms^{-1} increments. Low material feed rates were tested to generate a thin particle trajectory stream to provide a "lower" trajectory stream only and high material feed rates were tested, with the edge distance set to maximum for each belt speed tested [2] to produce both lower and upper trajectory streams.

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

Belt Speed (ms^{-1})	Low Feed Rate (tph)	High Feed Rate (tph)
1	2.6	19
2	2.6	31
3	2.6	37.8
4	2.6	37.8
5	2.6	37.8
6	2.6	37.8
7	2.6	37.8

Table 1: Experimental trajectory setup

Each test performed was videoed in the same way as the preliminary tests. 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, (Figure 4). These sections were then analysed and the data combined to produce overall trajectories. The results of the experimental trajectory analyses are presented in Figure 5 and 6. No trajectory curve was produced for a belt speed of V_b = 7 ms^{-1} for the low material feed rate due to the stream losing integrity, with the defined boundaries being impossible to detect.

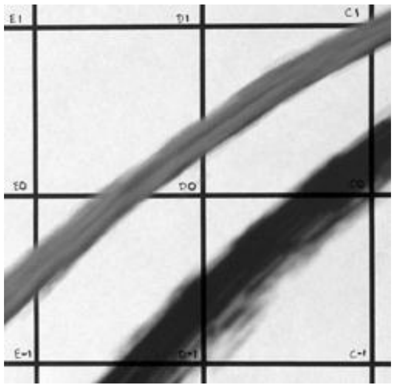

Figure 4: Example grid referencing, V_b = 2 ms^{-1}, m_s = 2.6 tph

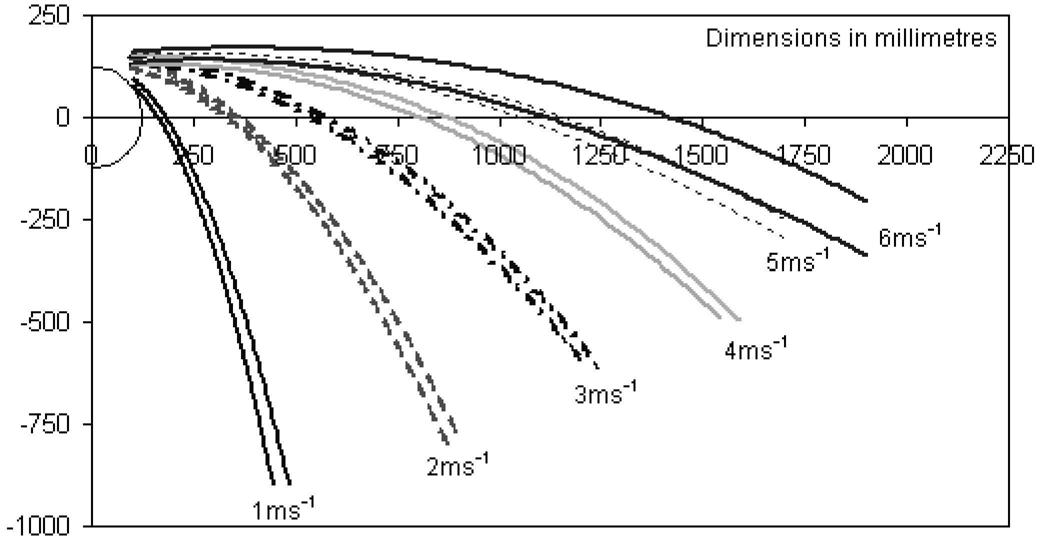

Figure 5: Experimental trajectories for low material feed rates

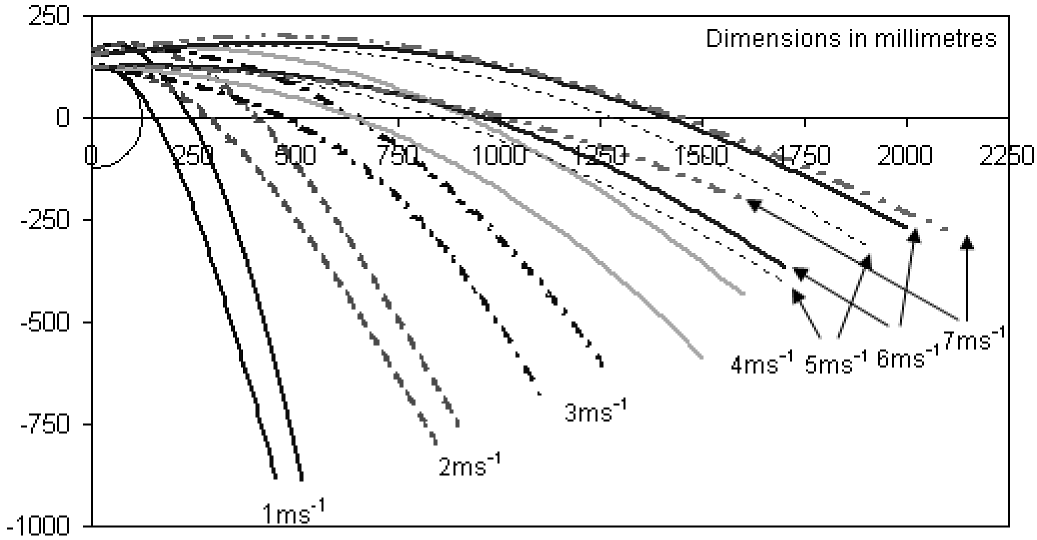

Figure 6: Experimental trajectories for high material feed rates

The results of the low material feed rate experiments showed for a belt speed of V_b = 6 ms^{-1}, there was very little difference to the trajectory profile produced for the V_b = 5 ms^{-1} test. A similar observation was seen for the high material feed rate experiments, where the trajectories for the three highest belt speeds (vis. V_b = 5, 6 and 7 ms^{-1}) were very similar and in fact, overlapped each other.

Two possible reasons for this were tabled, the particles were reaching terminal velocity at some point during the trajectory or there was material slippage present on the conveyor belt before discharge, thus reducing the velocity at which particles leave the conveyor. The latter option was thought the most likely and high speed video was used perpendicular to the flow stream to capture the particle discharge from the conveyor. Analysis was undertaken on the high material flow rate experiments only, due to the material burden having a substantial height, allowing relatively straightforward particle velocity tracking to be achieved. 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. The complete results are presented in Figure 7. 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 ms^{-1} for the lower and upper halves of the material. However, there is a substantial drop in particle discharge velocity for belt speeds of V_b = 6 ms^{-1} 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 continue the trajectory comparisons for belt speeds up to and including V_b = 5 ms^{-1} 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 slippage is due to the distance between the feed point and discharge being too short for the higher belt speeds.

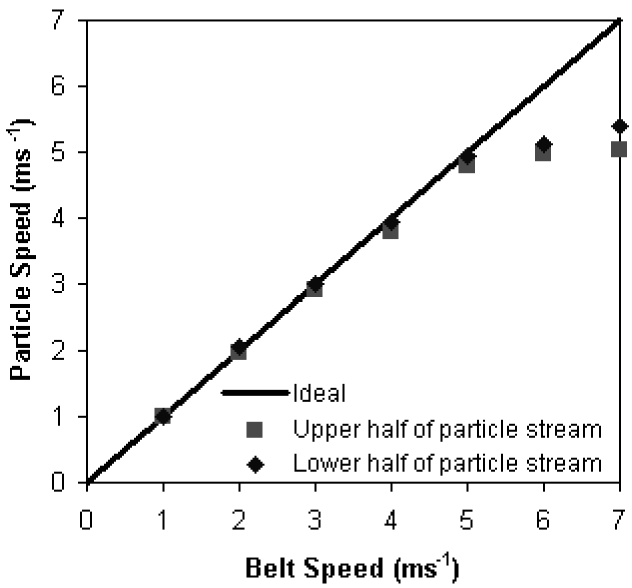

Figure 7: Comparison of belt speed to material discharge velocity

A significant finding from the high-speed experimental testing is that the underside of the trajectory stream does not stay flat after 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. The material profile changes through the transition zone, with the underside of the material changing 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’. Figure 3 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.

NUMERICAL TRAJECTORY MODELS

The trajectory of material leaving a conveyor has been the subject of predictive models dating back to the early 1900's and has seen a wide variation in the level of complexity of those that exist. Seven main methods can be found in the literature; C.E.M.A. [2,3,4,5,6], M.H.E.A. [7], Booth [8], Golka et al. [9], Korzen [10], Dunlop [11] and Goodyear [12]. For all methods, low-speed conveying conditions exist when material wraps around the head pulley to some angular position before discharge and high-speed conveying conditions occur when material leaves the conveyor at the point where the belt is at a tangent to the head pulley. Table 2 lists the discharge angles for the low-speed trajectory case presented in Figure 8a. It can be seen from the values in Table 2 that there is substantial variation. Further specifics of these models have previously been detailed by Hastie and Wypych [13] and Hastie et al. [14] and will not be repeated here. Considering the information provided in Figure 8, the decision was made to only produce numerical based trajectories up to and including a belt speed of V_b = 5 ms^{-1}. The parameters for the experimental geometry as well as the particle characteristics for polyethylene pellets have been applied to the seven trajectory methods. Some minor adjustments have been made to these methods such as the material height at discharge, h, and centroid height, a_1, which are used in the C.E.M.A. and M.H.E.A. methods and which have been determined directly from experimental measurements. The generated conveyor profiles for the numerous methods and belt speeds are presented in Figure 8.

Trajectory Method	Discharge Angle (from vertical)
C.E.M.A. / M.H.E.A.	16.7 º
Booth	19.8 º
Golka	34.0 º
Korzen	21.8 º
Goodyear	45.9 º

Table 2: Discharge angles for V_b = 1 ms^{-1}

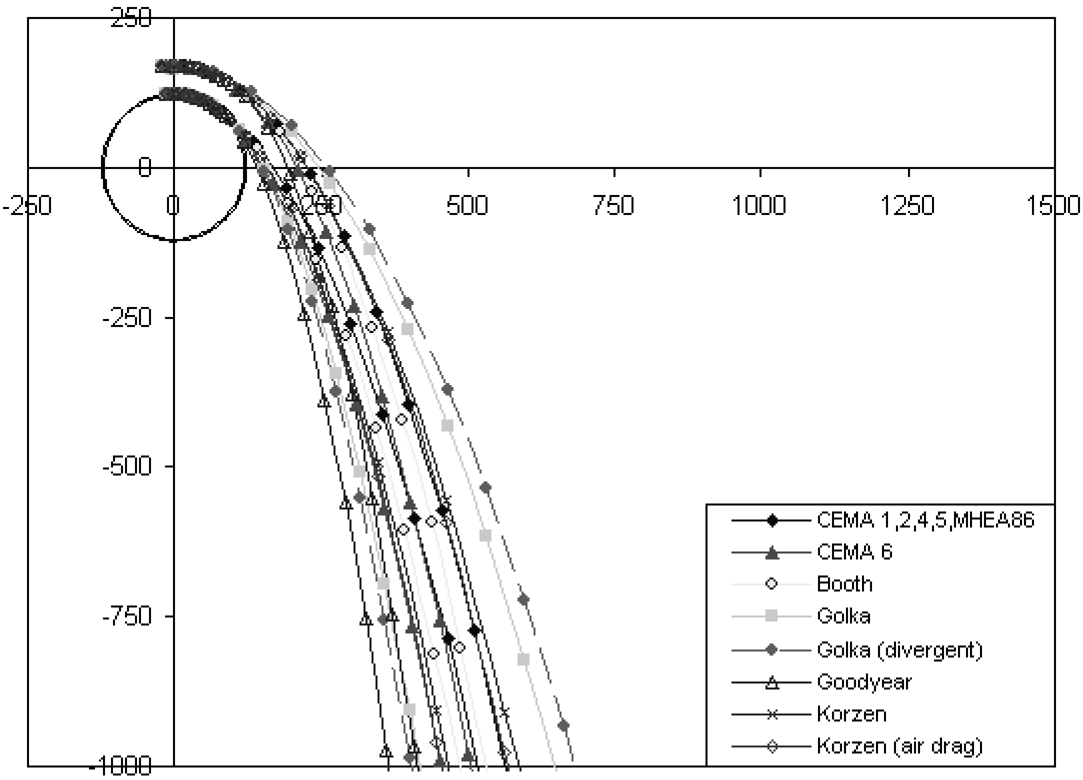

Figure 8a: Numerically determined conveyor trajectories for V_b = 1 ms^{-1}

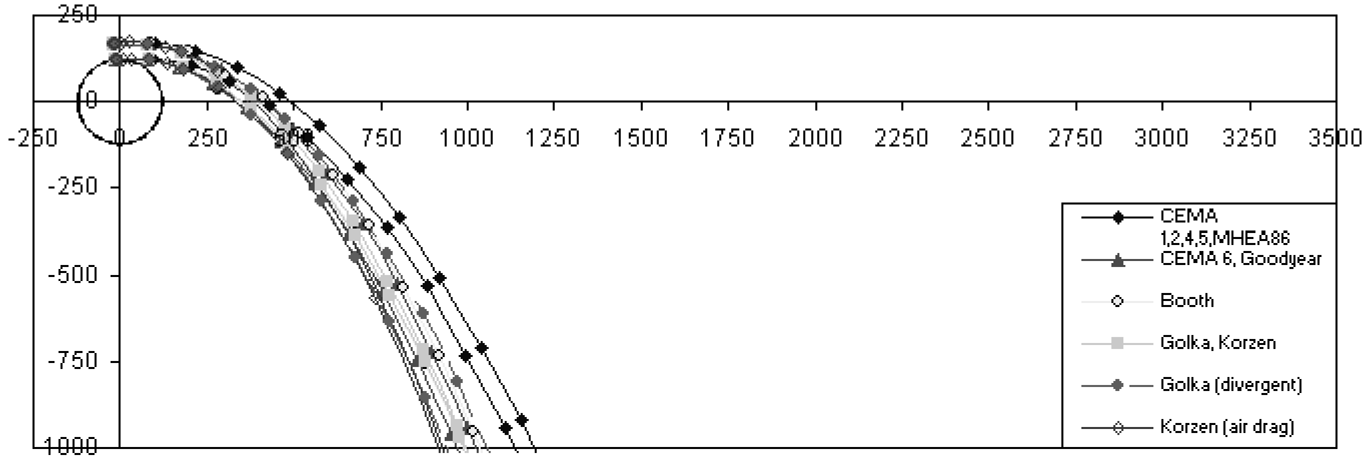

Figure 8b: Numerically determined conveyor trajectories for $V_b = 2\ ms^{-1}$

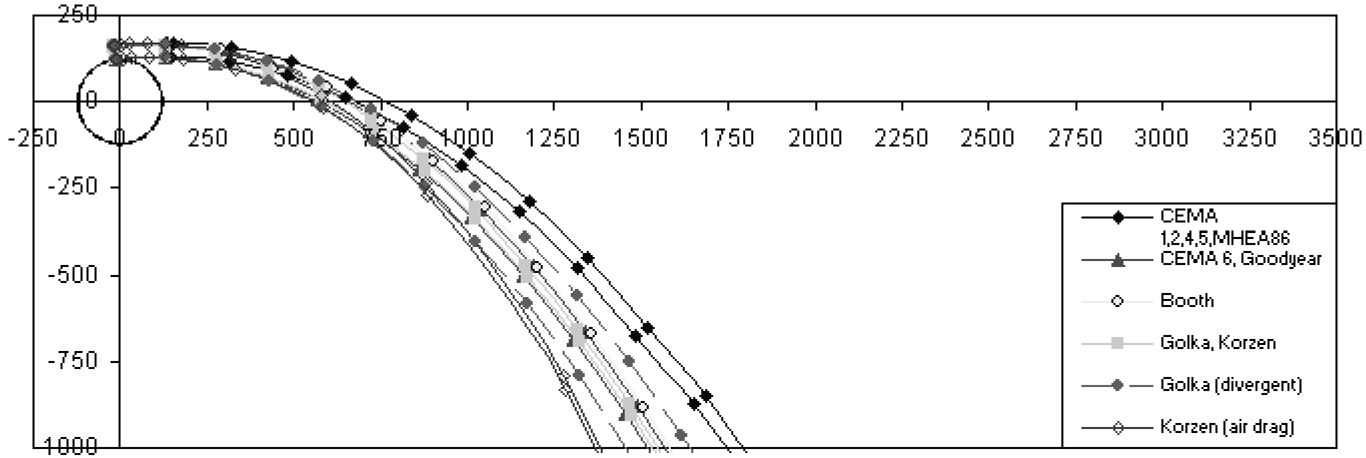

Figure 8c: Numerically determined conveyor trajectories for $V_b = 3\ ms^{-1}$

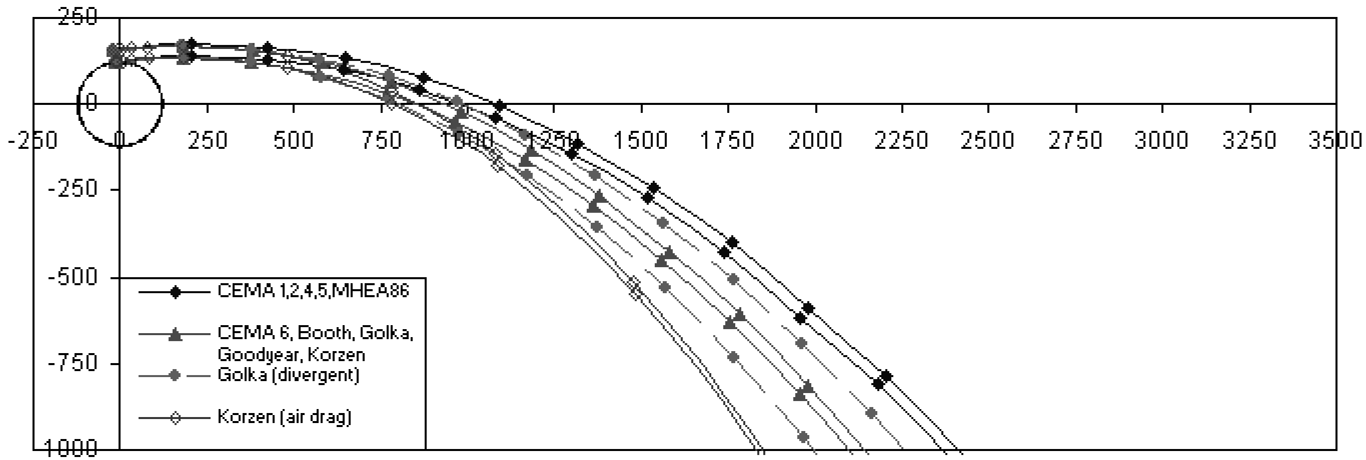

Figure 8d: Numerically determined conveyor trajectories for $V_b = 4\ ms^{-1}$

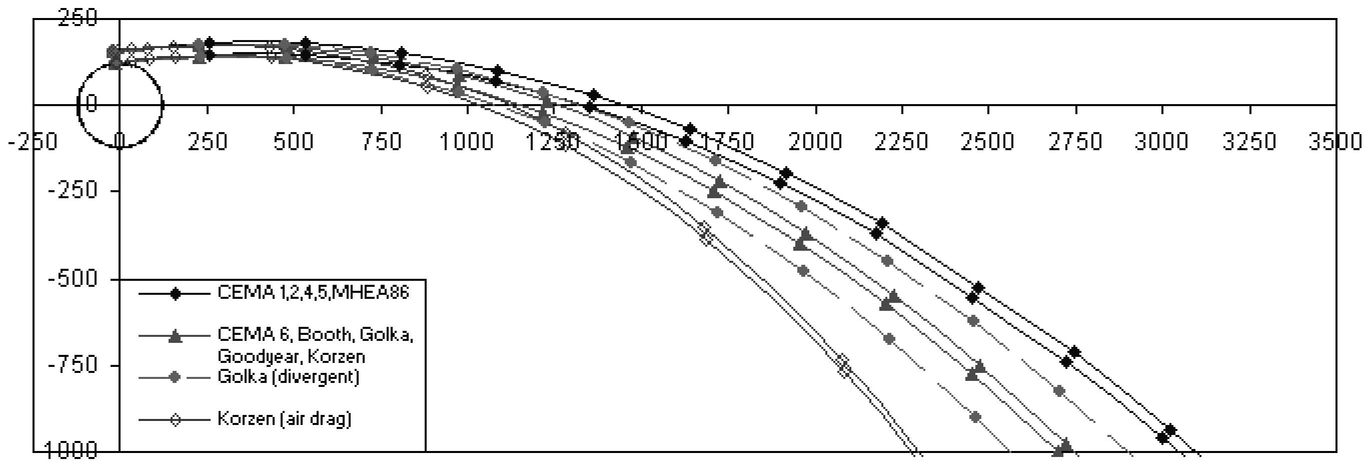

Figure 8e: Numerically determined conveyor trajectories for $V_b = 5\ ms^{-1}$

Reviewing the trajectory streams for each belt speed investigated, the following observations have been made;

- for a belt speed of 1 ms^{-1}, low-speed conveying conditions apply,
- for a belt speed of 1 ms^{-1}, each of the trajectory methods generates a distinctly separate profile for the lower and upper boundaries due to the variation in discharge angle,
- the Golka [9] method with and without applying divergent coefficients produces nearly identical profiles,
- the C.E.M.A. [3,4,5,6] and M.H.E.A. [7] methods produce identical profiles for each of the belt speeds investigated,
- for a belt speed of 2 ms^{-1} and above, high-speed conveying conditions apply,
- for a belt speed of 2 ms^{-1}, the C.E.M.A. [2] and Goodyear [12] methods produce identical profiles,
- for a belt speed of 2 ms^{-1}, the Golka [9] method without applying divergent coefficients and the Korzen [10] method without air drag produce identical profiles,
- for a belt speed of 2 ms^{-1}, the C.E.M.A. [3,4,5,6] and M.H.E.A. [7] methods clearly produce the largest trajectory and continue to do so for the higher belt speeds also,
- for all belt speeds exhibiting high-speed conditions, the Golka [9] method without divergent coefficients falls symmetrically inside the C.E.M.A. [2] method, and the Golka method with divergent coefficients falls symmetrically outside the C.E.M.A. method,
- as belt speed increases, there is a noticeable merging of several trajectory methods,
- for a belt speed of 3 ms^{-1}, the same trajectory method groupings exist as for the 2 ms^{-1} case,
- for a belt speed of 3 ms^{-1}, the Korzen [10] method applying air drag is beginning to diverge from the other trajectory methods and is falling closer to the conveyor head pulley,
- for belt speeds of 4 ms^{-1} and 5 ms^{-1}, the same trajectory method groupings apply and exhibit the same trends for both,
- the Korzen [10] method applying air drag is more noticeably falling closer to the conveyor head pulley than any of the other methods.

It is also important to mention that all of these trajectory methods are two dimensional models and as a result, can only produce trajectory profiles, their position corresponding to the central 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 and will be explained in Section 4.

DISCRETE ELEMENT MODELLING

Discrete element modelling (DEM) is becoming a more widely used tool for design and is ideal for generating conveyor trajectories. The simulations performed as part of this research have been achieved using the commercial software package, E-DEM, by DEM Solutions. Particles are not just able to be simulated as spheres but as composites of spheres to make up more complex shapes. This has added an extra degree to the trajectory comparisons by allowing investigation of the effect that shaped particles have over spherical representations. The polyethylene pellets used experimentally have been modelled as spherical particles with a diameter of 4.75 mm and as shaped particles consisting of two spheres of 4.3 mm diameter and merged to have a total length of 4.75 mm.

Calibration of the material feed rate was achieved by simulating the filling of a bin with a known number of particles at 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 a given material feed rate.

DEM simulations were performed for the low material feed rate used experimentally, (Table 1), for spherical and shaped particles. Belt speeds from 1 ms^{-1} to 5 ms^{-1} inclusive were simulated. The complete results of these two sets of simulations are presented in Figure 9 with the black data representing the spherical particle results and the grey data representing the shaped particle results. From the results, it can be seen that there is very little difference, if any, between the results achieved for the spherical and shaped particles. Also, it can 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 ms^{-1} belt speed simulations where there is a substantial loss of integrity of the flow stream. This was also observed during the experimental testing.

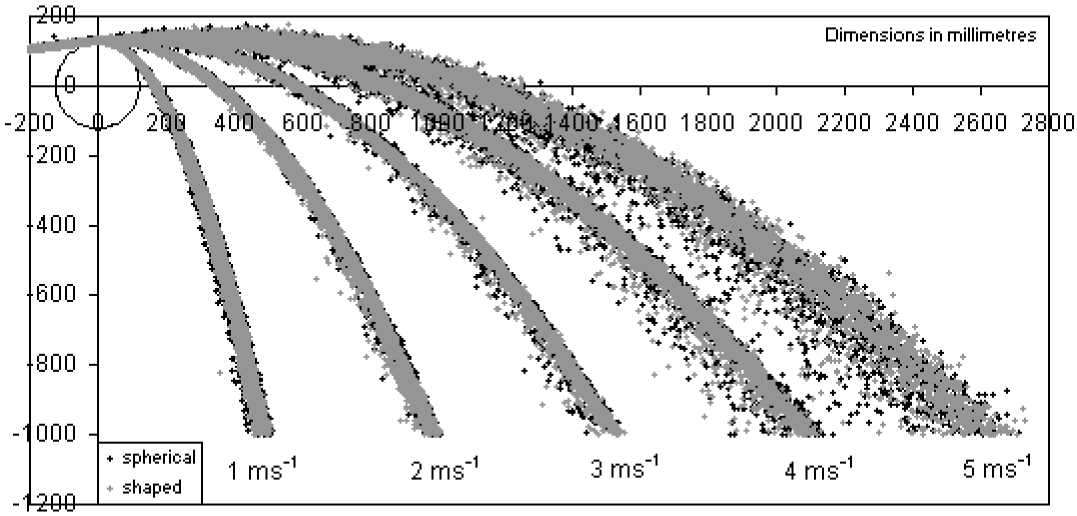

Figure 9: E-DEM trajectory simulations for low material feed rate using spherical and shaped particles

In a similar way to the low material feed rate trajectories, high material feed rates were simulated as per the data in Table 1. As a result of the trajectory curves being practically identical for both the spherical and shaped particles, only spherical particles were used to generate simulations for the high material feed rates. These results of course, have a wider trajectory profile than the low material feed rate simulations due to the additional material being conveyed.

TRAJECTORY COMPARISONS

Experimentally it has been shown that 'wings' develop at the lateral extremities of the trajectory stream for the higher material feed rates due to a lateral velocity component being introduced as material passes through the transition zone on the conveyor belt. Experimental comparisons with the trajectory models could not be achieved directly as the models provide a two dimensional representation of the trajectory stream, hence there is no way to account for the wings. This has lead to the following sets of direct comparisons being made: the experimental upper trajectory boundary being compared with the upper trajectory boundary predicted from the models, experimental trajectories versus full stream E-DEM simulations and trajectory models versus E-DEM simulations (thin axial slice only along the centreline).

Figure 10 plots the experimentally determined upper trajectory boundaries for belt speeds ranging from V_b = 1 ms^{-1} to 4 ms^{-1}. Also on this graph are the trajectory model predictions for the corresponding belt speeds. It can be seen that for V_b = 1 ms^{-1}, the experimental trajectory closely follows the Booth method. For belt speeds of V_b = 2ms^{-1}, 3 ms^{-1} and 4 ms^{-1}, the experimental trajectory follows the trajectory model grouping of CEMA 6, Goodyear, Korzen (no air drag), Golka (no divergent coefficients) and Booth. There are some minor variations between these curves which is most likely due to the analysis method used in the experimental testing.

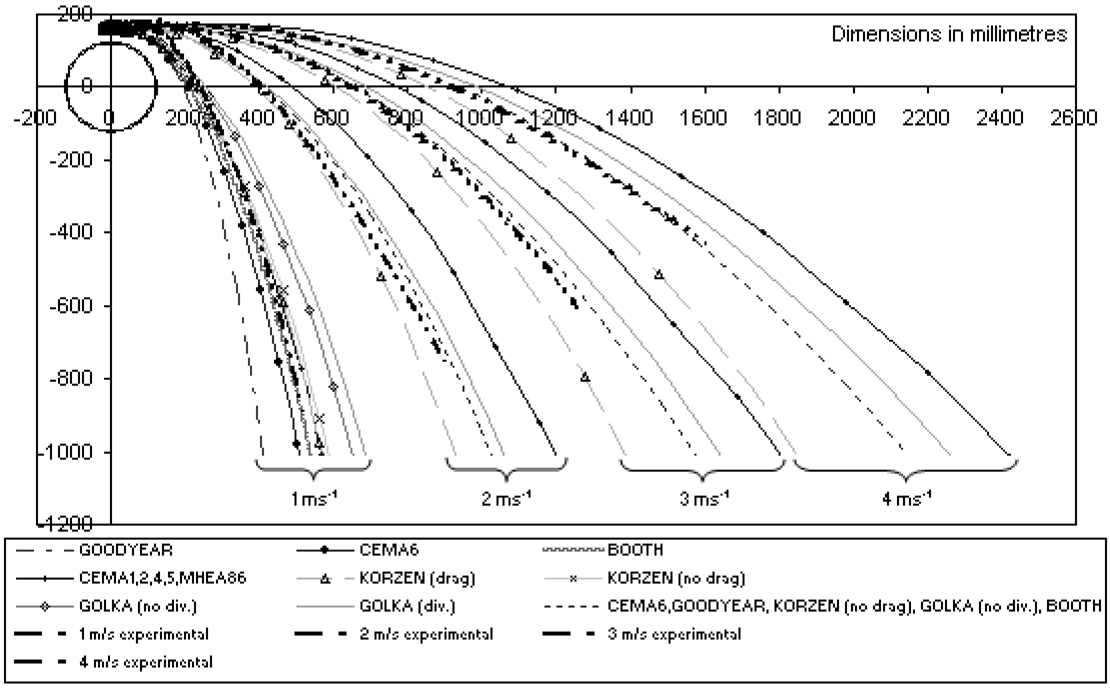

Figure 10: Upper trajectory boundary comparisons between the experimental tests and trajectory models

When considering the E-DEM trajectories produced and displayed in Figure 11, the wings observed experimentally were also present in the simulations. This indicates that the simulations were able to capture the dynamics of the material flow well, mimicking that occurring in reality. Figures 11 and 12 provide comparison graphs of the experimentally generated trajectories (vis. Table 1) and the corresponding E-DEM simulations. As is clear in Figure 11, the experimental curves fit almost identically for all five belt speeds investigated. Figure 12 shows the results for the high material feed rates and it is evident that there is some variation present for all belt speeds.

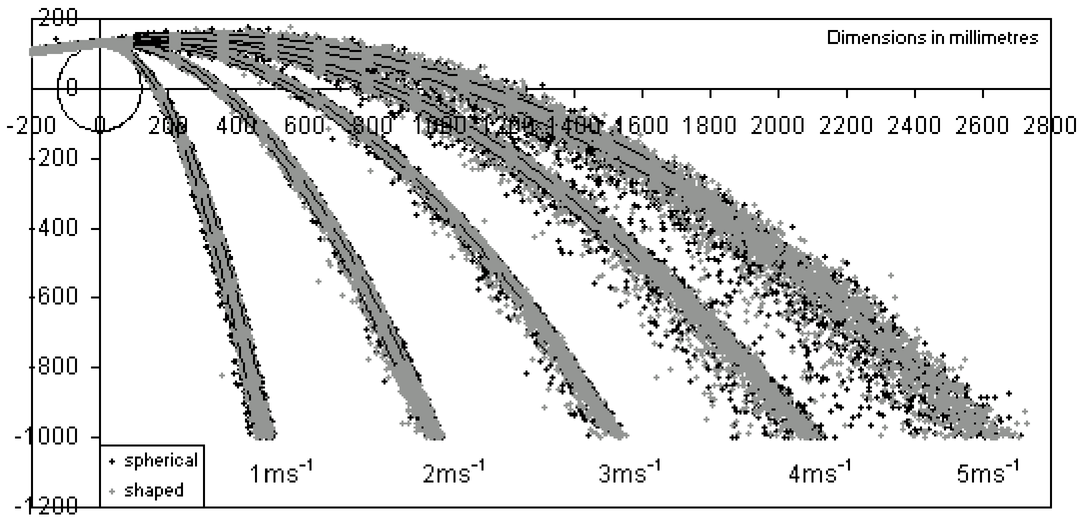

Figure 11: Low experimental trajectories super-imposed over the low material feed rate E-DEM trajectories for spherical and shaped particles

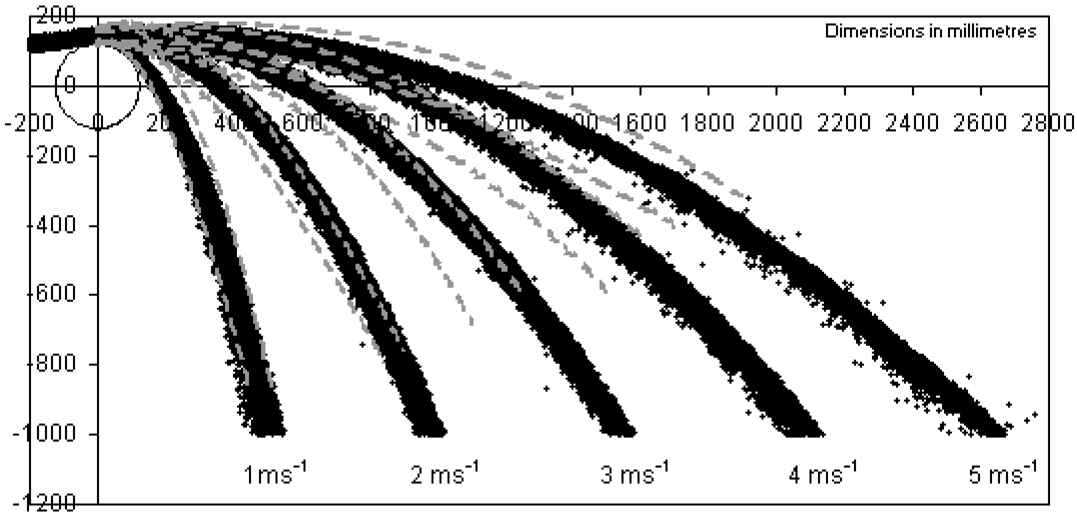

Figure 12: High experimental trajectories super-imposed over the high material feed rate E-DEM trajectories for spherical particles

E-DEM produces three dimensional outputs which does not allow direct comparison with the two dimensional trajectory models. To remedy this, during post processing 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. Figure 13 shows the results for the low-speed conveying condition, V_b = 1 ms^{-1} with an inset image showing a close up of the bottom of the stream. The Booth method shows the best agreement with the simulation data although the stream is slightly wider. Figure 14 displays the results for the high-speed conveying condition, V_b = 4 ms^{-1}. This time several trajectory model curves predict the same path so have been merged into one curve only. For this comparison, the simulation data fits extremely well with the trajectory models for CEMA 6, Goodyear, Korzen (no air drag), Golka (no divergent coefficients) and Booth. Not shown, are the results for V_b = 2 ms^{-1} and V_b = 3 ms^{-1}, but the results showed the same trend as in Figure 14.

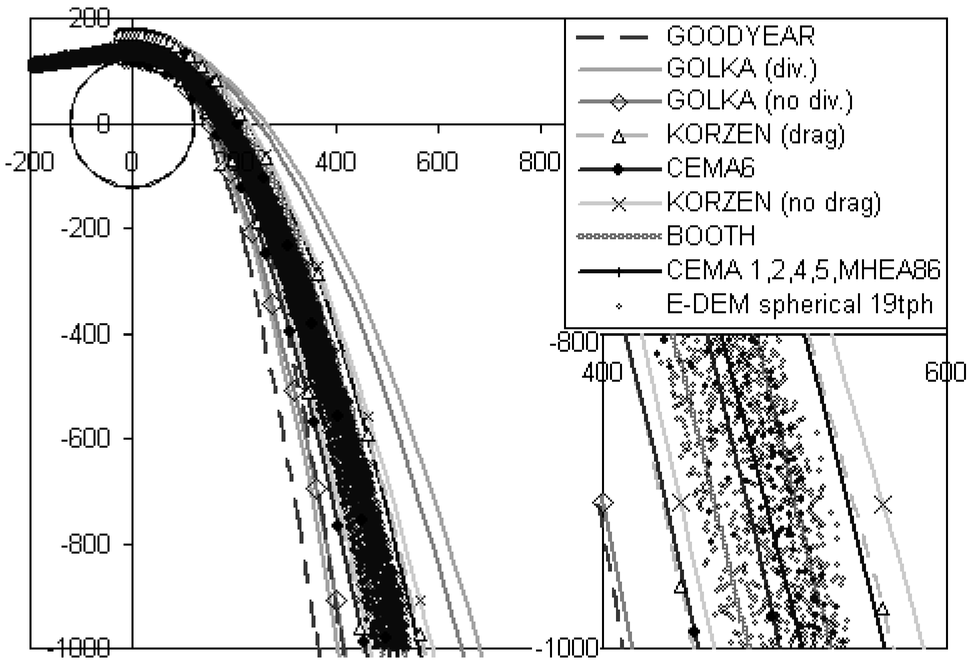

Figure 13*: Comparison of the high material feed rate E-DEM trajectories (with binning used) superimposed over the trajectory models for a belt speed of 1 ms^{-1}

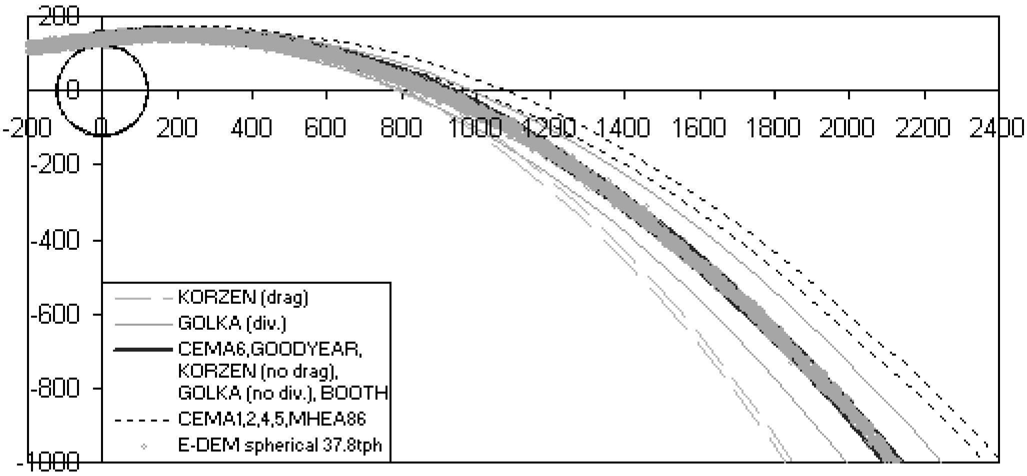

Figure 14*: Comparison of the high material feed rate E-DEM trajectories (with binning used) superimposed over the trajectory models for a belt speed of 4 ms^{-1}

*NOTE: The trajectory curves on Figure 13 and 14, viewing left to right, correspond to the legend entries reading down.

CONCLUSION

Findings of the experimental test program showed 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 discharge, thus may not be leaving at the same velocity as the belt. This could have serious consequences in relation to positioning of stockpiles or the design and positioning of conveyor transfers.

The comparisons presented above of experimental vs. trajectory models and trajectory models vs. E-DEM simulations have all shown a very close agreement with the Booth method for the range of belt speeds investigated. Comparisons between the experimental results and E-DEM simulations have shown a very good agreement for the low material feed rate cases but there is some minor variation when considering the high material feed rates.

The influence of particle shape in the E-DEM simulations does not appear to have much of an effect on the final trajectory. This could be a product specific finding and will need to be investigated further when simulating other materials.

Further experimental testing will be completed systematically to generate a larger database of information for which more detailed comparisons will be completed.

REFERENCES

[1] Andrews, D. (2008). *A Comparison of Belt Conveyor Trajectory Predictions*, B.E. (Mech. Eng.) Thesis, University of Wollongong, Wollongong, New South Wales, Australia. p. 71.

[2] C.E.M.A. (2005). *Belt Conveyors for Bulk Materials*. 6th Ed, Conveyor Equipment Manufacturers Association. p. 599.

[3] C.E.M.A. (1966). *Belt Conveyors for Bulk Materials*. 1st Ed, Conveyor Equipment Manufacturers Association. p. 332.

[4] C.E.M.A. (1979). *Belt Conveyors for Bulk Materials*. 2nd Ed, Conveyor Equipment Manufacturers Association. p. 346.

[5] C.E.M.A. (1994). *Belt Conveyors for Bulk Materials*. 4th Ed, Conveyor Equipment Manufacturers Association. p. 374.

[6] C.E.M.A. (1997). *Belt Conveyors for Bulk Materials*. 5th Ed, Conveyor Equipment Manufacturers Association. p. 430.

[7] M.H.E.A. (1986). *Recommended Practice for Troughed Belt Conveyors*, Mechanical Handling Engineer's Association. p. 199.

[8] Booth, E. P. O. (1934). *Trajectories from Conveyors - Method of Calculating Them Corrected*. Engineering and Mining Journal, Vol. 135, No. 12, December, p. 552 - 554.

[9] Golka, K., Bolliger, G. and Vasili, C. (2007). *Belt Conveyors Principles for Calculation and Design*. Lugarno, N.S.W., Australia, K. Golka, G. Bolliger, C. Vasili. p. 288.

[10] Korzen, Z. (1989). *Mechanics of Belt Conveyor Discharge Process as Affected by Air Drag*. Bulk Solids Handling, Vol. 9, No. 3, August, p. 289 - 297.

[11] Dunlop (1982). *Dunlop Industrial Conveyor Manual*.

[12] Goodyear (1975). *Goodyear Handbook of Conveyor & Elevator Belting*, p. Section 11.

[13] Hastie, D. B. and Wypych, P. W. (2007). *The Prediction of Conveyor Trajectories*. I nternational Materials Handling Conference: Beltcon 14, Johannesburg, South Africa, 1 - 2 August, p. 16.

[14] Hastie, D. B., Wypych, P. W. and Arnold, P. C. (2007). *The Profile of Conveyor Trajectories*. 9th International Conference on Bulk Materials Handling and Transportation, ICBMH 2007, Newcastle, Australia, 9 - 11 October, Australian Society for Bulk Solids Handling, p. 10.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Australian Research Council, Rio Tinto Technology and Innovation and Rio Tinto Iron Ore Expansion Projects for their financial and in-kind contributions to the Linkage Project which allowed this research to be pursued.

AUTHORS' CV

DAVID HASTIE

Mr. David Hastie B.E. (Mechanical), M.E. (Honours) has been employed at the University of Wollongong, Australia, since 1997. He is a member of the Institution of Engineers Australia and a member of the Australian Society for Bulk Solids Handling. In July of 2008 he took up an academic lecturing position within the Faculty of Engineering.

Currently, key areas of interest include conveyor transfers and trajectories and he has extensive experience in experimental investigations, instrumentation, data acquisition and analysis, computer programming, DEM computer simulation and digital video imaging and processing. His most recent research has been as research associate on a just completed three year project titled '*Quantification and Modelling of Particle Flow Mechanisms in Conveyor Transfers'*. He is also a part-time PhD candidate working on transfer chute quantification and modelling.

PETER WYPYCH

Peter Wypych B.E. (Mechanical, Honours 1), PhD is the Director of the ARC endorsed Key Centre for Bulk Solids and Particulate Technologies at the University of Wollongong. He has been involved with the research and development of solids handling and processing technology since 1981. Peter Wypych has published over 280 articles. He is currently Chair of the Australian Society for Bulk Solids Handling.

Peter Wypych is also the general manager of Bulk Materials Engineering Australia and has completed over 450 industrial projects, involving R&D of new technologies, feasibility studies, troubleshooting, general/concept design, optimisation, debottlenecking, safety/hazard audits and/or rationalisation of plants and processes for companies all around Australia and in the USA, Hong Kong, New Zealand, China, Singapore and Korea.

AUTHORS' ADDRESS

Mr David Hastie
Centre for Bulk Solids and Particulate Technologies
Faculty of Engineering
University of Wollongong
Northfields Avenue, Wollongong, NSW, 2522, Australia
Email: david_hastie@uow.edu.au

A/Prof Peter Wypych
Centre for Bulk Solids and Particulate Technologies
Faculty of Engineering
University of Wollongong
Northfields Avenue, Wollongong, NSW, 2522, Australia
Email: peter_wypych@uow.edu.au