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David B. Hastie
University of Wollongong, dhastie@uow.edu.au

P W. Wypych
University of Wollongong, peter_wypych@uow.edu.au

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Experimental Validation of Particle Flow Through Conveyor Transfer Hoods Via Continuum and Discrete Element Methods

D.B. Hastie* and P.W. Wypych
Centre for Bulk Solids and Particulate Solids, Faculty of Engineering
University of Wollongong, Northfields Avenue, Wollongong, 2522, New South Wales, Australia

* Corresponding author. Tel.: +61 2 4221 4397; Fax.: +61 2 4221 4397
E-mail address: dhastie@uow.edu.au (D.B. Hastie)

Abstract

A critical factor in the design of hood-spoon type conveyor transfers is to match the exit velocity of the material through a conveyor transfer to that of the conveyor belt receiving the material. If particle velocity increases too much issues such as particle attrition, dust generation, chute and belt wear and excessive noise can arise, whereas if particle velocity decreases, stagnation zones can develop, resulting in issues such as spillage or chute blockage. Numerous methods are available to analyse particle flow through a conveyor transfer, including; continuum based analytical methods, the discrete element method (DEM) and experimental analysis.

This paper details the findings for these three methods for granular cohesionless materials. The experimental investigations were performed on a conveyor transfer research facility located at the University of Wollongong, using high-speed video to capture the flow and subsequently analysed with Image Pro Plus. Two continuum based analytical analyses were then used to predict the flow through the conveyor transfers. Lastly, the use of DEM provided a third means of quantification and prediction of the particle velocity through the transfer hood with the data further processed using Matlab. These methods were then compared to determine whether continuum or discrete methods allow for accurate prediction of chute flow.

Keywords: Conveyor transfer; Velocity analysis; Particle flow; Continuum method; Discrete element method

Nomenclature

A_p	cross sectional area of flow stream	m^2
B	average width of stream through transfer hood	m
c	cohesion	kN/m^2
F_D	drag force	N
g	gravity	m/s^2
H_0	initial height of stream at impact with transfer hood	m
K_v	pressure ratio	-
m_s	material feed rate	t/h
N	normal force	N
R	transfer hood radius	m
V_a	stream velocity after impact with transfer hood	m/s
V_b	belt speed	m/s
V_p	stream velocity before impact with transfer hood	m/s
v	stream velocity	m/s
v_0	initial stream velocity	m/s
X	horizontal positioning of transfer hood	m
Y	vertical positioning of transfer hood	m
Δm	mass element	kg
α_p	impact angle	^{o}
γ	specific weight	kN/m^3
θ	angular position around hood (measured from horizontal)	^{o}
θ_e	angular position of product exiting hood	^{o}

θ_i	angular position of product impact point with hood	°
ϕ_w	wall friction angle	°
μ_e	equivalent friction	-
μ_w	coefficient of wall friction	-
φ	arbitrary angle	°

1. Introduction

Discrete element modelling (DEM) is becoming increasingly popular in the analysis and visualisation of material flow through conveyor transfer points. DEM validation is not novel as Gröger and Katterfeld (2007) have previously simulated material flow at transfer stations and verified the results experimentally. They primarily investigated the forces generated at an impact plate and the mass flow rates through the transfer station, however DEM validation of the particle velocity through a conveyor transfer is novel. Ilic et al. (2007) have presented comparisons between a continuum method and DEM focussing on a slewing stacker transfer chute, however there was no comparison made to experimental results. Even though there was some agreement between the continuum method and the DEM, there is no certainty that these methods accurately predict reality.

The design of conveyor transfers has often relied on trial and error to achieve the desired outcome and has been seen as a 'black art' rather than a science for many years. The development of continuum-based chute flow models, such as that of Roberts (1999; 2003) and Korzen (1988), has helped to better understand the flow behaviour of bulk materials. With the advent of DEM comes the possibility that expensive test chutes may no longer need to be constructed to test various designs, with the design process occurring solely on computer workstations. At present there is still some hesitance to rely on DEM alone as it is still considered to be in its infancy with much more validation required before designers put their full trust in it.

The presented research examines the inverted chute flow model of Roberts (2003), the continuum method of Korzen (1988) for non-cohesive materials and DEM simulations which are then compared to the results obtained from an experimental conveyor transfer research facility.

2. Conveyor Transfer Research Facility

The experimental component of this research is performed on the conveyor transfer research facility located at the University of Wollongong, consisting of three Aerobelt™ conveyors arranged to allow steady-state flow of material, as shown in Figure 1.

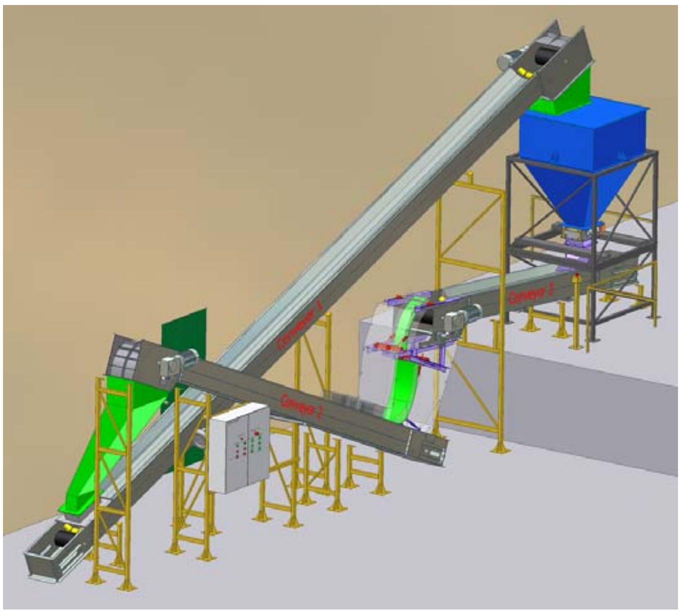


Figure 1 Conveyor transfer research facility

The feed bin supplies material to the first conveyor, inclined at 5º, while the other two conveyors are inclined at 23º. The conveyor transfer being investigated consists of a hood and spoon and is located directly after the first conveyor, however the focus here will only be on the transfer hood, detailed in Figure 2. It is important to note at this point that the design of a transfer hood generally compliments a given conveyor belt speed and that varying the belt speed can result in less than ideal results, this fact will be presented in the results. The hood is lined with 6 mm Polystone Ultra to minimise chute wear and frictional losses. From the horizontal (θ_e = 0º), 5º increments have been marked around the hood, indicating the locations where the velocity will be analysed. This allows for accurate determination of the point of impact of the trajectory stream, θ, coming from the feed conveyor. Polyethylene pellets have been selected as the test material, due to their granular sphero-cylindrical shape as well as robustness. Some particle and wall characteristics are listed in Table 1.

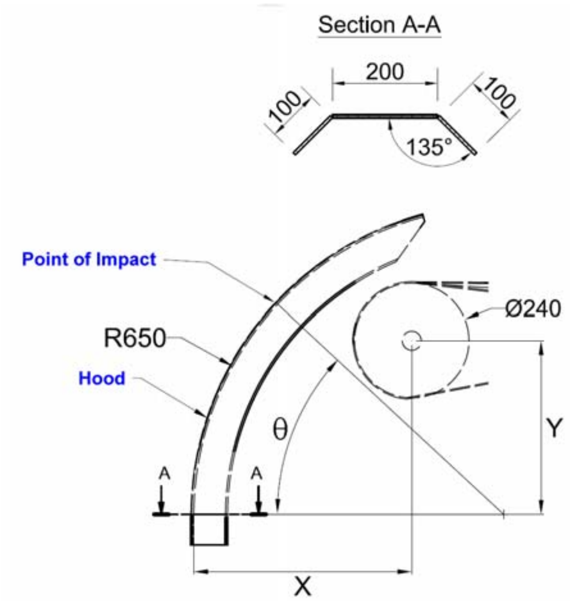


Figure 2 Detail of conveyor transfer hood

Table 1 Particle and bulk properties of polyethylene pellets

Loose-poured bulk density	515 kg/m^3	
Particle density	919 kg/m^3	
Particle size distribution (2.36 – 3.35 mm)	2.90 %	
Particle size distribution (3.35 – 4.00 mm)	11.73 %	
Particle size distribution (4.00 – 4.75 mm)	85.37 %	
Particle sphericity	0.873	**tan ϕ_w**
Wall friction angle (3mm Aerobelt)	25.7 º	0.481
Wall friction angle (4.5mm Acrylic)	21.5 º	0.394
Wall friction angle (6mm Acrylic)	19.1 º	0.346
Wall friction angle (6mm Polystone Ultra)	15.75 º	0.282
Wall friction angle (Polyethylene sheet)	12.5 º	0.222
Coefficient of restitution (average)	0.65	

The particle friction is also required for the DEM simulations, however there was some conjecture over the best method to use. The direct shear test to measure the instantaneous yield loci (IYL) was deemed unsuitable due to the material forming a relatively non-consolidated stream when fed onto the conveyor. Ideally the particle friction would be measured by shearing two pellets against each other under various loads, however there was no readily available test equipment to allow this. The decision was made to perform a wall yield loci test (WYL) on the polyethylene pellets by also using a sheet of polyethylene as the wall material to obtain an estimate.

2.1 Experimental Analysis of Particle Flow

One of the key features of the conveyor transfer research facility is that the transfer enclosure and hood and spoon have been constructed of acrylic. This provides the ability to record a variety of material flow characteristics with both high-speed video and digital still cameras. A Redlake X3 MotionPro high-speed video camera has been used to capture the particle flow through the hood at between 1000 and 1500 frames per second. The video footage will be captured from the side of the transfer hood and as such will be capturing particles at the extremities of the flow stream. These particles will also be in direct contact with the side wings of the hood, where wall friction effects may have an influence on the particle velocity. The fact that the particle stream is not consolidated should keep these effects to a minimum.

Two conveyor belt speeds, V_b, have been investigated, V_b=2m/s and V_b=3m/s. These both result in high-speed conveying conditions, with the material discharging from the point of tangency between the conveyor belt and the head pulley. Initially, a conveyor belt speed of V_b=1m/s was also to be investigated but the geometry of the conveyor resulted in slow-speed conditions. The product achieved a substantial angle of wrap around the head pulley before discharge and as a consequence the material had very little horizontal displacement, meaning the use of a transfer hood was not required.

To investigate the influence of material flow rate on the velocity of the particle stream, a low experimental product feed rate was selected as well as a product feed rate which allowed the conveyors to operate at full capacity, based on edge distance calculations (C.E.M.A., 2005). Table 2 summarises the feed rates used. Initially, a low feed rate of 2 tonnes per hour (tph) was used for the 3m/s belt speed, however this was found to be too low when analysing the data via Image Pro Plus, hence the increase to 10tph for the subsequent hood geometry.

One hood position was used for the V_b=2m/s hood geometry, whereas for the V_b=3m/s case, two hood positions were used. The initial hood position was aligned so that the incoming flow would cause a substantial angle of incidence with the hood, while the second case aligned the hood to minimise the angle of incidence. Figure 3 shows a snapshot of the steady-state flow through each of the transfer hood geometries for both the low and high feed rates.

Table 2 Product feed rates used in experimental tests

Belt Speed, V_b (m/s)	Low Feed Rate (tph)	High Feed Rate (tph)
2	2	31
3 (Position A)	2	38
3 (Position B)	10	38

A number of key observations can be made from Figure 3:

- for each of the high feed rates, the angle of incidence is less than the low feed rate “equivalent” due to the depth of the material stream,
- Figure 3(c) highlights a substantial amount of spray of particles after impact due to the high angle of incidence, whereas in Figure 3(d) there is no spray,

- Figure 3(b), 3(d) and 3(e) each show the product stream spreading onto the hood wings,
- the angle of incidence in Figure 3(f) is near ideal when compared to that of Figure 3(d),
- the position of the hood for V_b=3m/s position A (Figure 3(c) and 3(d)) did not allow for any measurement at the exit point of the hood, i.e. $\theta=0^o$.

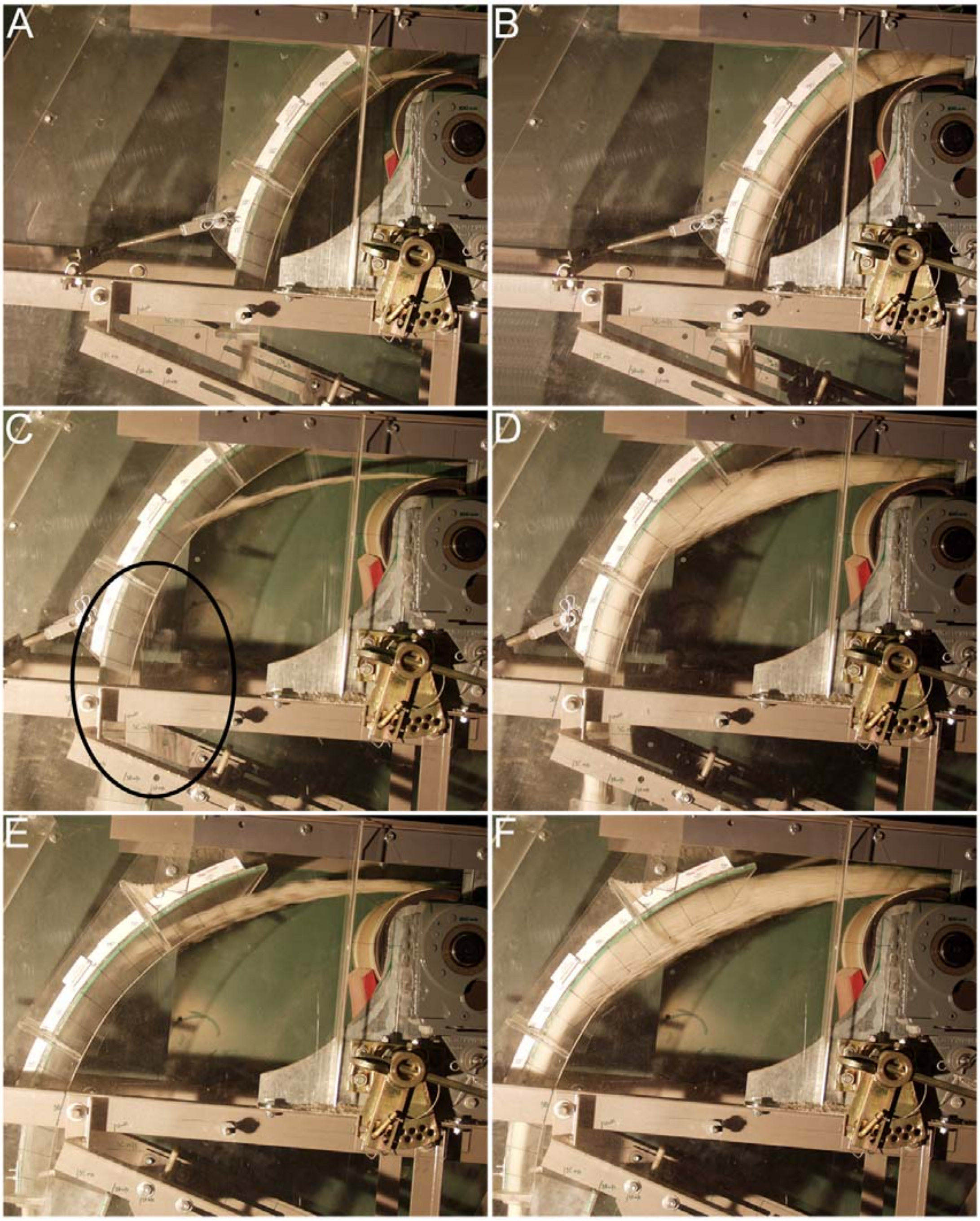


Figure 3 Material flow through the conveyor hood
(a) V_b=2m/s and m_s=2tph, (b) V_b=2m/s and m_s=31tph,
(c) V_b=3m/s Pos A m_s=2tph, (d) V_b=3m/s Pos A m_s=38tph,
(e) V_b=3m/s Pos B m_s=10tph, (f) V_b=3m/s Pos B m_s=38tph

The particle velocity was determined using the software package Image Pro Plus (IPP). Calibration of the linear distance was first performed to ensure IPP analysed the video footage correctly. The linear calibration was performed by selecting a known measurable distance on a frame of the video and entering the true length. The time step, see equation 1, was determined from the number of frames per second (FPS) being recorded by the high-speed camera.

$$\text{Time step} = \frac{1}{FPS - 1} \tag{1}$$

Utilising the manual tracking feature, particles are tracked by selecting the particle centroid at each time step at each five degree increment, as shown in Figure 4. The results for each particle are tabulated within IPP and then exported for further analysis. In most instances, the number of particle tracked at each angular position was between 10 and 20, dependant on clarity of the video footage. The average velocity was then determined for these particles, as well as the minimum and maximum velocity at each angular position.

Figure 4 Particle tracking using Image Pro Plus

The averaged particle velocities at each angular position for the six cases shown in Figure 3 are presented in Figure 5. The following observations can be made from the average particle velocity results:

- for V_b=2m/s, both the low and high feed rate start with an approximate velocity of 2m/s before increasing to a velocity of 2.75 to 2.9m/s at the hood exit,
- the V_b=3m/s position A tests with the high angle of incidence showed a pronounced drop in velocity soon after impact before steadily increasing to approximately 3m/s at hood exit,
- the V_b=3m/s position B tests showed a more consistent average velocity through the hood, even more so for the high feed rate test. There was still, however, a slight rise in overall particle velocity towards the hood exit.

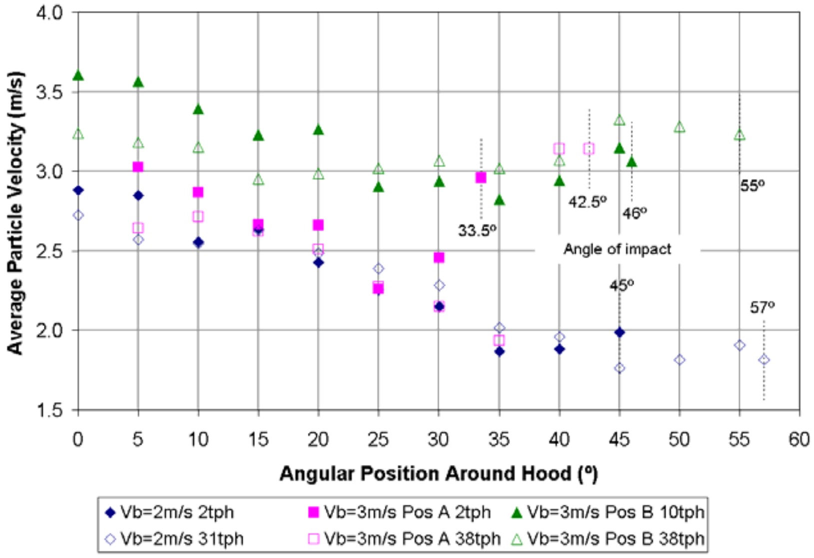


Figure 5 Average particle velocity at each angular position around transfer hood

3. Continuum Method Analysis

Predicting the flow through a conveyor hood is possible with the use of two continuum-based methods: the inverted chute-flow model (Roberts, 2003) and the model for cohesive material flow (Korzen, 1988). Each of these methods require parameters such as, initial particle velocity, hood impact angle and the initial and average height and width of the particle stream. If the transfer hood had not already been constructed, then estimates of these values would have been used in order to generate a solution. However, with this research comes the added benefit that these values can be extracted directly from the experimental test program to better compare the continuum methods with the experimental results, refer to Figure 6a and Figure 6b for examples of measuring the stream height and width.

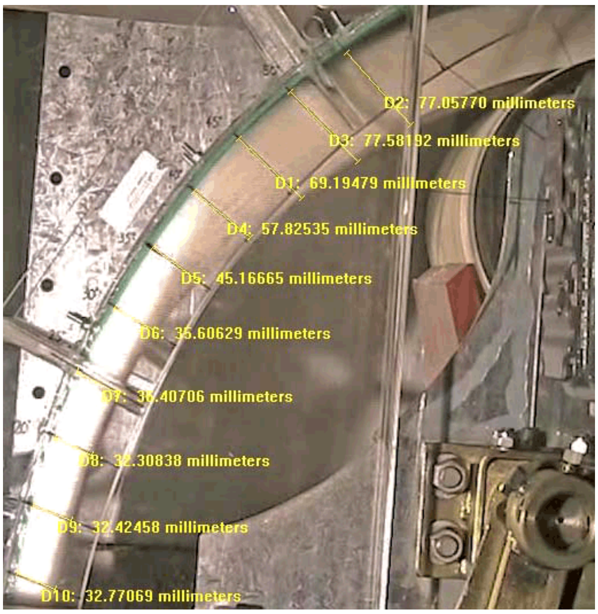


Figure 6a Material stream height through the hood

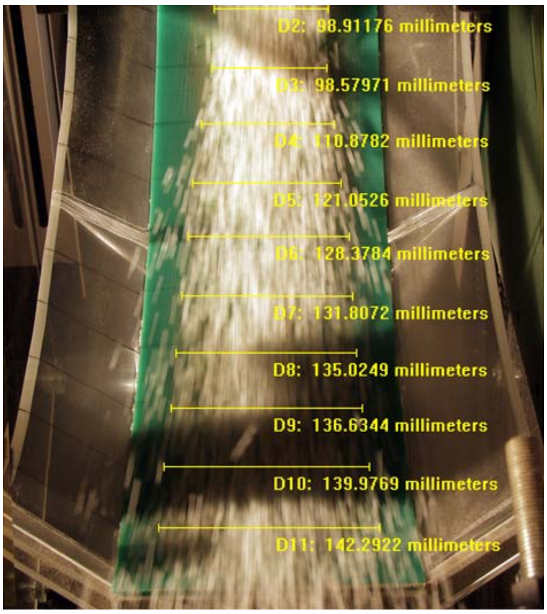


Figure 6b Material stream width through the hood

3.1 Continuum Method of Roberts

The inverted chute-flow method of Roberts (2003) is a widely accepted approach to predicting the stream velocity through a transfer hood for granular cohesionless materials, the force diagram is presented in Figure 7.

An equivalent friction, μ_e, is used, which incorporates the particle wall friction, the stream cross-section and the internal shear of the bulk solid, see equation 2, and is assumed to be an averaged constant for all angular positions analysed through the hood, as the stream thickness is comparatively low. The ratio of the pressure acting on the sides of the chute to the pressure acting on the bottom of the chute, K_v, is generally assumed to be a value between 0.4 and 0.6 according to Roberts (1999; 2003). There was no means of directly measuring these pressures and as such, an estimate of 0.4 has been used based on the fact that the height of the material stream is substantially less than the width of the stream.

The particle velocity at any given angular position through the hood can then be found using equation 3, by first determining the constant of integration, K, by substitution of the initial conditions, $v=v_0$ and $\theta=\theta_0$. The initial velocity used in this analysis can be assumed to be the belt speed of the feeding conveyor if the transfer hood is located close to the belt, or can be approximated from trajectory models. For the experimental work in this test program the actual velocity of the product stream was measured just before impact with the hood and has been applied directly.

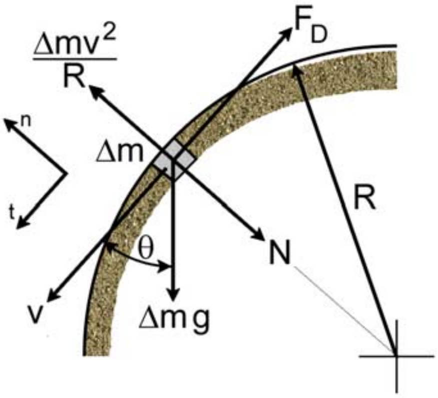


Figure 7 Force diagram for the inverted curved chute

$$\mu_E = \mu_w \left[1 + \frac{K_v v_0 H_0}{vB} \right] \qquad (2)$$

$$v = \sqrt{\frac{2gR}{4\mu_E^2 + 1}\left[\left(2\mu_E^2 - 1 \right) \sin\theta + 3\mu_E \cos\theta \right] + Ke^{2\mu_E\theta}} \qquad (3)$$

Applying the experimental impact angle as the starting point for the analysis for each belt speed and hood position, the results of the Roberts continuum analysis are presented in Figure 8. The data presented shows a significant increase in stream velocity through the hood for both the low and high feed rates for the 2m/s belt speed, whereas for both 3m/s belt speed cases there is a relatively small increase in stream velocity through the transfer hood.

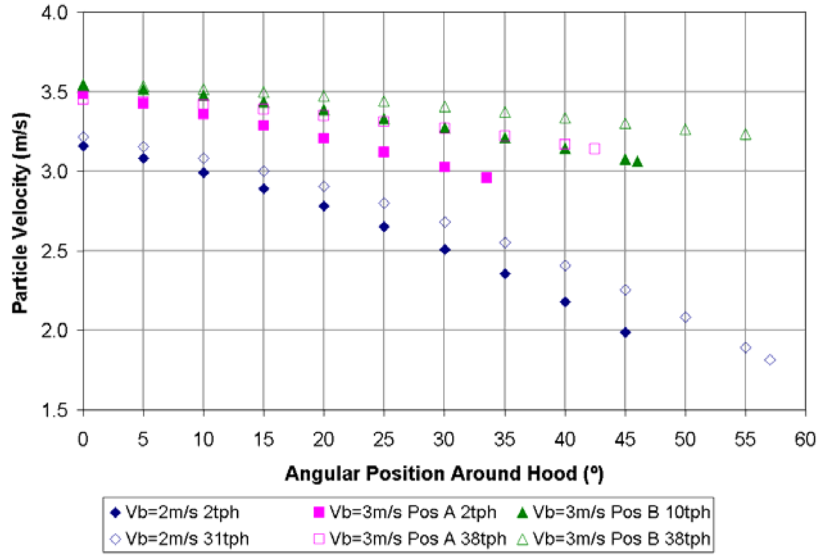


Figure 8 Predicted stream velocity through hood by Roberts method

3.2 Continuum Method of Korzen

Korzen (1988) investigated the dynamics of material flow on impact plates for both cohesive and non-cohesive materials. Figure 9 is a representation of the stream behaviour through this flow zone. This cohesive material model was originally intended to have a zone of built up stationary material attached to the impact plate which the main flow stream passed over. Korzen assumed this curved surface was of constant radius and the subsequent velocity analysis in equation 4 used the internal friction coefficient, μ, due to the flow stream shearing against the stationary material. As the material used in this research is non-cohesive and free flowing, it has been assumed that the curved shearing surface can be replaced by a curved chute of constant radius, resulting in the coefficient of wall friction, μ_w, being used in the velocity analysis of equation 4.

The velocity of the material stream at an arbitrary angle, φ, can be expressed by equation 4 and the constant of integration, K, can be solved using $v(\varphi)=v_p$, $\varphi=\alpha_p$ and $A(\varphi)=A_p$ as the initial conditions.

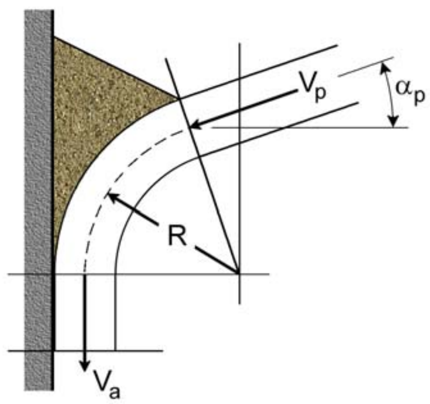


Figure 9 Flow representation for analysis by Korzen

$$v(\varphi)^2 = Ke^{-4\mu_w\varphi} + \frac{2gR}{(1+16\mu_w{}^2)}\left[5\mu_w \sin\varphi + \left(4\mu_w{}^2 - 1\right)\cos\varphi\right] - \frac{cBgR}{2\mu_w \gamma A(\varphi)} \tag{4}$$

This method requires the cross sectional area of the material profile at each angular position as a function of mass flow rate, stream velocity and bulk density. As previously mentioned, the experimental testing has provided the direct measurement of the height and width of the product stream, thus the true cross sectional area of the product stream at each angular position through the resulting flow can be determined. It should also be noted that for this experimental test program, the material chosen is non-cohesive, therefore c=0 and the right most part of equation 4 equals zero, negating the need to determine the stream cross sectional area. As a result, the Korzen continuum method takes on a similar form to that presented by the Roberts method.

Applying the experimental impact angle as the starting point for the analysis for each belt speed and hood position, the results of the Korzen continuum analysis are presented in Figure 10. The data presented shows a significant increase in stream velocity through the hood for both the low and high feed rates for the 2m/s belt speed in the same way as the Roberts method, whereas for both 3m/s belt speed cases there is nearly no change in stream velocity through the transfer hood.

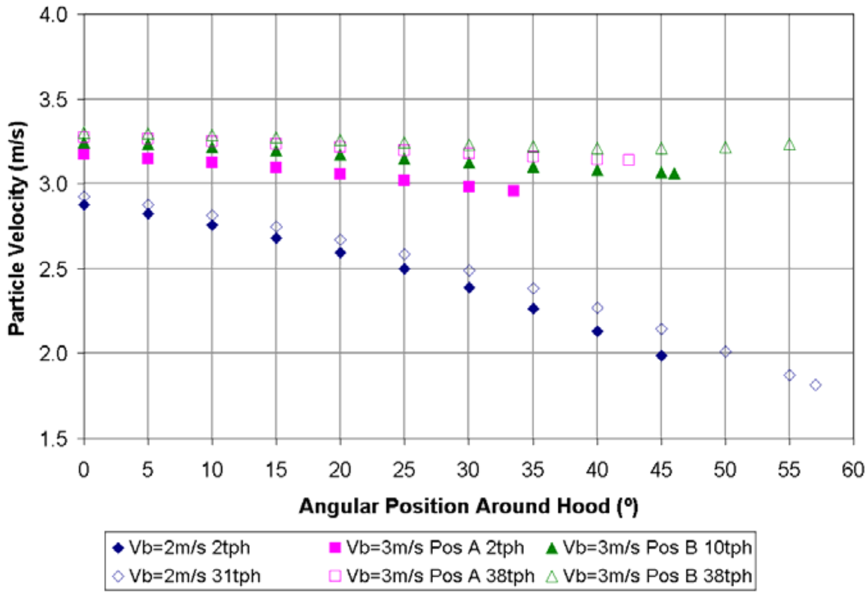


Figure 10 Predicted stream velocity through hood by Korzen method

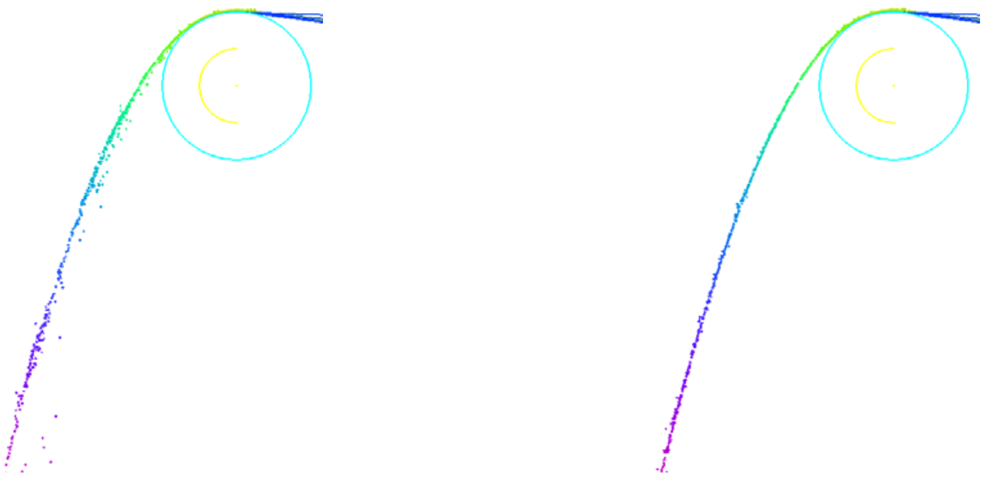
4. Discrete Element Method Simulation of Particle Flow

The programming code behind discrete element modelling can vary greatly in terms of interaction laws and time integration. The commercial software Chute Maven^{TM} has been utilised for this simulation research which uses the linear spring-dashpot contact model. As with all DEM, the contact model comprises normal and shear force components. The normal force component comprises linear elastic and viscous damping components and an equivalent coefficient of restitution is used to define the normal viscous damper coefficient. The explicit central difference scheme is used for the time integration (Hustrulid, 1997).

Chute Maven^{TM} focuses on the simulation of particle flow through conveyor transfers. A three dimensional CAD model is imported into the software defining the various conveyor components, including; conveyor belt(s), head pulley, skirts, injection box(es) and transfer chute(s). Particle and system parameters are of course required and the measured parameters supplied in Table 1 are used. The Chute Maven^{TM} software only allows for the simulation of spherical particles, which could lead to an over-prediction of the velocity through the transfer hood as the simulated spherical particles should be more “free-flowing”.

The degree to which particles roll or slide during a simulation is quantified by a restrain parameter. The restrain of the particles is defined as 100% for fully sliding and 0% for fully rotating particles, other percentages refer to combinations of the two. On inspection of the particle output data, it was found that particles are set as either sliding or rotating for the duration of the simulation based on the percentage restrain initially chosen. In an attempt to quantify a representative restrain value, the high-speed video footage from the experimental tests was reviewed. It was concluded that the percentage of particles which fully rotate on the surface of the Polystone Ultra liner was dependant on stream thickness. In regions of substantial stream thickness with minimal voidage, the percentage of particles able to rotate was low, visually around 10 percent. However, the number of particles able to fully rotate or roll is even lower due to the compaction of the particles. In regions of low stream thickness, it was observed that approximately 30 percent of particles could roll as the stream was less constrained. To assume that all particles are fully restrained, especially for a free flowing material, is not ideal, thus a restraint of 80 percent was selected for the DEM simulations, based on experimental observation.

As a validation of this assumption, a selection of belt speeds and material feed rates were selected and DEM simulations performed as a sensitivity analysis, focusing on variation of restrain, while leaving all other parameters constant. Three particle restrains were investigated, 100%, 80% and 50%. On review of the outputs it was found that as the particle restrain was reduced, there was an increase in the number of particles which would diverge from the main flow stream, see Figure 11. However, analysis of the main steady-state flow stream found no change in the average stream velocity at the exit of the hood for a given belt speed regardless of material feed rate. This finding indicates that the assumption to use 80% restrain for the DEM simulations is acceptable. Additionally, a particle restrain of 0% was simulated, corresponding to 100% of the particles rolling. No quantifiable results could be obtained from this simulation as the particles failed to convey along the conveyor belt due to the extremely high slip present between the particles and the belt.



(a) (b)

Figure 11 (a) simulation using 50% restrain (b) simulation using 100% restrain

Further validation was performed to investigate the issue of particle friction, raised in section 2. Two DEM simulations were completed, as shown in Table 3, where only the coefficient of particle friction was modified in each test. The value for coefficient of particle friction used in test 1 was based on the wall yield loci test on a sheet of Polyethylene and test 2 was based on the result of an instantaneous yield loci test. The resulting average stream velocities at each 5º angular position around the hood are presented in Table 4. At the point of discharge from the transfer hood (i.e. θ = 0º), there is effectively no change in the average stream velocity between the two tests. This appears to indicate that the coefficient of particle friction is not one of the primary parameters that will affect the outcome of a simulation and as such the concern raised over which method to use in determining the coefficient of particle friction was somewhat unwarranted.

Table 3 DEM simulation parameters

Test	Belt Speed (m/s)	Feed Rate (tph)	Coefficient of Particle Friction	Coefficient of Wall Friction	% Restrain
1	2	5	0.222	0.282	80
2	2	5	0.966	0.282	80

Table 4 Average stream velocity (m/s) from particle friction validation

	θ – Angle from Horizontal (º)									
Test	0	5	10	15	20	25	30	35	40	45
1	3.264	3.177	3.083	2.961	2.849	2.707	2.567	2.410	2.230	2.140
2	3.261	3.164	3.076	2.965	2.838	2.704	2.577	2.414	2.238	2.161

Three DEM simulations were prepared using the low product feed rates shown in Table 2, to allow direct comparisons with the experimental results. DEM simulations for the high material feed rates would require a substantially higher number of particles and would see a corresponding increase in simulation time. The decision was made not to perform high feed rate simulations but to instead look for other ways to produce comparisons. The effect of material feed rate in the DEM simulations was investigated by preparing additional tests, the full series of DEM simulations being:

- 2, 5 and 10 tph for a belt speed of 2m/s, and
- 2, 5, 10 and 15 tph for the 3m/s belt speed hood positions

The results of these tests would hopefully present trends which could be applied to predict what would happen at the higher feed rates. On completion of the simulations, an example of which can be seen in Figure 12, the simulated product streams were extracted and compared with the following observations being made;

- as product feed rate increases, so too does the height of the material stream, which in turn reduces the angle of incidence at the point of impact with the transfer hood,
- hood position A for the 3m/s belt speed shows substantial particles diverging from the main particle stream due to the high angle of incidence, which is backed in Figure 3c where particles can be seen diverging in the experimental hood,
- hood position B for the 3m/s belt speed has a more controlled stream flow as a result of the optimised positioning of the hood, minimising the angle of incidence of the material in-flow.

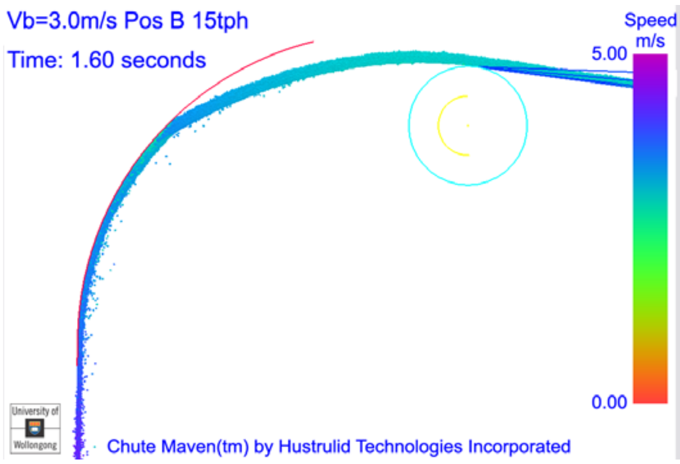


Figure 12 Example output from a DEM simulation

Further post processing of the simulation data focussed on the average stream velocity through the transfer hood for each belt speed and hood position and the results are presented in Figure 13. Matlab was used for this analysis and only particles with their centres within 3mm of the Polystone Ultra liner and also within 50mm either side of the central flow axis were selected. In all cases there was a transient behaviour of the average stream velocity at the point of impact with the transfer hood. It is also evident that once this initial transient zone has passed, the average particle velocity for each group of tests falls along the same line, resulting in the average exit velocity of the stream being the same. This fact would seem to indicate that regardless of the material feed rate used, the average exit velocity of the stream will be equivalent to those shown in Figure 13. This trend may or may not hold true for other products and will be investigated in future research.

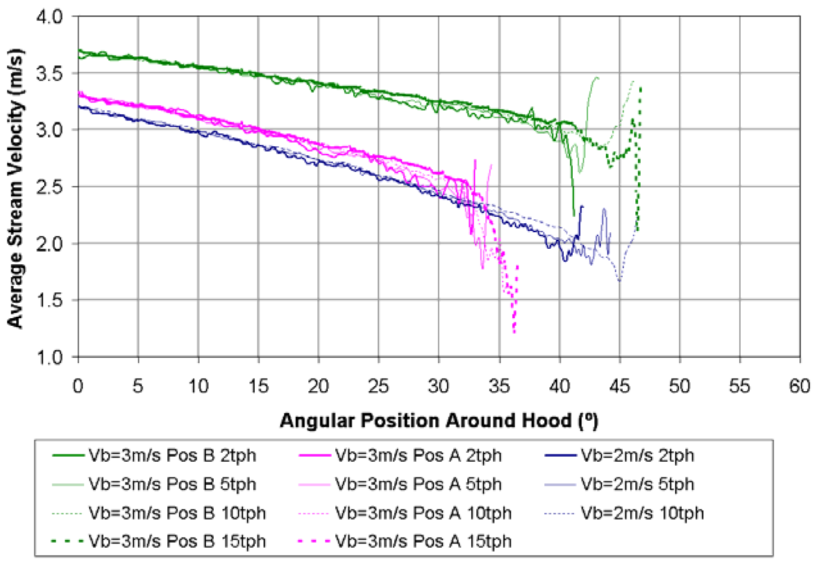


Figure 13 DEM simulation results for all material feed rates

5. Comparisons

The results of the three methods have been presented above, but to fully appreciate the comparison between each method for each belt speed and transfer hood geometry, Figures 14 to 16 are presented. Both the low and high feed rates have been plotted for the experimental, Roberts and

Korzen methods while for the DEM, only the low feed rate has been plotted, for the reasons explained in section 4.

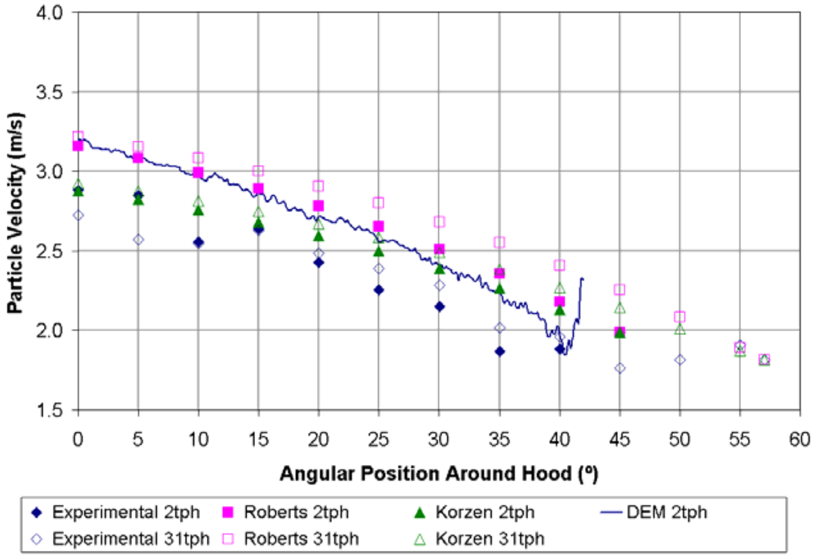


Figure 14 Comparison of methods for a belt speed of 2m/s

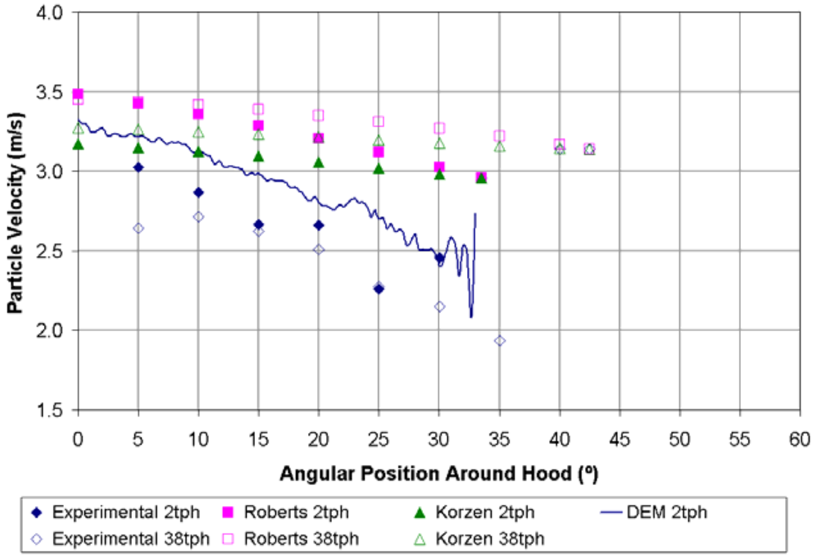


Figure 15 Comparison of methods for a belt speed of 3m/s with the hood in position A

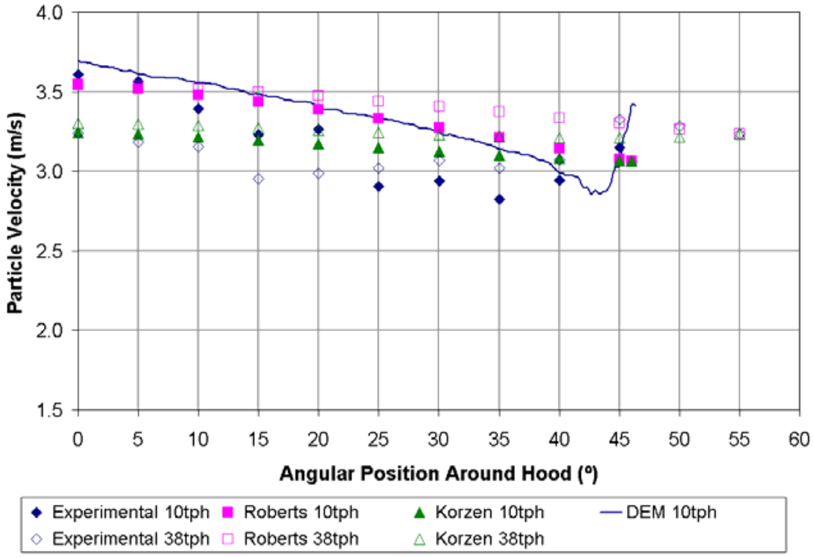


Figure 16 Comparison of methods for a belt speed of 3m/s with the hood in position B

Transient behaviour is evident in the DEM results shown in Figures 14 to 16, whereas this was not seen in the experimental results. One reason for this is that the experimental particle velocities have been obtained from the extremities of the flow stream, whereas the velocity results from the DEM simulations have been extracted from the central axis of the flow stream. The experimental results cannot therefore show the full effect of the impact of the particle stream with the transfer hood.

There is a general over-prediction of the experimental results by the Roberts, Korzen and DEM methods, however some results do give an under-prediction. The findings are summarised in Table 5 below.

Table 5 Percentage under- or over-prediction of the Roberts, Korzen and DEM methods when compared to the experimental results

	Roberts		Korzen		DEM
Belt speed (m/s)	Low	High	Low	High	Low
2	+ 9.6 %	+ 18.1 %	- 0.1 %	+ 7.5 %	+ 11.2 %
3 position A	+ 13.2 %	+ 30.2 %	+ 4.1 %	+ 23.6 %	+ 6.3 %
3 position B	- 1.0 %	+ 9.4 %	- 10.1 %	+ 2.0 %	+ 2.4 %

6. Conclusion

An experimental conveyor transfer facility has been constructed with the fundamental aim of validating both continuum-based methods and DEM simulations used to predict the particle flow through conveyor transfer hoods.

Experimentally, two conveyor belt speeds have been investigated (2m/s and 3m/s) and additionally two conveyor hood positions were investigated for the 3m/s belt speed, one in an optimal position to minimise the angle of incidence of the incoming particle stream and the other offset to induce an increased angle of incidence, conducive of a poorly installed and/or aligned transfer hood. This was to explore the effect of the angle of incidence on the subsequent stream velocity through the transfer hood. As was shown in Figure 3, there was a noticeable change to the flow pattern of the material stream due to the differing position of the hood for the 3m/s belt speed.

The continuum method of Roberts has been used for prediction of chute flows for some time, however the results presented here show that there are some inaccuracies with this method compared to the results obtained experimentally. In the cases presented in Figures 14 to 16, there was a distinct over-prediction of the stream velocity through the transfer hood.

The Korzen method behaved in much the same way as the Roberts method, however the resulting hood exit velocity of the particle stream better approximated the experimental hood exit velocity, matching with the 2m/s belt speed and 3m/s belt speed position A cases. The Korzen method actually under-predicted the hood exit velocity for the 3m/s belt speed position B case, which, experimentally showed a near ideal angle of incidence and smooth consistent flow through the hood. Although the hood exit velocity was better predicted with the Korzen method, it cannot be overlooked that the stream velocities through the transfer hood were still over-predicted.

Both the Roberts and Korzen methods are both suited to rapid-flow thin-stream analyses which could account for some of the variation between the results obtained and those of the experimental tests. Also, there is no facility within either methods to account for non-spherical particles. To account for the non-spherical nature of the material being used, the sphericity factor could be incorporated into the analyses but this will need further investigation. In the conveyor trajectory model of Korzen (1989), the effects of air drag are included and perhaps this could also be applied to the chute flow models of both Roberts and Korzen. Another option of worthy consideration is the use of other friction models rather than Coulomb friction.

The DEM simulations produced as part of this research showed that regardless of the material feed rate for a given belt speed and/or hood position, the hood exit velocity was identical.

The Chute Maven^{TM} software allows for only spherical particles to be simulated. With the inability to simulate the true particle shape, differences between the DEM and experimental results will be observed, including differing particle interaction with model boundaries and also the fact that air drag effects cannot be modelled. As with the continuum methods, the sphericity of the particles used could be applied to the resulting velocity analyses, but again, further investigations would be required.

Visually, the experimental results shown in Figure 3 and the particle stream outputs of the DEM in Figure 12 showed similar trends. This seems to imply that the DEM software is capable of simulating the behaviour of the material flow stream quite reasonably. The initial impact of the particle stream on the transfer hood results in transient behaviour, which is due to intersecting and merging flow paths. This aspect of the chute flow cannot be handled by the continuum-based methods. In contrast, the DEM simulations are able to reproduce this transient behaviour in a similar way to that seen experimentally.

Further research will investigate the behaviour of other materials through the same transfer hood in an attempt to establish trends which can be applied in a broader context. Also, as stated above, the applicability of integrating particle sphericity into the continuum methods and also to the results of the DEM simulations will be investigated.

The possibility of including impact load measurements on the experimental transfer hood is something that would add an additional level of analysis and comparison to the research. The impact forces cannot be determined from the DEM software but other DEM software has this capability and may be sourced as part of this work.

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