

The Profile of Conveyor Trajectories

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SUMMARY

This paper presents seven material discharge trajectory methods and explains the differences between them. Most of these methods involve a series of equations to determine first whether low-speed or high-speed conveying condition apply, then the material discharge angle for low-speed conditions and finally the X and Y coordinates of the trajectory profile. There are also simplified methods which rely on graphical determination of the trajectory profiles. The methods have been analysed to investigate which included parameters can be declared as variables for a given conveying condition and then evaluated to determine the impact of the variations. These parameters include, adhesive stress, coefficients of static and kinetic friction, air drag, particle shape and size, divergent coefficients and material bulk density.

NOMENCLATURE

a_1	height to material centroid, m	V_b	belt velocity, m s^{-1}
b	belt thickness, m	V_{cr}	critical velocity, m s^{-1}
C	constant of integration, -	V_d	discharge velocity, m s^{-1}
d_k	equivalent spherical particle diameter, m	V_s	tangential velocity, m s^{-1}
dm	unit mass of particle, g	α_d	discharge angle, $^\circ$
g	gravity, m s^{-2}	α_{d1}	discharge angle for the lower trajectory, $^\circ$
h	material height, m	α_{d2}	discharge angle for the upper trajectory, $^\circ$
h_d	height of material stream at discharge, m	α_r	angle where material begins to slip on the belt, $^\circ$
R_b	belt radius, m	γ	specific gravity of material, kN m^{-3}
R_c	radius to centre/centroid of material stream, m	μ_k	kinetic coefficient of wall friction, -
R_p	head pulley radius, m	μ_s	static coefficient of wall friction, -
V_1	velocity of lower stream, m s^{-1}	σ_a	adhesive stress, kN m^{-2}
V_2	velocity of upper stream, m s^{-1}		

1 INTRODUCTION

The accurate determination of the trajectory of material from the head pulley of a conveyor is extremely important in the complex design of conveyor transfers. Incorrect trajectory path predictions can result in several detrimental issues arising within a conveyor transfer, including; particle attrition, chute wear, dust generation, spillage, chute blockage and excessive noise all due to incorrect design parameters.

There is much information presented in the literature discussing the design of the hood (or upper) section of a transfer chute. Of critical importance is the material stream flow into or onto these sections. For one, the angle of incidence should be kept sufficiently low to minimise any reduction in velocity of the material as it flows through the chute. Without an accurate prediction of a trajectory path there is no way to adequately determine this angle of incidence. The profile of the trajectory stream is also of importance in the design of a conveyor transfer. One method of determining the trajectory might result in a converging stream while another produces a diverging stream or one of constant depth.

The focus of this paper is to investigate and review various aspects of the trajectory methods available in the literature, including those by C.E.M.A. [1,2,3,4,5], M.H.E.A. [6], Booth [7], Golka [8,9], Korzen [10], Goodyear [11] and Dunlop [12]. These methods vary considerable with respect to the number of distinct parameters being used in the determination of the material trajectory, from the very basic to complex iterative approaches. The investigation includes altering values of the parameters exhibiting variability, determining the extent to which they influence the trajectory being generated. The profile of the material stream through the trajectory path also is discussed. These trajectory methods are evaluated for both horizontal and inclined conveyors for a range of belt speeds and pulley diameters to evaluate both low-speed and high-speed conditions.

2 VARIATIONS OF TRAJECTORY METHODS

There are a number of unique approaches to determining the material discharge trajectory from a conveyor head pulley, such as basic projectile motion principles [1,2,3,4,5,6,11], complex iterative solutions

[7,10], graphical methods [7,12], one method including air drag [10] and another incorporating divergent coefficients [8,9]. These are detailed further in the following section.

The methods of C.E.M.A. [1,2,3,4] and M.H.E.A. [6] use identical methods to determine the discharge trajectory, the only difference being C.E.M.A. uses imperial units and M.H.E.A. uses metric. This results in minor variations in the tabulated data due to unit conversion. These methods determine the central trajectory but also allows for the upper and lower paths to be determined. Once the tangential velocity has been determined, it is established whether low-speed or high-speed conditions apply. For low-speed conditions a discharge angle is determined, equation 1, but for high-speed conditions, the material discharges at the point of tangency between the belt and head pulley. The low-speed trajectory is dependent on the discharge angle and as can be seen from equation (1), for a given conveyor geometry the only variable is belt speed.

$$\alpha_d = \cos^{-1} \left[\frac{V_b^2 R_c}{g (R_p + b)^2} \right] \quad (1)$$

The trajectory is plotted by first projecting a tangent line from the point at which material leaves the pulley, for both low-speed and high-speed conditions. A time interval is marked along this line for each 1/20th of a second, which equates to 50 mm for each metre per second of the tangential velocity. Projecting vertically down from these points are the fall distances supplied. Joining of these points produces the trajectory.

C.E.M.A. [5] has a slight modification to the way in which it determines the time interval along the tangency line for high-speed conditions. The time interval is determined based on the belt velocity not the tangential velocity.

Booth [7] modified the existing theory as he was not satisfied that it was truly accurate. Booth believed the incorporation of the angle at which material began to slip on the belt, α_r , aided in better accuracy. For high-speed conditions there is no material slip and the method used by C.E.M.A. and M.H.E.A. is applied using the drop heights supplied by Booth [7]. For low-speed conditions, an initial estimate of the discharge angle is found from equation (2) and the angle at which material slip first occurs on the belt, α_r , is determined by solving equation (3). The analytical analysis by Booth produces equation (4) and by setting $V(\psi) = V_b$ and $\psi = \alpha_r$, the constant of integration, C, is determined. Equations (2) and (4) can then be solved simultaneously using $V(\psi) = V_d$ and $\psi = \alpha_d$ to determine the discharge angle and also the discharge velocity. To produce the low-speed trajectory the method as for the high-speed condition is applied for the determined discharge angle.

$$\cos \alpha_d = \frac{V_b^2}{g R_b} \quad (2)$$

$$\cos \alpha_r - \frac{V_b^2}{g R_b} = \frac{1}{\mu_s} \sin \alpha_r \quad (3)$$

$$\frac{V^2(\psi)}{2 g R_b} = \frac{(2 \mu_s^2 - 1) \cos \psi - 3 \mu_s \sin \psi}{(4 \mu_s^2 + 1)} + C e^{2 \mu_s \psi} \quad (4)$$

The coefficient of static friction between the conveyor belt and the material being conveyed is used in equation (3) and (4) and can vary greatly from product to product and even within the same product. This parameter is the only one, other than belt speed which is variable and will influence the resulting material trajectory.

Golka [8,9] used Cartesian coordinates to develop his method to determine conveyor trajectories. In doing so, two distinct discharge angles were developed, α_{d1} for the lower trajectory and α_{d2} for the upper trajectory, equation (5) and equation (6) respectively. Three individual cases were developed to accommodate low-speed and high-speed conditions and the transition between them, see Table 1.

$$\alpha_{d1} = \cos^{-1} \left[\frac{V_1^2}{g R_p} \right] \quad (5)$$

$$\alpha_{d2} = \cos^{-1} \left[\frac{V_2^2}{g (R_p + h_d)} \right] \quad (6)$$

where,

$$V_2 = V_1 \left(1 + \frac{2h}{R_p} \right)^{0.5} \quad \text{and} \quad h_d = R_p \left(\left(1 + \frac{2h}{R_p} \right)^{0.5} - 1 \right)$$

Table 1 Discharge angle determination for the Golka [8,9] method

	CONDITION	α_{d1}	α_{d2}
CASE 1	$V_1 < V_{cr1}$ and $V_2 < V_{cr2}$	Use equation (5)	Use equation (6)
CASE 2	$V_1 > V_{cr1}$	Point of tangency	Point of tangency
CASE 3	$V_1 < V_{cr1}$ and $V_2 > V_{cr2}$	Use equation (5)	Point of tangency

In this method, there are no supplied drop heights for a given distance along a tangent line. The use of the Cartesian coordinate system allows for the direct determination of the X and Y coordinates of the trajectory using selected time intervals. In the calculation of the X and Y coordinates, Golka [8,9] includes two divergent coefficients, one for the lower trajectory and one for the upper trajectory. These coefficients are meant to represent a number of parameters such as air resistance, size distribution, permeability and particle segregation. There is no explanation given as to how the values are reached which could cause substantial variations in the resultant trajectory curves. Further discussion of this is given in section 3.4.

From equation (5) only belt speed will alter the discharge angle for the lower trajectory stream (for a given pulley size), however for the upper stream, the velocity, V_2 , is proportional to the belt speed and the height of material at discharge, h_d , which is proportional to the initial height of material lying on the belt before discharge, h . It is assumed that with this method, along with all the others, that the conveyor belt is loaded to full burden, although obviously if a reduced material feed rate was applied, the height of the upper trajectory would decrease.

Korzen [10] employs a complex iterative approach to determine the material trajectory. This method addresses adhesive materials, inertia and material slip into its calculations and also distinguishes between static wall friction, μ_s , and kinetic wall friction, μ_k . The angle at which material first slips on the belt under low-speed conditions is determined from equation (7), having numerous variables which could alter the trajectory path, including, static friction, adhesive stress, and specific gravity, explained further in section 3. Rather than calculating a material height which would most likely vary greatly from the other methods, it has been made constant by applying the value used by C.E.M.A. [5].

$$\alpha_r = \tan^{-1} \mu_s \pm \sin^{-1} \left[\sin(\tan^{-1} \mu_s) \cdot \left(\frac{V_b^2}{R_c g} - 2 \frac{\sigma_a}{\gamma h} \right) \right] \quad (7)$$

The slip angle is required to evaluate the constant of integration, C, in equation (8), using $V(\psi) = V_b$ and $\psi = \alpha_r$. To determine the discharge angle, the conditions $V^2(\psi) = R_c g \cos \psi$ and $\psi = \alpha_d$ are used in equation (8).

$$V^2(\psi) = 2gR_c \left[\frac{(4\mu_k^2 - 1) \cos \psi - 5\mu_k \sin \psi}{(1 + 16\mu_k^2)} \right] + Ce^{4\mu_k \psi} \quad (8)$$

At this stage the iterative solution begins based on Reynolds Number and air drag coefficient adjusted for particle shape. The effect of particle shape is detailed in section 3. If air drag is to be neglected, only the first step of the iterative process is performed, however when including air drag effects, the iterative process is continued

until an error of approximately 1% is reached for subsequent steps. The process ultimately determines the Y coordinate, resultant velocity and resultant angle for a given X coordinate. The range of the trajectory is only limited by the input range of X values used.

Korzen [10] does state that for particles larger than 1g in size, air drag effects can be neglected. As particle shape and size is one of the variable parameters used in this method, the effects of changing this parameter are demonstrated in section 3.5.

Goodyear [11] uses simple projectile motion equations to determine the trajectory path, equation (9) and equation (10). As with previous methods, the high-speed conditions result in the material discharging from the point of tangency and the low-speed conditions require the calculation of the discharge angle as in equation (2) except using R_c instead of R_b .

$$X = V_b t \quad (9)$$

$$Y = \frac{1}{2} g t^2 \quad (10)$$

From the discharge point, whether at tangency or at the discharge angle, a tangent line is drawn. Along this line are multiple X coordinates based on equation (9), at regular time intervals. The corresponding Y coordinates are the drop heights from each of these X points and when joined produce the trajectory. Other than belt speed, there are no variable parameters which can be altered to produce a different trajectory.

Dunlop [12] uses two approaches dependant on whether low-speed or high-speed conditions are applied. For low-speed conditions a graph has been produced as it is stated that the mathematics behind the determination of the low-speed trajectory is too complicated [12]. Knowing the belt speed and the head pulley diameter it is a simple task to determine the discharge angle and the X distance along the tangent line that the drop heights, equation (10), are placed. There are limitations to using the low-speed method, the graph only has pulley diameters in the range of 312mm to 1600mm. It is also stated [12] that if there is no intersection point between the belt speed and the desired pulley diameter, the method for high-speed conditions must be applied. For the high-speed condition, the X and Y coordinates of the trajectory are determined using equation (9) and equation (10) and are plotted from the tangent line drawn from the point of tangency. As with the Goodyear [11] method, there are no variable parameters other than belt speed.

3 TRAJECTORY PROFILES

3.1 Direct Trajectory Comparisons Using Common Parameters

To allow a direct comparison of the trajectory profiles for each method outlined in section 2, a set of parameters has been selected, Table 2, however not all methods use all parameters. To allow a wider range of comparisons, three belt speeds, ($V_b=1.25\text{ms}^{-1}$, 3.0ms^{-1} and 6.0ms^{-1}) and three pulley diameters, ($D_p=0.5\text{m}$, 1.0m and 1.5m) will be used. A belt inclination angle of 0° has been selected (i.e. horizontal geometry) however the influence of varying the inclination angle will be discussed in section 3.2.

Table 2 Parameters used for trajectory comparisons

Belt Width	0.762	m	Divergent Coefficient, Lower	0.1
Belt Thickness	0.01	m	Divergent Coefficient, Upper	-0.1
Belt Speed	1.5	m/s	Coefficient of Static Friction	0.5
Pulley Diameter	1	m	Coefficient of Kinetic Friction	0.4
Surcharge Angle	20	°	Equivalent Spherical Particle Diameter	0.001 m
Troughing Angle	20	°	Air Viscosity	1.8E-5 Ns/m ²
Belt Inclination Angle	0	°	Product Density	2000 kg/m ³
Adhesive Stress	0	kPa		

Declined conveyors have not been incorporated into the comparisons as they are only addressed by three methods, C.E.M.A. [1,2,3,4,5], M.H.E.A. [6] and Goodyear [11], while Dunlop [12] alludes to declined conveyor belts having the same discharge angle as a horizontal or inclined conveyor via a worked example.

Low-speed trajectory profile predictions for all methods are presented in Figure 1. It is evident that at this low belt speed there are two distinct groupings of methods but as the belt speed increases, the groupings become less defined. At a vertical displacement of 4000mm there is a horizontal range of approximately 750mm and

even at a vertical displacement of 1000mm there is still a 300mm range. This fact alone could have a marked effect on the design of a transfer chute dependant on which trajectory method is applied. Further comparisons were made by varying the pulley diameters and for a given belt speed it was observed that a larger discharge angle resulted for a larger pulley diameter, causing the trajectory to throw further from the discharge point. It was also found that regardless of the variations in complexity between the methods of Booth [7] and Dunlop [12], they all produced a near identical curve.

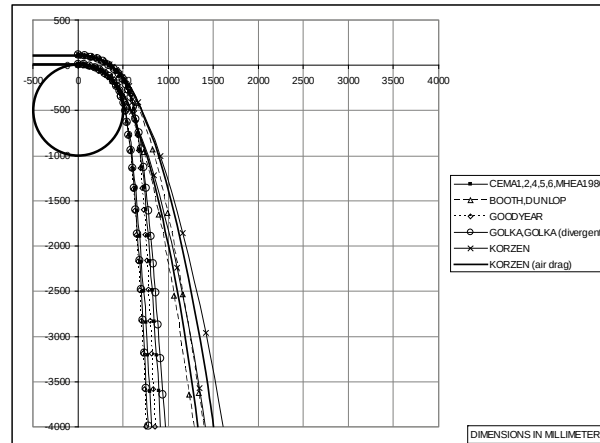


Figure 1 Low-speed condition, horizontal conveyor, lower and upper trajectory path
Pulley diameter, $D_p=1.0\text{m}$, belt velocity, $V_b=1.25\text{ms}^{-1}$

In order to investigate the change in trajectory profile due to belt speed, two high-speed belt conditions have been selected, $V_b=3.0\text{ ms}^{-1}$ and $V_b=6.0\text{ ms}^{-1}$. In Figure 2 and Figure 3 the inclusion of air drag by Korzen [10] results in a trajectory prediction clearly much shallower than all other methods. If air drag is neglected, the resulting trajectory prediction is located amongst the scattering of the other methods.

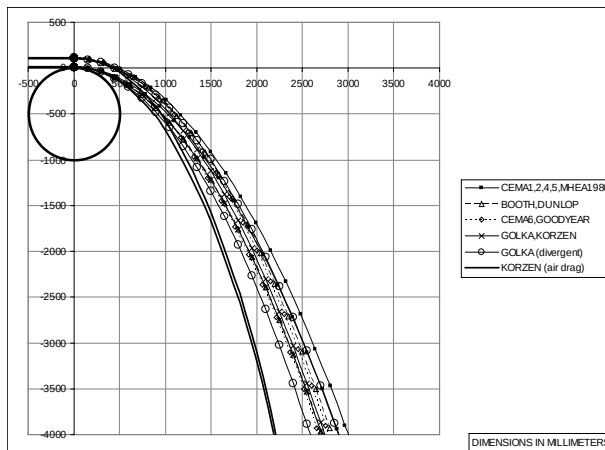


Figure 2 High-speed condition, horizontal conveyor,
lower and upper trajectory path, pulley diameter,
 $D_p=1.0\text{m}$, belt velocity, $V_b=3.0\text{ms}^{-1}$

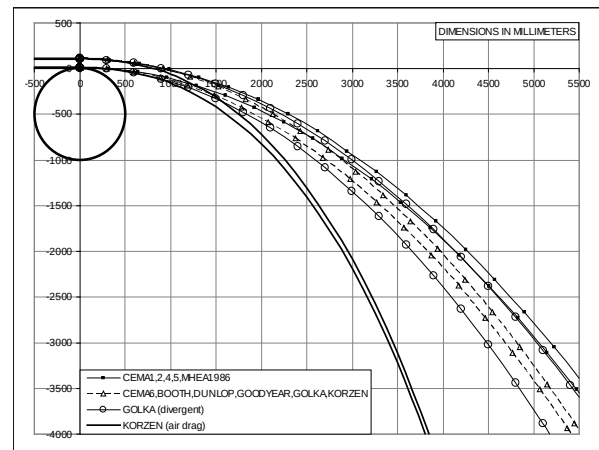


Figure 3 High-speed condition, horizontal conveyor,
lower and upper trajectory path, pulley diameter,
 $D_p=1.0\text{m}$, belt velocity, $V_b=6.0\text{ms}^{-1}$

In section 2 it was explained that Golka [8,9] uses divergent coefficients to obtain a better approximation of the trajectory paths. A set of values has been used to produce trajectories based on Golka's method [8,9] and the influence of varying the divergent coefficients is explained further in section 3.4. If the divergent coefficients are neglected, the resulting trajectories are identical to the Korzen [10] method when air drag is neglected, as the equations are identical. In both belt speed cases shown, the early C.E.M.A. [1,2,3,4] and M.H.E.A. [6] methods

generate the highest trajectory curve and as the discharge velocity increases, the variation from the other curves becomes more defined. As with the low-speed conditions, the Booth [7] and Dunlop [12] methods again produce near identical trajectory curves.

3.2 Effect of Belt Inclination Angle on Trajectory Profile

When varying the belt inclination angle in the comparisons above, initially there was no visible difference to the trajectories from a horizontal belt to those of an inclined belt for low-speed conditions. There are five unique equations across the trajectory methods above to determine the critical angle where the transition from low-speed to high-speed conditions occurs. The example of equation (11) represents that of C.E.M.A. [1,2,3,4,5] and M.H.E.A. [6].

$$V_{b,cr} = \sqrt{\frac{gR_b^2 \cos \alpha_b}{R_c}} \quad (11)$$

For the three pulley diameters selected, the variation in critical belt speed has been quantified and presented in Figure 4. It is evident that as belt inclination increases, the transition from low-speed to high-speed conveying occurs at lower belt speeds. This will have no effect on the actual profile of a given trajectory but will alter where high-speed trajectories begin. For high-speed conditions there will be a variation in the profile of the trajectory as the tangent line for inclined conveyors will be pointing upward and the trajectory will commence before the vertical axis is reached.

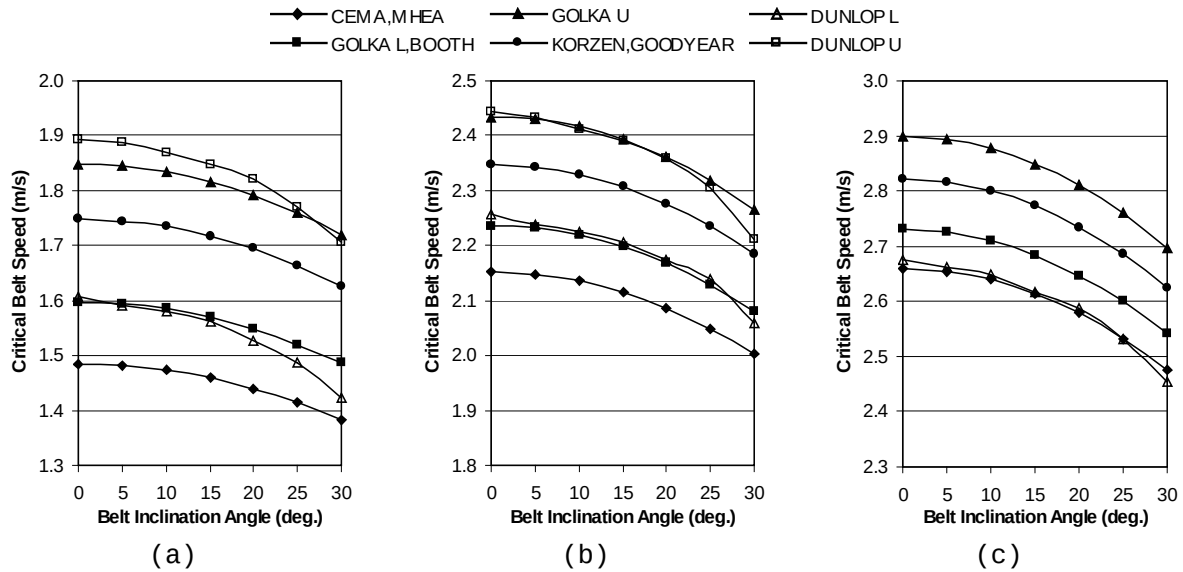


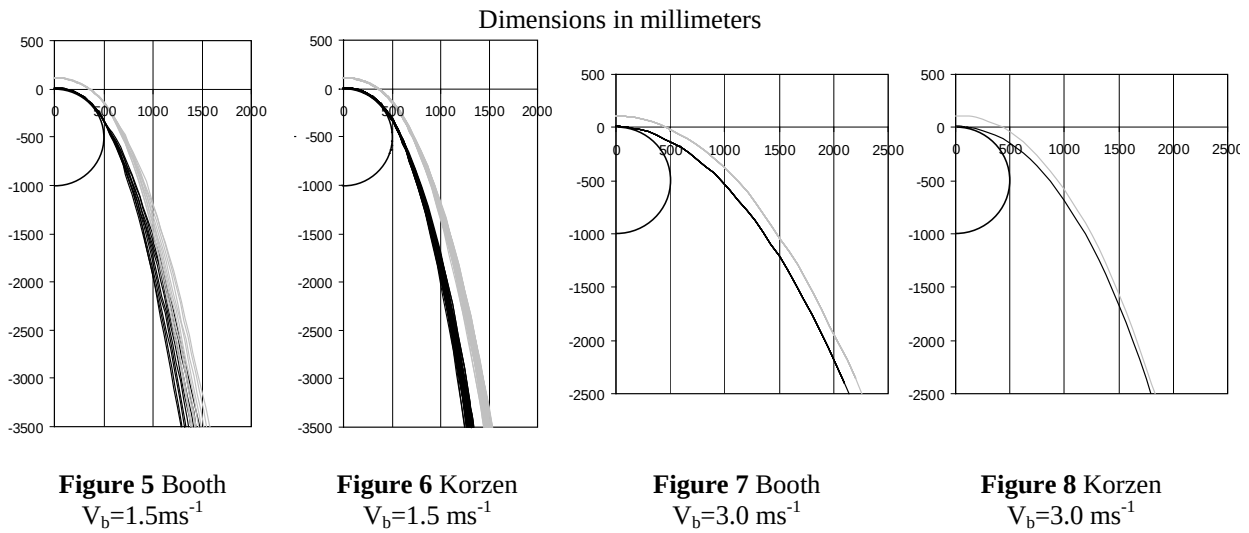
Figure 4 Critical belt speed versus belt inclination angle for varying pulley diameters
(a) $D_p=0.5\text{m}$, (b) $D_p=1.0\text{m}$ and (c) $D_p=1.5\text{m}$

3.3 Effect of Modifying Static and Kinetic Wall Friction on Trajectory Profile

The range of static wall friction, μ_s , is up to the point where slippage occurs and kinetic wall friction, μ_k , is in the motion range. It is generally accepted that $\mu_k < \mu_s$ [13]. To evaluate the effect of varying static wall friction on the Booth method [7], nine values between 0.1 and 0.9 were selected and using the parameters of Table 2, nine profiles have been determined for both the lower and upper trajectories and displayed in Figure 5 for low-speed and Figure 7 for high-speed conditions. For the Korzen method [10], both, μ_s and μ_k are used. To investigate the effects of varying μ_s and μ_k on the resultant trajectories from the Korzen method, the combinations listed in Table 3 have been used, keeping in mind the general understanding that $\mu_k < \mu_s$. This results in 36 individual profiles for both the lower and upper trajectories as shown in Figure 6 for low-speed and Figure 8 for high-speed conditions.

Table 3 Combinations of coefficient of static and kinematic friction used for the Korzen method [10]

		μ_s								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
μ_k	0.1		✓	✓	✓	✓	✓	✓	✓	✓
	0.2			✓	✓	✓	✓	✓	✓	✓
	0.3				✓	✓	✓	✓	✓	✓
	0.4					✓	✓	✓	✓	✓
	0.5						✓	✓	✓	✓
	0.6							✓	✓	✓
	0.7								✓	✓
	0.8									✓
	0.9									



For the low-speed conditions of both methods, the profiles generated form a band that increases as the vertical displacement increases. At a vertical displacement of 3.5m, the range is given in Table 4. For high-speed conditions only one unique trajectory curve was produced for both methods, compare Figure 6 with Figure 8. This is due to the coefficient of static and kinetic wall friction only being used in the determination of low-speed discharge angles.

Table 4 Range of trajectory profiles for low-speed conditions by Booth [7] and Korzen [10]

Trajectory	Booth	Korzen
Lower	1280 to 1470mm (190mm)	1255 to 1345mm (90mm)
Upper	1385 to 1575mm (190mm)	1445 to 1545mm (100mm)

3.4 Effect of Divergent Coefficients on Trajectory Profile

As previously mentioned, Golka [8,9] uses divergent coefficients, but without explanation of how they are quantified. Hence the method is open to some interpretation. As an example of the effect of this parameter, a range of divergent coefficient values ranging from 0 to ± 0.4 have been applied to the parameters of Table 2 using a belt speed on 3ms^{-1} to produce upper and lower trajectory streams. It is evident from Figure 9 that this one parameter alone has a dramatic affect on the resulting trajectories.

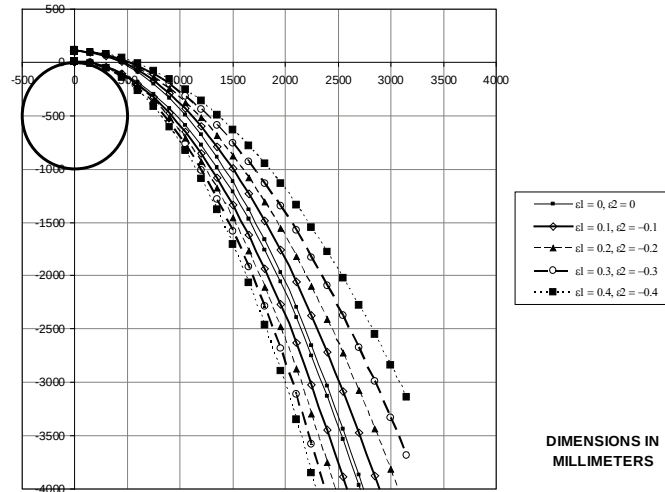


Figure 9 Variation in trajectories based on different divergent coefficients [8,9]

3.5 Effect of Modifying Particle Shape and Size on Trajectory Profile

Again applying the parameters of Table 2 and varying only the equivalent spherical particle diameter, d_k , it is clear that there is an effect on the resulting trajectory curves. As an illustration of this, three values of d_k have been selected, see Table 5. The resulting trajectory curves are displayed in Figure 10, Figure 11 and Figure 12. Each of these figures include the no air drag condition for comparison purposes. Figure 10 plots the trajectory curves for the smallest particle size and shows the largest variations. Figure 12 plots the trajectory curves for the largest particle size (i.e. 1g) and shows a near identical path to the no air drag trajectory. This corresponds with the claim made by Korzen [10] that air drag can be neglected for particles over 1g in mass.

If a particle size distribution (PSD) was present for a given conveying condition, a combination of the results obtained in Figure 10, Figure 11 and Figure 12 would result. Due to the likelihood of some degree of segregation occurring as a result of this PSD, there would be a tendency for the fines to behave as shown in Figure 10 while the courser material would behave more like that shown in Figure 12.

Table 5 Selected equivalent spherical particle diameters for comparison

d_k (mm)	Unit mass of particle (g)
0.5	0.0001
1	0.001
10	1.05

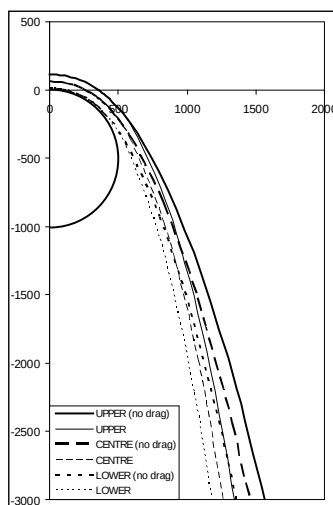


Figure 10 $d_k=0.5\text{mm}$, $d_m=0.0001\text{g}$

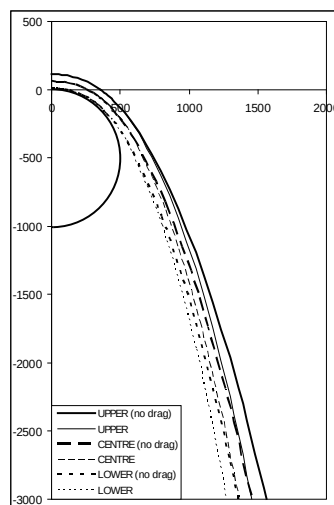


Figure 11 $d_k=1.0\text{mm}$, $d_m=0.001\text{g}$

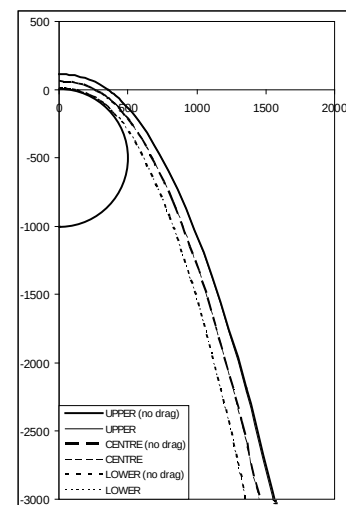


Figure 12 $d_k=10\text{mm}$, $d_m=1.05\text{g}$

3.6 Effect of Modifying Adhesive Stress on Trajectory Profile

There is an adhesive stress component present in Equation (7) of the Korzen method [10]. In the case of the comparisons presented above, the adhesive stress has been set to zero to keep comparisons consistent against other methods. To illustrate the effect of varying the adhesive stress, a pulley diameter of $D_p=1.0\text{m}$ was selected and a range of adhesive stresses from 0kPa to 2kPa was applied, Figure 13.

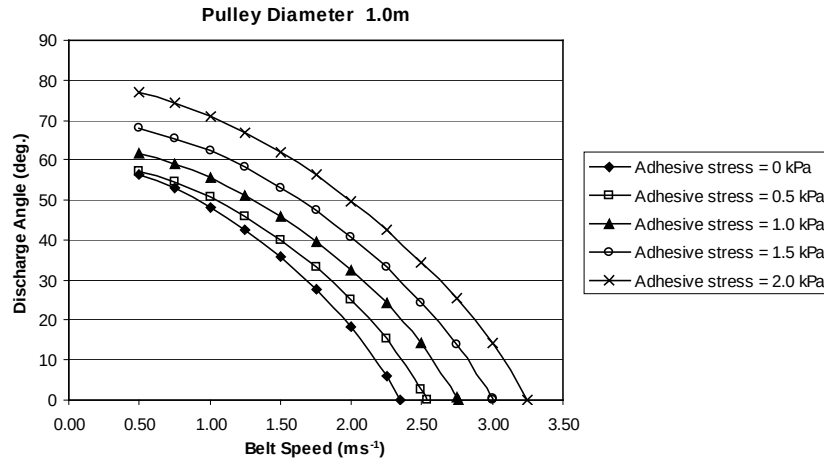


Figure 13 Effect of adhesive stress on discharge angle in the Korzen [10] method

As the adhesive stress is increased for any given belt speed, the resulting discharge angle increases. Also as the adhesive stress increases there is also an increase in the range of belt speeds before the transition from low-speed to high-speed condition occurs. If the adhesive stress is increased to 2.5kPa for this set of comparisons, a discharge angle of 91.3° results for a belt speed of 0.5ms^{-1} which is obviously at an angle past the most horizontal point on the head pulley and would in actual fact result in material doubling back on itself. If the adhesive stress is increased further no solution is possible when attempting to solve equation (7).

3.7 Effect of Modifying Bulk Density on Trajectory Profile

The Korzen method [10] is the only one to incorporate material bulk density into the equations. Bulk density is required to determine the bulk specific gravity of the material for the adhesive component, the discharge velocities of the lower and upper trajectory streams and the unit particle mass. Using the parameters of Table 2 and only varying the bulk density, it was found that as bulk density is reduced, the trajectory profile becomes more shallow and by increasing it, the trajectory profile converges on the profile generated when air drag is neglected.

4 CONCLUSION

This paper has presented a number of the more widely used and/or readily available trajectory prediction methods published in the literature. They range in complexity from the basic, Goodyear [11] and Dunlop [12], to the complex, Booth [7], Golka [8,9] and Korzen [10]. Some methods include a multitude of parameters such as C.E.M.A. [1,2,3,4,5] and M.H.E.A. [6] while others incorporate parameters which no others address, such as divergent coefficients [8,9] and air drag [10].

Low-speed belt condition comparisons show there are two distinct groupings of trajectory predictions. However as the belt speed increases, the groupings are less defined.

The method of determining the divergent coefficients introduced by Golka [8,9] has not been explained however a large variation in the resulting trajectories is possible for only minor changes to their values.

The method of Korzen [10] has by far the most parameters which can influence the final trajectory profile. Static and kinetic wall friction, particle shape and size, adhesive stress and bulk density all affect the resulting trajectory profiles.

For high-speed belt conditions, some of the basic methods approximate a trajectory which is also predicted by the more complex methods. Incorporating air drag into the trajectory predictions causes a dramatic variation from the other trajectory methods. When considering air drag, it makes sense that material will drop away much quicker than the other methods but whether it is truly representative of an actual trajectory needs to be explored further.

Finally, it is fair to say that the differing approaches to determining the material trajectory result in some significant differences which cannot all be correct. With the commissioning of a unique conveyor transfer research facility at the University of Wollongong, it is the intention to address as many of these issues as possible in an attempt to validate particular trajectory methods to allow a more accurate determination of conveyor trajectories. This will also aid in future design and simulation research.

5 ACKNOWLEDGMENTS

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