

DESIGN CONSIDERATIONS AND PERFORMANCE EVALUATION OF SCREW CONVEYORS

by

Alan W. Roberts
Emeritus Professor and Director,
Centre for Bulk Solids and Particulate Technologies,
The University of Newcastle, Australia.

SUMMARY. This paper is concerned primarily with screw conveyors with fully enclosed tubular casings. The throughput, torque and power are significantly influenced by the vortex motion of the bulk solid being conveyed. The vortex motion, together with the degree of fill, govern the volumetric efficiency and, hence, the throughput. This, in turn, influences the torque, power and conveying efficiency. A theory is presented to predict the performance of screw conveyors of any specified geometry. The influence of the flow properties of the bulk material on the conveyor performance is illustrated.

1. INTRODUCTION

Screw conveyors may be grouped, broadly, into two categories, the U-shaped trough type conveyor and the fully enclosed conveyor incorporating a tubular casing. Screw conveyors with U-shaped trough type casings are widely used in industry, their operation being restricted to low angles of elevation, low speeds and low fill ratios. The low fill ratios are to protect the hanger support bearings when long conveying distances are employed. Screw conveyors with fully enclosed tubular type casings are more versatile. They operate over a wide range of speeds and angles of elevation up to the vertical. They perform well at higher fill ratios, with the conveying action due to the helical screw being enhanced by the resistance to rotary or vortex motion of the bulk solid being provided by the total casing surface. Their disadvantage is the limitation in conveying distance since they need to operate without intermediate support bearings. This problem may be overcome with shaftless screws which employ helical flights of heavy cross section supported on plastic, wear resistant liners attached to the inside surface of the casing.

This paper focuses primarily on fully enclosed, tubular casing type screw conveyors. Of particular interest is the performance with respect to throughput, torque and power. While the paper draws upon on earlier work performed during the period 1962-64 [1,2], it concentrates on more recent work dealing with the influence of vortex motion on the conveying action [3]. The emphasis is given to vertical and steeply inclined conveyors, with an outline being presented regarding the prediction of performance at lower angles of elevation down to the horizontal.

Particular attention is given to the application of the measured flow properties of the bulk material being conveyed. In this regard the significance of screw blade and casing friction on the conveyor performance is discussed. The use of the correct bulk density of the conveyed material taking account of the moisture and consolidation conditions is emphasized. Case study examples are presented in order to illustrate the application of the design procedures to practical industrial applications.

2. ENCLOSED SCREW CONVEYORS

The relevant details of the enclosed screw or auger conveyor are shown in Figure 1. The power driven screw flight is supported in bearings and revolves in a stationary tubular casing. Practical limitations require a liberal clearance between the flight and the casing and this has been shown to be beneficial rather than detrimental to performance. The screw flight is allowed to project beyond the casing at the lower or intake end, this projection being referred to as the "choke". The screw must be immersed into the feed material at least to the level of the lower end of the casing, otherwise the conveyor will not elevate the bulk material.

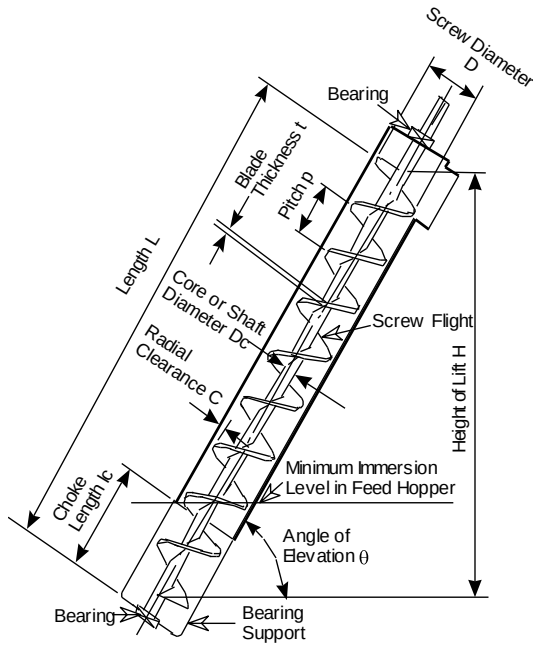


Figure 1. Enclosed Screw or Auger Conveyor

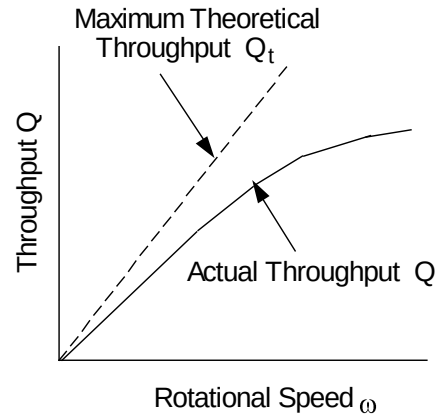


Figure 2. Conveyor Throughput

2.1 Conveyor Throughput

The throughput of an enclosed screw conveyor is influenced by the rotational or vortex motion of the bulk material during transportation and the degree of fill or "fullness" of the screw. As the rotational speed of the conveyor increases, the rotational or vortex motion decreases up to a limiting value, making for a more efficient conveying action. However, when a gravity feed system into the screw intake is employed, the feed rate cannot match the potential conveying capacity, and a reduction in fill ratio or "fullness" occurs. The net result is for the throughput of the screw conveyor to reach a limiting value as illustrated in Figure 2. By employing a positive feed system to increase the "fullness", the efficiency of the conveyor can be improved.

The volumetric throughput of a screw conveyor is given by

$$Q = Q_t \eta_V \quad (\text{m}^3/\text{s}) \quad (1)$$

where $Q_t = \Gamma \omega D^3$ (2)

$$\Gamma = \frac{1}{8} \left[\left(1 + 2 \frac{C}{D} \right)^2 - \left(\frac{D_c}{D} \right)^2 \right] \left[\frac{p}{D} - \frac{t_s}{D} \right] \quad (3)$$

Q_t = maximum theoretical volumetric throughput with conveyor running 100% full and the bulk material moving axially without rotation

η_V = volumetric efficiency

D = screw diameter (m)

D_c = core or shaft diameter (m)

p = pitch (m)

ω = angular velocity of screw (r/s)

C = radial clearance (m)

t_s = thickness of screw blade (m)

The volumetric efficiency of a screw conveyor is the product of two components as indicated:

$$\eta_V = \eta_{VR} \cdot \eta_F \quad (4)$$

where η_{VR} = conveying or vortex efficiency accounting for the rotational or vortex motion

$$\eta_F = \text{'Fullness' Efficiency} = \frac{h_{av}}{p} \quad (5)$$

h_{av} = average height of material on the screw surface (See Figure 4)

2.2 Effect of Conveyor Diameter - Corresponding Speeds

Corresponding speeds are given by non-dimensional specific speed number N_S defined by

$$N_S = \frac{\omega^2 R_0}{g} = \frac{N^2 D}{1789} \quad (6)$$

where R_0 = outer radius; g = gravitational acceleration; N = rotational speed (rev/min)

It follows from equation (6) that screw conveyors of large diameter attain their maximum output at lower speeds than conveyors of smaller diameter [1].

2.3 Mass Throughput – Influence of Bulk Density

The mass throughput of a screw conveyor in kg/s is given by

$$Q_m = \rho Q = \rho Q_t \eta_v \quad (7)$$

where ρ = bulk density, kg/m^3

It is important that attention be given to the correct choice of bulk density. For virtually all bulk materials, the bulk density increases with consolidation pressure approaching a maximum limiting value as illustrated by Figure 3. This shows, by way of example, the bulk density as a function of major consolidation pressure for a typical coal sample. Also shown is the packing ratio that relates the bulk density to the solids density. As the pressures increase, the bulk density approaches a limiting value corresponding to the maximum packing ratio

Usually the consolidation pressures at the loading or feed point, denoted by 'L' in Figure 3, are low and the bulk density is also low. The conveying action causes the bulk material to be compressed resulting in an increase in pressure to point 'R' in Figure 3. The conveyor fill ratio then decreases and the bulk density increases. To estimate the bulk density under conveying conditions, it is first necessary to determine the major consolidation pressure acting on the screw surface. This procedure is described in Section 7.

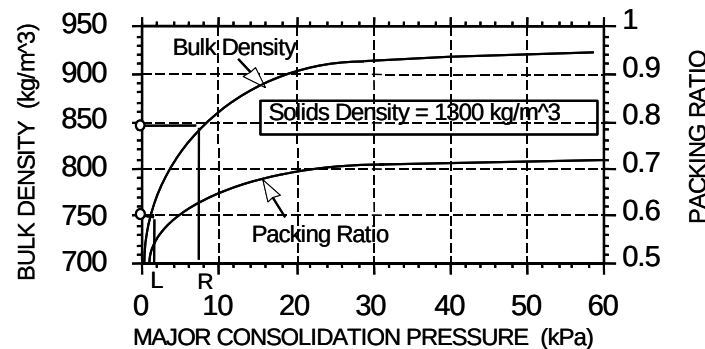


Figure 3. Bulk Density and Packing Ratio for Coal

3. VOLUMETRIC THROUGHPUT - VERTICAL CONVEYOR

3.1 Conveying Action

Figure 4 shows the conveying action within a vertical screw conveyor. The velocity diagram for a particle in contact with the screw surface at a particular location is shown. V_S is the screw velocity due to its rotation, V_R is the relative velocity of the particle with respect to the screw surface and V_A is the absolute velocity of the particle defined by the helix angle λ . This means that the particle moves in a helical path of opposite hand to the screw helix.

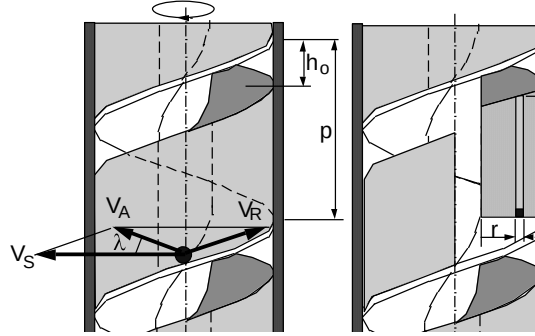


Figure 4. Mechanics of Conveying Action

Figure 5 shows the velocity diagram in which the absolute velocity is resolved into two components, the useful conveying velocity V_L and the rotational component V_T . Since the helix angle α of the screw flight varies with the radius, being smaller at the outer periphery and larger at the shaft, the angle λ will also vary in the radial direction from the outside of the flight to the shaft. This means that the rotational velocity V_T will vary from the outside to the shaft. The variation in V_T with radius describes the vortex motion in the screw and is expressed by

$$V_T r^n = \text{Constant} \quad (8)$$

The constant 'n' is the vortex index. It has been shown by Roberts [2,3] that $n \approx 0$, that is, the velocity component V_T is constant and does not vary with the radius. This means that the height 'h' of material on the screw flight is constant and does not vary with the radius.

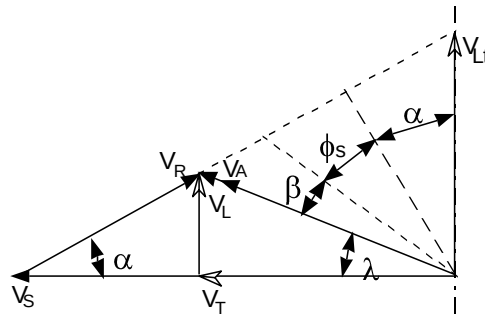


Figure 5. Velocity Diagram

Referring to Figure 5, the actual conveying velocity V_L , when expressed as a ratio of the maximum theoretical conveying velocity V_{Lt} , provides a measure of the conveying efficiency allowing for losses resulting from the rotational or vortex motion. It may be shown that

$$\frac{V_L}{V_{Lt}} = \frac{\tan \lambda}{\tan \alpha + \tan \lambda} \quad (9)$$

3.2 Effective Radius

For the conveying efficiency to be determined, it is necessary to first determine the variation of the path helix angle λ as a function of the radius and rotational speed of the conveyor. With the knowledge that $V_T \approx \text{constant}$ and does not vary with the radius, the analysis of the screw conveyor may be simplified by lumping the rotational mass and resultant forces at the effective radius R_e defined by

$$R_e = \frac{2}{3} \left[\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2} \right] \quad (10)$$

where R_o = outside radius of screw flight. R_i = inner radius of radius of shaft.

The helix angle of the screw flight corresponding to R_e is

$$\alpha_e = \tan^{-1} \left[\left(\frac{p}{\pi D} \right) \left(\frac{R_o}{R_e} \right) \right] \quad (11)$$

where p = pitch $D = 2 R_o$ = screw flight diameter

3.3 Helix Angles of Particle Path

The relationship between the helix angle λ of the path and the speed of rotation of the conveyor has been studied by Roberts [1-3]. For the particular case of the effective radius R_e , it may be shown that the relationship between the specific rotational speed N_S and the helix angle λ_e defining the effective absolute path is given by

$$N_S = \frac{R_o}{R_e} \left[1 + \frac{\tan \lambda_e}{\tan \alpha_e} \right]^2 \left[\frac{k_F \sin (\alpha_e + \phi_S)}{\mu_c \cos (\alpha_e + \phi_S + \lambda_e)} - k_S \right] \quad (12)$$

where $k_F = (1 - \mu_c k_S) \leq k_F \leq 1.0$ (13)

$$\text{and } k_S = 2 k_j \frac{p}{D} \left[\frac{1}{1 - \frac{R_i^2}{R_o^2}} \right] \eta_F \quad (14)$$

ϕ_S = friction angle for screw surface; $k_j = 0.4$; η_F = fill ratio or fullness
 μ_c = friction coefficient for bulk material on casing surface

N_S is the 'specific speed' defined by equation (6). The coefficients k_F and k_S in equation (12) take into account the bulk solid stress fields within the screw space and depend on the internal friction of the bulk solid. The angle λ_e increases with speed of rotation reaching, asymptotically, a limiting value defined as follows:

$$\text{as } N_S \rightarrow \infty, \lambda_e \rightarrow 90^\circ - (\alpha_e + \phi_S)$$

That is, λ_e approaches a constant value defined by the helix angle of the screw and the friction angle of the bulk solid in contact with the screw surface. The helix angle λ_o at the outer periphery adjacent to the inside surface of the casing is obtained from the following equation:

$$\tan \lambda_o = \tan \alpha_o \left[\frac{R_o}{R_e} \left(1 + \frac{\tan \lambda_e}{\tan \alpha_e} \right) - 1 \right] \quad (15)$$

3.4 Conveying or Vortex Efficiency

It now follows from Equation (9) that the conveying or vortex efficiency is given by

$$\eta_{VR} = \frac{V_{Le}}{V_{Lt}} = \frac{\tan \lambda_e}{\tan \alpha_e + \tan \lambda_e} \quad (16)$$

α_e = effective helix angle - equation (11); λ_e = effective helix angle of the path - equation (12)

3.5 'Fullness' or Fill Ratio - Gravity Feed

Under gravity feed, such as illustrated in Figure 1, the feeding action in the choke controls the conveyor throughput. For a free flowing bulk solid, the fill ratio may be approximated by

$$\eta_F = C_{F0} - C_F \sqrt{N_S} \leq 1.0 \quad (17)$$

where $C_{F0} \approx 0.90 - 1.12$; $C_F \approx 0.06 - 0.085$; N_S = specific speed defined by equation (6). The combination of the fill ratio η_F and vortex efficiency η_{VR} allows the volumetric efficiency $\eta_V = \eta_{VR} \eta_F$ to be obtained. Hence the throughput can then be determined.

4. FORCED FEEDING

An appropriate forced feeding arrangement may be used to meet a specified throughput, particularly when cohesive bulk solids are to be conveyed. For example, forced feeding is employed in the Siwertel type ship unloader which employs a counter rotating lower casing with feed vanes as illustrated in Figures 6 and 7. The screw conveyor capacity is controlled by the feeding device and not by the conveyor itself. To avoid blockages in the screw intake, it is essential that the conveyor speed is high enough for the fill ratio $\eta_F < 1$.

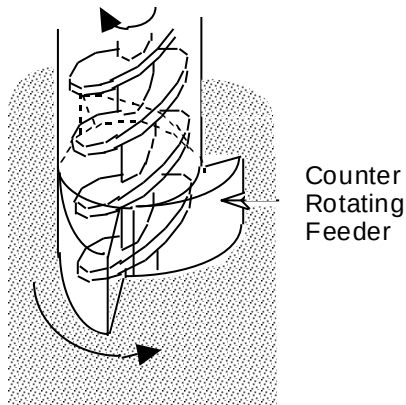


Figure 6. Forced Feeding

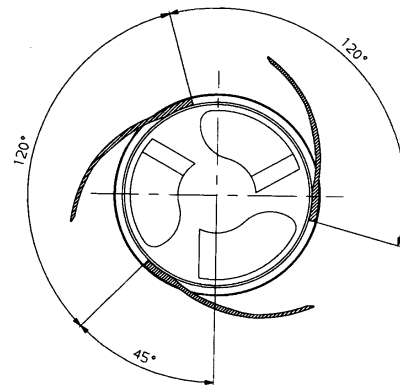


Figure 7. Plan View of Feeder

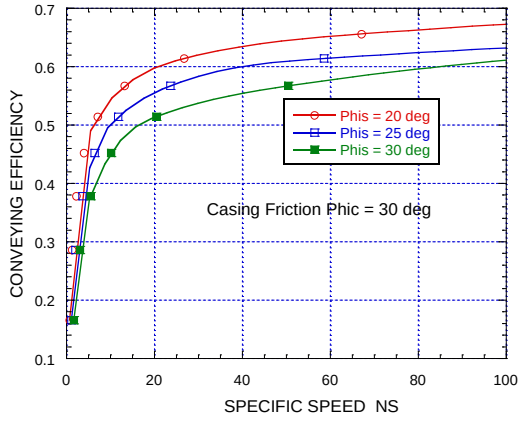
Consider a three vane feeder of the type shown in Figure 6. A plan view is illustrated in Figure 7. The feed rate may be estimated as

$$Q_m = 60 \rho b d \pi D_e N_F n_b \eta_{Fe} \quad (\text{t/h}) \quad (18)$$

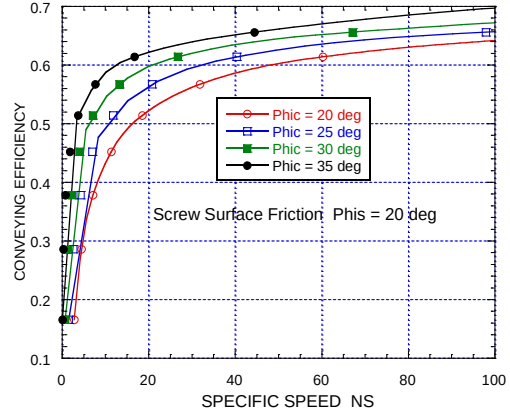
where ρ = bulk density, t/m^3 b = width of effective feeder opening, m
 d = depth of effective feeder opening, m D_e = effective diameter of feeder, m
 N_F = feeder speed n_b = number of blades = 3
 η_{Fe} = feeding efficiency

5. INFLUENCE OF SCREW AND CASING FRICTION

The performance of screw conveyors is significantly influenced by the friction generated between the bulk material and the screw and casing surfaces. As an illustration, Figures 8 and 9 compare the conveying efficiencies η_{VR} for a vertical screw conveyor for a range of friction angles ϕ_s and ϕ_c for the screw surface and casing surface respectively. The conveyor fill ratio is arbitrarily chosen as $\eta_F = 80\%$. This means that the volumetric efficiency will be $\eta_V = 0.8 \eta_{VR}$.



**Figure 8. Conveying Efficiency
Effect of Screw Surface Friction**



**Figure 9. Conveying Efficiency
Effect of Casing Surface Friction**

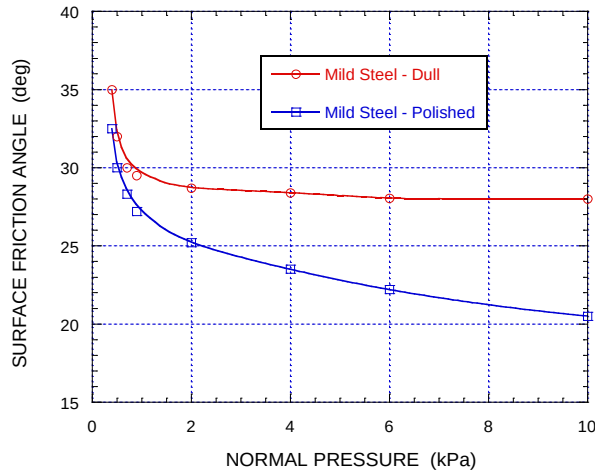


Figure 10. Friction Angles for a Particular Coal on Mild Steel Surfaces

The surface friction angles for cohesive bulk solids are found to decrease with increase in normal pressure as illustrated in Figure 10. The graphs compare the friction angles for a particular moist coal in contact with mild steel with dull finish and with mild steel with polished finish. The reduction in friction with increase in the polished finish is clearly evident, particularly as the normal contact pressure increases. For screw conveyors the pressures are usually low, and hence the friction angles will be high. This requires the pressures relevant to the conveyor to be determined as discussed in Section 7.

6. OPERATION AT VARIOUS ANGLES OF ELEVATION

6.1 Special Case of Horizontal Conveyor

Research indicates that for horizontal screw conveyors, the angle β , shown in Figure 5, is zero. That is, the helix angle of the path is independent of the screw speed and is given by

$$\lambda = 90^\circ - (\alpha + \phi_s) \quad (19)$$

As an approximation, this relationship may also be assumed for screw conveyors operating at low angles of elevation up to say, $\theta = 25^\circ$. The conveying or vortex efficiency derived from equations (10) and (13) is given by

$$\eta VRh = \frac{1}{\tan \alpha_e \tan(\phi_s + \alpha_e) + 1} \quad (20)$$

The subscript 'h' denotes horizontal position. As an example, η_{VR} values computed using equation (14) for a screw with a core or shaft diameter one third the screw diameter are plotted in Figure 11. The effect of both pitch to diameter ratio as well as screw friction is illustrated.

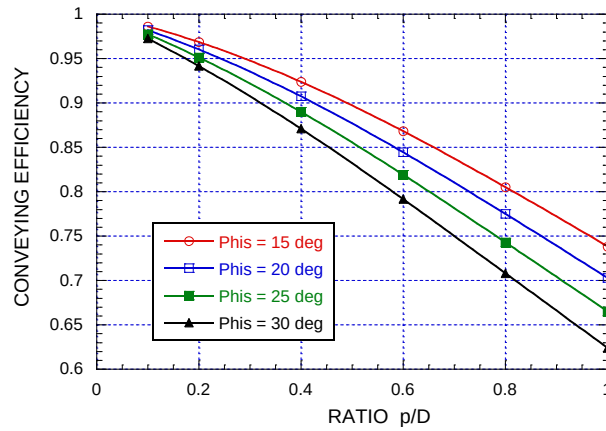


Figure 11. Conveying Efficiency for Horizontal Conveyor - $D/D_C = 3.33$

6.2 Arbitrary inclination angle

The analysis for operation at any elevation angle θ is more complex. For inclination angles ranging from 30° to 90° , equation (12) may still be applied, but in the modified form

$$N_S = \frac{R_0}{R_e} \left[1 + \frac{\tan \lambda_e}{\tan \alpha_e} \right] \left[\frac{2}{\mu_c \cos(\alpha_e + \phi_s + \lambda_e)} \frac{k_F f_1(\theta) \sin(\alpha_e + \phi_s)}{k_S f_2(\theta)} - k_S f_2(\theta) \right] \quad (21)$$

The functions $f_1(\theta)$ and $f_2(\theta)$ need to be defined. Once $N_S = f(\lambda_e)$ has been determined, then equation (16) is used to determine η_{VR} . Hence the throughput may be calculated.

An alternative, somewhat empirical approach solution is as follows:

- Compute the conveying or vortex efficiency η_{VR} for a vertical conveyor in accordance with Sections 3.2 and 3.3.
- Compute the conveying efficiency η_{VRh} for a horizontal conveyor using equation (16)
- Interpolate the conveying efficiency for inclination angle θ as follows:

$$\eta_{VR\theta} = \eta_{VRh} - (\eta_{VRh} - \eta_{VR}) \sin \theta \quad (22)$$

7. FORCE ANALYSIS - VERTICAL CONVEYORS

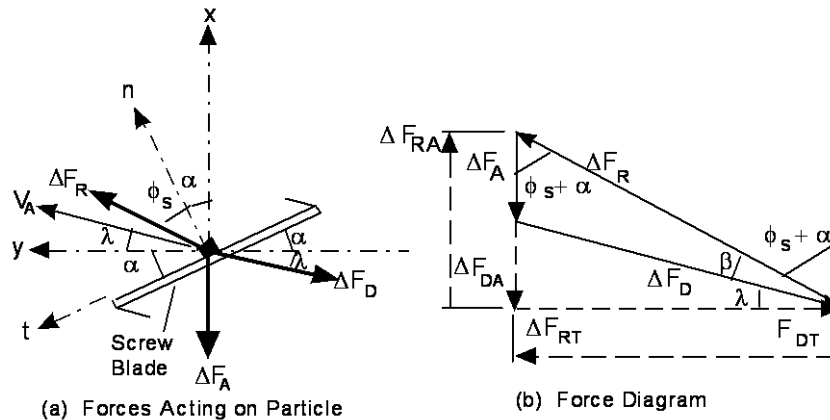


Figure 12. Forces Acting on Bulk Particle in Contact with Screw Surface

The forces acting on particles in a screw conveyor are shown in Figure 12. The velocity components are also shown. A particle at the outer periphery in contact with the stationary casing exerts a force ΔF_N against the casing, mainly as a result of the centrifugal pressure. The centrifugal pressure gives rise to the normal pressure p_n acting at the casing. A frictional drag force $\Delta F_D = \mu_c \Delta F_N$ acts in a direction opposing the absolute velocity as indicated in Figure 12(a). Here μ_c is the coefficient of friction for the bulk solid particle on the casing surface.

The weight of bulk material retained on each pitch is

$$W = \pi (R_o^2 - R_i^2) \rho g \eta_F \quad (23)$$

The axial force is

$$\Delta F_{RA} = W \left\{ 1 + \mu_c \left[\frac{\tan \alpha_e}{\tan \alpha_e + \tan \lambda_e} \right]^2 \frac{N_s R_e}{R_o} \right\} \quad (24)$$

The correct choice of screw and casing friction angles ϕ_s and ϕ_c respectively depends on the flow properties which depict the friction angles as a function of pressure as illustrated in Figure 10. For this reason, the pressures on the helical blade and casing need to be determined

The axial pressure on the screw blade is

$$\sigma_a = \rho g p \eta_F \left\{ 1 + \mu_c \left[\frac{\tan \alpha_e}{\tan \alpha_e + \tan \lambda_e} \right]^2 \frac{N_s R_e}{R_o} \right\} \quad (25)$$

The average normal pressure on the casing is given by

$$\sigma_{ac} = \rho \omega^2 \frac{R_m}{2 R_o} (R_o^2 - R_i^2) \left[\frac{\tan \alpha_e}{\tan \alpha_e + \tan \lambda_e} \right]^2 \quad (26)$$

8. SCREW TORQUE AND POWER - VERTICAL CONVEYOR

8.1 Screw torque, T_{sp}

The screw torque per pitch due to the bulk solid on the flight face may be determined from the following equation,

$$T_{sp} = \frac{2}{3} \frac{L}{p} \Delta F_{RA} R_e \tan (\alpha_e + \phi_s) \quad (27)$$

where ϕ_s = friction angle for bulk solid on screw surface; R_e = effective radius;

α_e = effective helix angle; L = length of screw conveyor; p = pitch

8.2 Shaft torque, T_{sh}

The normal pressure due to the bulk solid on the shaft is

$$\sigma_n = K \rho g p \eta_F \quad (28)$$

Torque due to the bulk solids moving relative to the shaft is

$$T_{sh} = 2 \pi R_i^2 \sigma_n \frac{L}{p} \quad (29)$$

K accounts for the pressure distribution around the shaft. It is assumed that $K = 0.4$

8.3 Total screw torque and power

The total torque is $T = T_{sp} + T_{sh}$ (kNm)

$$\text{Power } P = \frac{0.105 T N}{\eta_d} \quad (\text{kW}) \quad (30)$$

where $N = \text{rpm}$ $\eta_d = \text{drive efficiency}$

9. SCREW TORQUE AND POWER - ARBITRARY INCLINATION ANGLE

In this case the axial force per pitch may be computed as follows

$$\Delta F_{RA} = W (\sin \theta + \mu_E \cos \theta) \quad (31)$$

where W is as defined by equation (23). $\mu_E = \text{equivalent friction coefficient to allow for drag of the casing walls during motion. It is expressed by}$

$$\mu_E = \mu_c (1 + K_\theta \eta_F) \quad (32)$$

where $K_\theta = \text{pressure ratio} = 0.4 \text{ to } 0.6$ depending on consolidation of bulk solid.

The screw torque and power are then computed following the procedures given in Section 6.

10. CASE STUDY EXAMPLES

10.1 Predicted and measured performance

The procedures for computing the throughput and power presented in this paper are examined in relation to the performance of an actual screw conveyor elevating wheat. The conveyor operates in the vertical position and is gravity fed. The predicted and measured results are compared in Figure 13. The agreement is considered to be quite satisfactory.

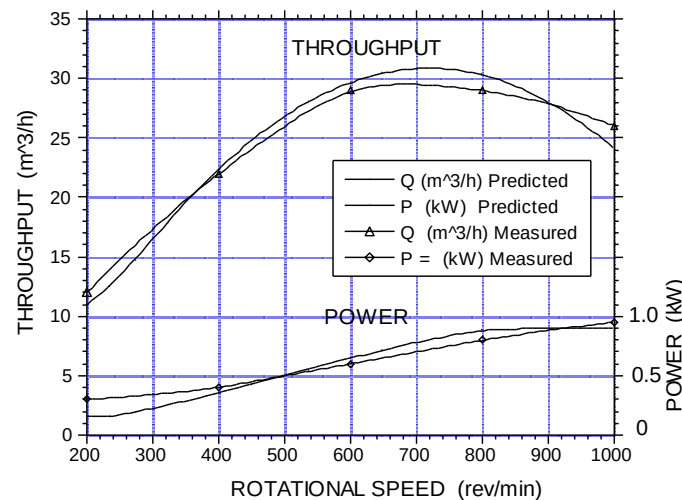


Figure 13. Predicted and Actual Performance of a Screw Conveyor Handling Wheat

$D = 150\text{mm}$; $D_c = 50\text{mm}$; $p = 150\text{mm}$; $L = 2.44\text{m}$; $\theta = 90^\circ$; $\phi_s = 20^\circ$;

$\phi_c = 25^\circ$; $k_j = 0.45$; $C_{F0} = 1.0$; $C_F = 0.083$; $\rho = 900\text{kg/m}^3$

10.2 Example on forced feeding

A vertical screw conveyor elevator with a forced feeding system is used in an unloading operation. The screw diameter $D = 0.5 \text{ m}$, shaft diameter $D_c = 0.25 \text{ m}$, pitch $p = 0.375 \text{ m}$, length $L = 10 \text{ m}$. The conveyor is to elevate coal of bulk density $\rho = 0.8 \text{ t/m}^3$. $\phi_s = 20^\circ$, $\phi_c = 25^\circ$. The required throughput is 400 t/h which is controlled by the feeder at the screw intake.

Figure 14 shows the fill ratio or 'fullness', conveying or vortex efficiency and power as a function of speed for $Q_m = 400 \text{ t/h}$. The power curve is that to elevate the coal and does not include the power consumed by the feeder. Based on the fill ratio, the minimum conveyor speed is 250 rpm . For practical reasons, a fill ratio $\eta_F < 0.9$ is required. Hence the minimum speed is 270 rpm . The graphs show that while the 'fullness' decreases with an increase in

conveyor speed, this is somewhat offset by increase in vortex efficiency. Referring to the power curve, the advantage of operating at a lower speed with a higher fill ratio is shown.

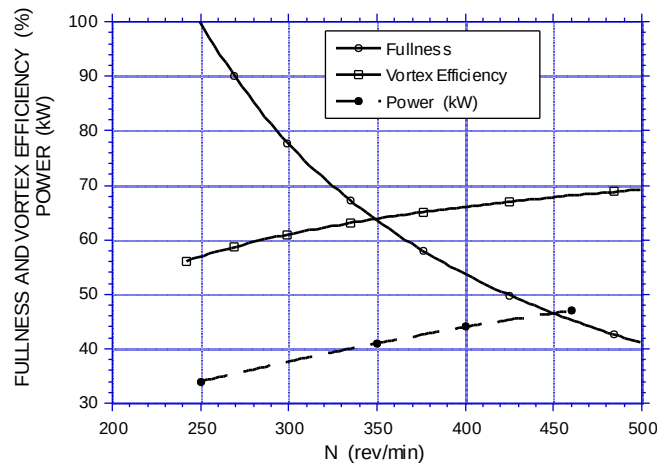


Figure 14. Fullness, Volumetric Efficiency and Power for $Q_m = 400$ t/h

11. CONCLUDING REMARKS

The performance of screw conveyors is significantly influenced by the vortex motion of the bulk solid being conveyed. The vortex motion, together with the degree of fill, govern the volumetric efficiency and, hence, the throughput. This, in turn, influences the torque, power and conveying efficiency. The flow properties of the bulk material being conveyed are shown to have a significant influence on the performance.

12. REFERENCES

1. Roberts, A.W. and Willis, A.H. "Performance of Grain Augers". *Proc. Instn of Mech. Engrs.* 176 (1962) 165.
2. Roberts, A.W. "An Investigation of Grain Vortex Motion with Relation to the Performance within Vertical Grain Augers" *Proc. of the Instn. of Mech. Engrs*, 178 (1963-1964), 293.
3. Roberts, A.W. "The Influence of Granular Vortex Motion on the Volumetric Performance of Enclosed Screw Conveyors". *Powder Technology*, 104, (1999) 56-67.