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Process modelling vertical screw transport of bulk material flow

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Abstract

Vertical screw conveying bulk and powdered materials are an integral part of many production processes in various industries and agriculture. With a wide range of applications in various industries, vertical screw conveyors, along with such qualities as the ease of construction, the continuity of transportation, integrity, the ability to transport and dusty badly smelling goods, have a significant drawback - the material, in addition to the translational motion in the direction of the axis of the conveyor, makes a rotary movement towards the peripheral speed of the screw, which reduces the productivity and increases the power consumption of the conveyor. The use of a simplified model of the movement of the material leads to the creation of inefficient machines, the structure and parameters of working bodies of which differ significantly from optimal. Adequate mathematical description of this process should allow the designers to significantly improve the efficiency of the vertical screw conveyors by means of calculation and selection of optimum values for the geometrical, kinematic and dynamic parameters of working bodies.

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*Keywords:*conveyor, bulk materials, auger, pitch, particle, screw blade, tube.

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1. Introduction

Generally, conveying is accomplished by a combination of mechanical, inertial, pneumatic, and gravity forces. Conveyors utilizing primarily mechanical forces are screw, belt, and mass conveyors [1]. Screw conveyors are widely used for transporting and/or elevating particulates at controlled and steady rates. They are used in many bulk materials applications in industries ranging from industrial minerals, agriculture (grains), pharmaceuticals, chemicals, pigments, plastics, cement, sand, salt and food processing. They are also used for metering (measuring

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the flow rate) from storage bins and adding small controlled amounts of trace materials (dosing) such as pigments to granular materials or powders. If not designed properly for the transported material, problems experienced include: surging and unsteady flow rates, inaccurate metering and dosing, inhomogeneity of the product, product degradation, excessive power draw, high start-up torques, high equipment wear and variable residence time and segregation [2].In a variety of industries meet screw conveyors: horizontal; vertical; in the form of combinations of the horizontal and vertical; inclined and combinations inclined conveyors and other [7].

2. The apparatus, operating principles and basic parameters of screw conveyors

The screw conveyor consists of a shaft that carries helicoids flightings on its outer surface. These flightings are enclosed either in a trough for horizontal augers or in a tube for elevating augers. The tube or the trough is held stationary while the rotation of the flightings causes the material to move longitudinally. Figure 1 shows the essential components of a screw conveyor. At the inlet side, the auger flightings extend beyond the tube. Generally, a hopper is provided to hold the material while it is conveyed into the tube. Augers can be permanently installed in a machine, or at a site, or they can be portable. The augers are driven either at the intake side or the discharge side.

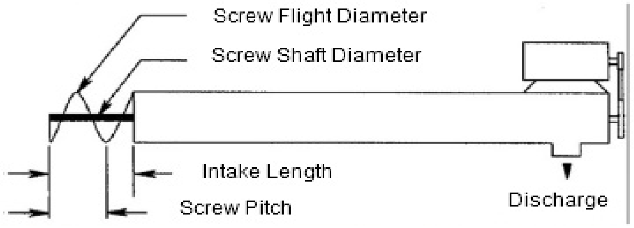

Fig. 1. A schematic diagram of a screw conveyor.

The auger length is defined as the length of the tube assembly including any intake but not including the intake hopper and/or the head drive. The intake length is the visible flighting at the intake of the auger. The intake shall be guarded or otherwise designed to provide a deterrent from accidental contact with the rotating flighting. The outside diameter of the tube is referred to as the auger size. A standard pitch auger is the one whose pitch is approximately equal to the outside diameter of the helicoidalflighting. Generally, the pitch is not less than 0.9 and not more than 1.5 times the outside diameter. Standard pitch augers are used for horizontal and up to 20° inclination angles. For inclination angles greater than 20°, half - standard pitch screws are used. Double - and triple - flight, variable - pitch, and stepped - diameter screws are available for moving difficult materials and controlling feed rates [8].

Screw conveyors are very effective conveying devices for free flowing or relatively free flowing bulk solids, giving good throughput control and providing environmentally clean solutions to process handling problems because of their simple structure, high efficiency, low cost and maintenance requirement. Screw conveyors vary in size from 75 to 400 mm in diameter and from less than 1 m to more than 30 m in length (Athanasiov et. al., 2006). The performance of a screw conveyor, as characterized by its capacity, volumetric efficiency, and power requirements, is affected by the conveyor geometry and size, the properties of the material being conveyed, and the conveyor operating parameters such as the screw rotational speed, screw clearance and conveying angle (Srivastava et al., 2006) [9].

Application of engineering principles for reducing energy requirement in the form of mechanical and electrical power is necessary to reduce cost of production. Factors affecting capacity include auger dimensions (diameter, auger geometry), shear-plane flighting orientation, auger speed, angle of inclination, commodity being conveyed, and entrance-opening configuration. For economical installation and dependable performance, the capacity and power requirement of each component of a system must be accurately predicted [9].

3. Disadvantages of screw conveyors and work to improve them

At the present time the most of investigations are based on the estimated scheme which substitutes the flow conveying with the conveying of a particle leaning against the screw blade and pushed to the tube. The particle's moving for an upright screw conveyer in stationary condition can be described by following differential equations:

$$\left.\begin{aligned} & N_s\cos\alpha_R - f_s N_s\sin\alpha_R - f_t N_t\cos\beta - mg = 0\,; \\ & f_t N_t\sin\beta - f_s N_s\cos\alpha_R - N_s\sin\alpha_R = 0 \\ & -N_s + mR\omega_0^2\left[\frac{\sin\alpha_R\sin\beta}{\cos(\beta-\alpha_R)}\right]^2 = 0 \end{aligned}\right\} \tag{1}$$

where f_s = friction coefficient of material against the screw blade, f_t = friction coefficient against the tube, m = mass of the material particle, N_s = normal reaction of the screw blade, N_t = normal reaction of the tube, R = screw blade radius, $\alpha_{\mathrm{R}} = arctg\,\dfrac{t}{2\pi \mathrm{R}}$ = the helix angle on outer radius, $t = 2\pi Rtg\alpha_R$ = lead of the screw, β = the angle contained by absolute velocity vector v of the material particle and the screw axis, ω_0 = screw angular velocity, $g = 9{,}81\text{м}/c^2$ = free fall acceleration.

The equation for determination of angle β:

$$\frac{R\omega_0^2 f_t}{g}\left[\frac{\sin\alpha_R\sin\beta}{\cos(\beta-\alpha_R)}\right]^2 - \frac{f_s + tg\alpha_R}{\sin\beta(1-f_s tg\alpha_R) - \cos\beta(f_s + tg\alpha_R)} = 0\,. \tag{2}$$

Analysis of amount results of handling process taken from solution of the relation (2) with using a computer shows that functioning efficiency of upright screw conveyers is considerably influenced by geometrical and kinematical parameters of the conveyer tools (the radius and the helix angle of the screw blade and rotational speed of the shaft). Indeed, material flow moving will be simulate with a particle moving, but the amount will be differ (2).

The equilibrium of material volume element engaging sector of a blade with the central angle $d\varphi$ is plotted in Fig. 2. In order to proceed from particle moving it's necessary to ascertain flow cross section shape. If consider moving granular material flow as moving liquid flow, as the pressure is the free surface, the flow free surface equation is the following:

$$z = z_0 + \frac{\omega^2 x^2}{2g} \text{ or } z = ax^2 + b\,, \tag{3}$$

where ω = material angular velocity.

To determinate coordinates for the intersection point of the flow free surface and the screw blade r it's necessary to study particle equilibrium at this point. Suppose, the particle is on flow free surface, leans against the screw blade at the distance r from the axis, pushed to material flow and gyrating by concentric rotational speed ω_0

There are equations of particle moving:

$$\left.\begin{aligned} & N_s\cos\alpha_r + f_s N_s\sin\alpha_r + f_t N_t\sin\alpha_r - mg = 0 \\ & f_m N_m\cos\alpha_r + f_s N_s\cos\alpha_r - N_s\sin\alpha_r = 0 \qquad , \end{aligned}\right\}$$

$$-N_m + mr\omega_0^2 = 0$$

where f_m = internal friction coefficient of the material, N_m = normal reaction of flowing material, $\alpha_r = arctg(\frac{R}{r} tg\alpha_R)$ - the helix angle at the distance r from the axis.

Solving this set of equations and relation (3) simultaneously yields the following relation for coordinate of the intersection point of flow free surface and the screw blade:

$$f_m\omega_0^2 r^2 - f_s(f_m R\omega_0^2 tg\alpha_R + g)r - gRtg\alpha_R = 0\,. \qquad (4)$$

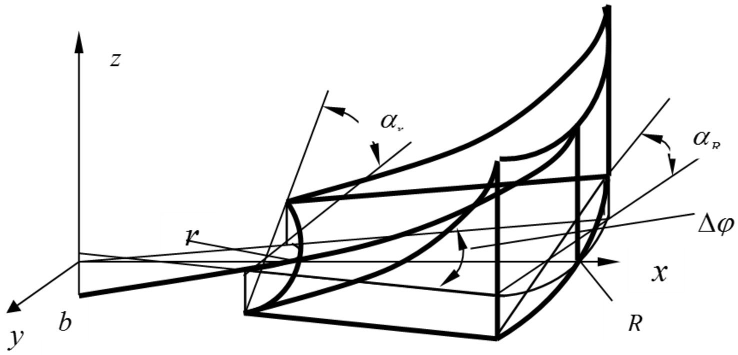

Fig. 2. The equilibrium of material volume engaging sector of a blade.

As the helix angle changes from the axis to periphery, in order to describe material flow moving it's necessary to substitute in relation (1):

$$N_s \sin\alpha_\rho = P_s S_v;\; N_s \cos\alpha_\rho = P_s S_h\,. \qquad (5)$$

Taking into account (5) the set of equations (1) yields:

$$\left.\begin{array}{l} P_s S_h - f_s P_s S_v - f_t P_t S_t \cos\beta - \gamma V = 0\,; \\ f_t P_t S_t \sin\beta - f_s P_s S_h - P_s S_v = 0\,; \\ -P_t S_t + \frac{\gamma}{g} V \rho_c \omega_0^2 \left(\frac{\sin\alpha_R \sin\beta}{\cos(\beta - \alpha_R)} \right)^2 = 0\,, \end{array}\right\} \qquad (6)$$

where P_s - pressure of the material volume engaging sector of the blade with the central angle $d\varphi$ on the screw blade, S_h - horizontal projection of the sector of the blade with the central angle, S_v - vertical projection of the sector of the blade with the central angle $d\varphi$,V - material volume engaging the sector of the blade $d\varphi$, ρ_c - the distance from the screw axis to the material volume element centre of mass, γ - bulk weight of the material.

Horizontal projection area of the sector of the blade $d\varphi$ between the limits r and R (Fig. 3)

$$S_h = \int_r^R x\Delta\phi dx = \frac{R^2 - r^2}{2}\Delta\phi \tag{7}$$

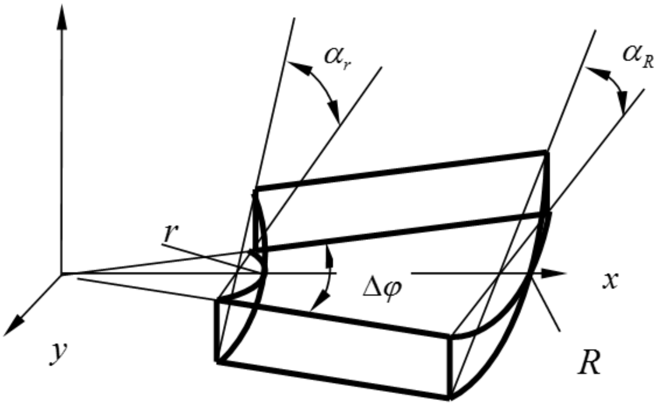

Fig. 3. The sector of the blade and its horizontal and vertical projections.

Vertical projection area of the sector of the blade $d\varphi$:

$$S_v = \int_r^R xtg\alpha_x \Delta\phi dx .$$

As $xtg\alpha_x = t = const$, so that

$$S_v = \int_r^R t\Delta\phi dx = t(R - r)\Delta\phi = R(R - r)tg\alpha_R \Delta\phi . \tag{8}$$

Material volume engaging the sector of the blade $d\varphi$ (Fig. 2) is equal to material volume which is a part of body of revolution formed by plane xOy , cylinder surface formed by rotation (around axis *z*) of vertical elements passing through points of plane xOy of plot $y^2 + x^2 = R^2$ and curve surface formed as plot $z = f(x)$ or $z = a(x^2 + y^2) + b$ rotates around axis z . The equation for the material volume can be determinated by relation (3).

$$V = \int\int_S f(\rho)d\rho d\theta = \int_0^{\Delta\phi} d\theta \int_r^R f(\rho)\rho d\rho = \left[(R^2 + r^2)a + 2b\right]\frac{R^2 - r^2}{4}\Delta\phi , \tag{9}$$

where $\rho = \sqrt{x^2 + y^2}$, $x = \rho\cos\theta$, $y = \rho\sin\theta$.

Coordinate for the centre of mass of material element, taking into account (9), can be determinated by relation:

$$\rho_c = \frac{\int\limits_V x dv}{V} = \frac{\int\limits_0^{\Delta\phi}\int\limits_r^R f(\rho)\rho^2 \cos\theta d\rho d\theta}{\int\limits_0^{\Delta\phi}\int\limits_r^R f(\rho)\rho d\rho d\theta} = \frac{\sin\Delta\phi \int\limits_r^R (a\rho^2 + b)\rho^2 d\rho}{\Delta\phi \int\limits_r^R (a\rho^2 + b)\rho d\rho},$$

where $\Delta\phi$ is infinitesimal so that $\frac{\sin\Delta\phi}{\Delta\phi} \approx 1$, so that after integrating.

$$\rho_c = \frac{\frac{a}{5}\left(R^5 - r^5\right) + \frac{b}{3}\left(R^3 - r^3\right)}{\frac{R^2 - r^2}{4}\left[a\left(R^2 + r^2\right) + 2b\right]}. \tag{10}$$

Introducing relations (7-10) in set of equations (6) yields the following relation for angle beta

$$\frac{f_t \rho_c \omega_0^2}{g}\left[\frac{\sin\alpha_R \sin\beta}{\cos(\beta - \alpha_R)}\right]^2 - \frac{f_s S_h + S_v}{(S_h - f_s S_v)\sin\beta - (S_v + f_s S_h)\cos\beta} = 0. \tag{11}$$

4. Summary

Establishment of laws of flow of material transported in the vertical screw conveyor is of practical importance because it allows the design of screw conveyors more reasonable to choose their design and operating parameters, creating the preconditions for the production of high-performance conveying machines.

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