Some design questions of vertical screw conveyors

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Summary

Vertical screw conveyors are hardly mentioned in the home technical literature They are very rarely applied in practice in spite of their many advantages. The probable reason of it that designing vertical screw conveyors requires much experience and theoretical knowledge. This presentation deals with the explanation and calculation of two important parameters of the design, namely the critical angular velocity and the conveying speed.

Introduction

The home literature deals with the vertical screw conveyors unduly little and they are rarely used materials conveying equipments in spite of their several advantages. Their application advantages are the economy, small space need horizontally and vertically, flexible unloading possibility (the chute can be connected at any height and angle to the housing wall circumference) as well as the light structure. A drawback can be mention that the operation of the equipment needs the presence of friction. Therefore it is not recommended for conveying highly abrasive materials.

This study deals with two important operation parameters of vertical screw conveyors: the critical angular velocity (rpm) and the convey rate including their determination. In the theoretical investigations the motion of a single grain is analysed. It can be made because different experiments proved that the application of particle model results in negligible inaccuracies and the results can be generalised. It is especially worth to mention that the theoretical research verified the phenomenon that after a short acceleration period a steady-state material flow is evolved in the screw conveyor.

The equilibrium equations of the vertical screw conveyor for steady-state motion can be derived from the differential equation describing the actions in an arbitrary alignment screw conveyor of δ angle to the horizontal [1] by substituting $\delta = \pi/2$:

(1/*a*) $$-g\sin\alpha - \mu_1 \frac{|\mathbf{B}|}{m} + \mu_2 \frac{|\mathbf{N}|}{m}\sin\beta = 0\,,$$

(1/*b*) $$\frac{|\mathbf{N}|}{m} = r\omega_0^2 - 2r\omega_0\dot{\varphi}_r + r\dot{\varphi}_r^2\,,$$

(1/*c*) $$\frac{|\mathbf{B}|}{m} = g\cos\alpha + \mu_2 \frac{|\mathbf{N}|}{m}\cos\beta\,,$$

(1/*d*) $$\sin\beta = \frac{\omega_0\cos^2\alpha - \dot{\varphi}_r}{\sqrt{\omega_0^2\cos^2\alpha - 2\omega_0\dot{\varphi}_r\cos^2\alpha + \dot{\varphi}_r^2}}\,,$$

(1/*e*) $$\cos\beta = \frac{\omega_0\cos\alpha\sin\alpha}{\sqrt{\omega_0^2\cos^2\alpha - 2\omega_0\dot{\varphi}_r\cos^2\alpha + \dot{\varphi}_r^2}}\,,$$

where

- r convolution radius,
- m mass,
- β angle between the vector of absolute velocity and the binormal vector,

$\dot{\varphi}_r$ angular velocity of relative motion,
μ_1 friction coefficient between the mass point and the convolution surface,
μ_2 friction coefficient between the mass point and the housing,
B constraint force on the spiral curve,
N constraint force on the housing wall,
ω_0 angular velocity of the screw conveyor axis,
g specific gravity.

It is noteworthy that the above system of equations is only formally different form those results published in papers [2], [3], [4], about conveying screw conveyors theory. In addition equations (1/*c*) and (1/*e*) are alternates rather than independent expressions.

Notations can be understood from the *Fig. 1*, where the line in angle α is the image of the evolved α angle helix in plane. In the figure $\mathbf{v}_k$ is the circumferential velocity ($|\mathbf{v}_k| = r\omega_0$) of the helix and $\dot{s}$ is the speed of the mass point relative to the helix ($\dot{s} = r\dot{\varphi}_r / \cos\alpha$), v is the absolute velocity of the mass point. $\mathbf{S}_1$, and $\mathbf{S}_2$ are the friction forces on the convolution surface and on the housing wall. **t** and **b** vectors are unit vectors of trihedral coordinate system of surface.

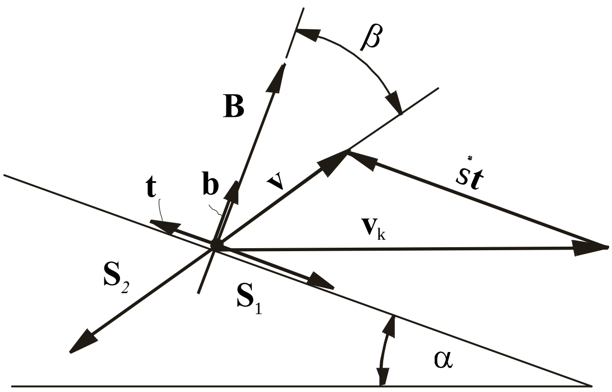

Fig 1. Velocity components of a mass point and the system of forces while the mass point is moving on the convolution surface

Critical value of angular velocity

The conditions of the relative motion occurrence are fundamental question of design. For the investigation the initial values $\dot{\varphi}_r(0) = 0$, $\mathbf{v}=\mathbf{v}_k$ and $\beta = \pi/2 - \alpha$ belonging to the start time (t=0) are substituted into equation system (1). Then $\sin\beta = \cos\alpha$ and $\cos\beta = \sin\alpha$ hold. Therefore the equilibrium equations – after substitution – are

$$-g\sin\alpha - \mu_1 \frac{|\mathbf{B}|}{m} + \mu_2 \frac{|\mathbf{N}|}{m}\cos\alpha = 0 ,$$

$$\frac{|\mathbf{N}|}{m} = r\omega_0^2 ,$$

$$\frac{|\mathbf{B}|}{m} = g\cos\alpha + \mu_2 \frac{|\mathbf{N}|}{m}\sin\alpha .$$

It can be concluded from the first row that the mass point moves in the direction **t** only if value of the positive sign term which is proportional to the square of angular velocity ω_0 is higher than the sum of the absolute value of negative sign terms.

After arranging and substituting one obtains:

$$-\frac{\sin\alpha + \mu_1 \cos\alpha}{\cos\alpha - \mu_1 \sin\alpha} + \frac{\mu_2 r \omega_0^2}{g} = 0,$$

and utilising the $\mu_1 = \mathrm{tg}\rho$ identity results in

(2) $$\omega_0 \geq \omega_{0\,krit} = \sqrt{\frac{g}{\mu_2 r}\mathrm{tg}(\alpha + \rho)}\,.$$

Hence the critical angular velocity of screw conveyor axis can be computed if the geometry and friction coefficient data are available. Determination of the critical value is essentially important for the construction and design practice because it produces the minimal angular velocity below which value the conditions for the relative motion do not exist and the screw conveying is impossible. Consequently the initial data of ω_0 must be higher than the critical value. (It is mentioned that the developed formula expresses the same as the well known critical revolution speed relationship in the literature.)

Conveying capacity of vertical screw conveyor

For the determination of the capacity it is assumed that the material flows in concentric layer along helixes which have the same coil pitch and different radii. Utilisation of this means that one can determine the velocity of all grains if the magnitude and the direction of the velocity of a single particle is known. Moreover, since the axial displacement of the layers are the same in accordance with the assumption all the particles moves with the same speed axially (i.e. in direction z). In short, it is enough to determine the v_z velocity of a single particle to compute the z directional conveying capacity.

The conveying capacity:

(3) $$Q = 3{,}6 A v_z \rho_h \phi \qquad [\mathrm{t/h}],$$

where

- A conveying cross section [m^2],
- v_z conveying velocity of material in the axial diretion of screw conveyor (m/s],
- ρ_h bulk mass density of conveyed material [kg/m^3],
- ϕ loading (filling) coefficient.

The cross section of screw conveyor housing is $A = D^2\pi/4$, where D is the nominal diameter of the screw conveyor.

A csigaváIyúban keresztmetszete: $A = D^2\pi/4$, ahol D a szállítócsiga névleges átmérője.

The conveying velocity

One can recognize in Fig. 1 that the axis of screw conveyor is perpendicular to the base of slope of angle α, so that the conveying velocity(v_z) is the vertical component of absolute velocity (**v**) which makes β angle to the binormal vector. As a result of the horizontal velocity component the path of the material is a helix of $\pi/2-(\alpha+\beta)$ coil pitch [1], [3].

The conveying velocity which decisively influences the conveying rate is interpreted as the axial component (v_z) of the absolute velocity (**v**). This is

(4) $$v_z = \dot{s}\sin\alpha = \frac{r}{\cos\alpha}\dot{\varphi}_r \sin\alpha = r\dot{\varphi}_r \mathrm{tg}\alpha\,,\ \text{vagy}$$

(5) $$v_z = \dot{s}\sin\alpha = r\omega_0 \frac{\cos(\alpha+\beta)}{\cos\beta}\sin\alpha \,.$$

According to the expressions (4) and (5) the determination of conveying velocity needs the knowledge of relative motion angular velocity ($\dot{\varphi}_r$) or the β conveying angle which characterise the direction of absolute velocity (**v**). They are computed from the algebraic equation system (1) by using a numerical procedure. On the basis of (1), (4) and (5) $v_z = v_z(\alpha, \mu_1, \mu_2, \omega_0)$, thus the conveying velocity is function of coil pitch angle, the friction coefficients and the angular velocity of screw conveyor. Due to the sophisticated implicite relationships, the computations need computer implementation.

The application software developed in our institution was elaborated primarily in order to compute conveying velocity. The program uses the revolution speed (n), nominal diameter (D), friction coefficients (μ_1, μ_2) and the s/D rate as input data from which the conveying angle (β) the angular velocity of relative motion ($\dot{\varphi}_r$) and the conveying velocity (v_z) are computed. In addition the software is applicable to make different analyses and to construct diagrams that assist the design.

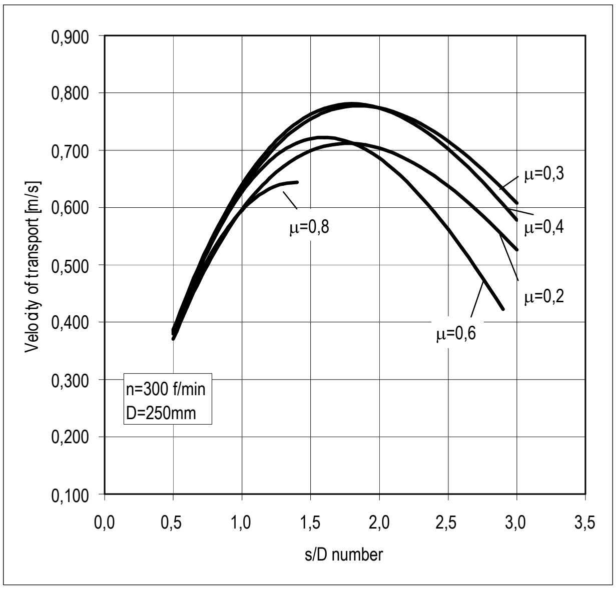

Figure 2. The conveying speed as function of s/D rate at different friction coefficients

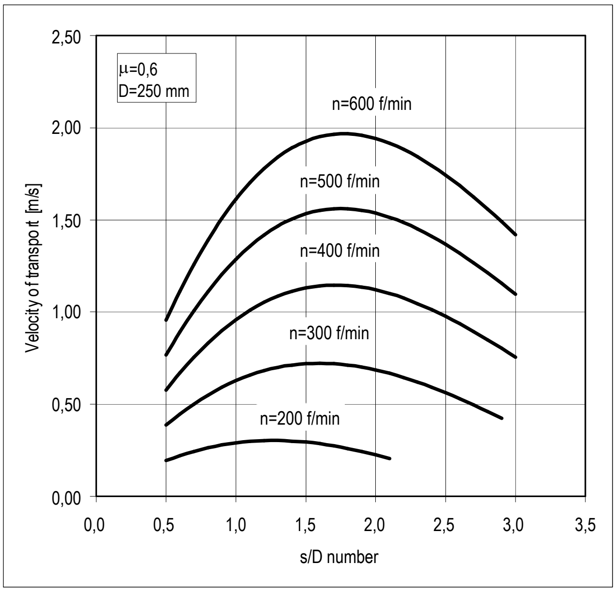

Figure 3. The conveying speed as function of s/D rate at different revolution per minute values

As example *Figs 2* and *3* are shown, where the conveying velocity curves are depicted as functions of s/D rate. In *Fig. 2* the effect of friction coefficient can be analysed. The place of maximum of curves can be considered as optimal s/D rates, since the highest conveying velocities and rates belong to them which can be reached in the given conditions. The curves in Fig. 3 exhibit velocity functions for fixed friction coefficient (μ=0,6) and different revolution per minute values. Obviously, the character of curves is the same as those previously (*Fig. 2*) and as it was expected, the curves move upward with increasing revolution speed i.e. there are higher conveying velocities at higher rpm values.

The design cannot change usually the friction coefficient, therefore the selection of the coil pitch angle and the proportional (coil pitch/diameter) rate, the angular velocity and the proportional revolution speed may result in the desired conveying velocity and the conveying rate. The diagrams similar to *Fig. 2* and *3* can support this difficult course of decision-making.

It is noteworthy, that the results do not give a good account of the current design practice. It is well known that the design engineers choose the s/D rate around 1, which corresponds near computed optimum values at quite low rotation speed values (100... 200 rpm).

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