THE PROCESS OF GRAIN RELOCATION WITH SCREW CONVEYORS

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Summary. Simple construction and reliability of screw conveyors have resulted in their general application in diferent agricultural machines. Although they are widely used as means of transport (relocation), there is scarce literature concerning an influence of the main exploitation parameters on their efficiency, energy consumption or number of damages to the relocated grain. In the presented work an attempt was made at a synthesis of versatile theoretical research as well as its exemplification in agricultural machines. An interesting part of the paper are results and analysis of grain relocation using video-computer technology concerning the mechanism of grain damaging. The paper ends with conclusions and proposals as to principles of exploitation of the above-mentioned conveyors during grain relocation.

Key words: screw conveyors, efficiency, energy consumption, grain damage

INTRODUCTION

Due to simple construction and high reliability of screw conveyors, they are commonly applied in various agricultural machines. Despite their broad application, there is scarce literature concerning an influence of their main exploitation and construction factors on the efficiency, energy consumption and damage of relocated grain during the relocation process.

Considering the above-mentioned fact, this paper attempts at a synthesis of the accessible research on these facilities, explaining the reciprocal relationships among the mentioned factors and geometrical and kinematical parameters of the screw conveyor.

EFFICIENCY OF SCREW CONVEYORS

A range of different research methods have been used to determine the efficiency of screw conveyors [Römer and Urban 1955, Antoniak 1964, Fafara 1967, Brusewitz and

Persson 1969, Janczin 1969, Borisow 1972, Głozman and Baitalski 1978, Klimowski 1978, Smereczyński et al. 1978, Dreszer 1981, 1984,].

Apart from technical possibilities of the researchers or properties of the tested materials (grain, straw, dough-like masses etc), the main aim has always been to find the relationships between a conveyor's efficiency and the greatest possible number of factors (properties) affecting it. Thus, a whole range of different research methods and approaches were created. They resulted in dependencies (formulas) containing in their construction (contents) a number of either experimentally or theoretically determined coefficients limiting the results comparability [Antoniak 1964, Gożdziecki and Świątkiewicz 1975, Dmitrewski 1978].

In practice, it was accepted that the approximate efficiency of screw conveyors should be determined using the half-empirical formula

$$Q = S \cdot n \cdot s \cdot \rho \cdot \psi \cdot k \tag{1}$$

where:

Q – mass efficiency (mass stream), kg · s⁻¹, $S = \frac{\Pi(D^2 - d^2)}{4}$ – horizontal projection of screw coil, m², *s* – screw coil lift, m,

D -screw coil diameter, m,

d – diameter of screw coil shaft,

a = utalleter of screw coll shart,

k – coefficient considering conveyor's inclination angle,

n-rotational speed, rot $\cdot s^{-1}$,

p – slide density of grain kg \cdot m⁻³,

 ψ - coefficient of conveyor's filling.

A precise determination of mathematical dependencies among the factors mentioned in formula (1) and the conveyor's efficiency Q requires a particular theoretical analysis and experimental tests. Such studies were conducted, among others, by [Römer and Urban 1955, Brusevitz' and Peterson 1969, Ignatov 1969; Borisov 1972, Tedder *et al*.1974, Klimowski 1978, Smereczyński 1978;].



Fig. 1. An analysis of the work of a screw coil acc. to Kanafojski [1963], Fąfara [1967]:a) speed distribution on a screw coil, b) elementary volume of material relocated in a unit of time,c) development of screw line

An analysis of work and determination of theoretical efficiency of a screw conveyor were presented by Kanafojski and Smreczyński [1978] accepting initially that static friction μ_s of mass element *m* is equal to 0, then the speed vector v_n perpendicular to the surface of screw coil is diverted by angle α in relation to the main axle of screw coil *z* as in (Fig. 1).

Peripheral speed of the considered material point *m* will be equal to $v_o \cdot cos \alpha$

Considering kinetic friction μ_k , causing diversion of the vector's v_n direction by the friction angle φ , we obtain axial component *v* of relocation speed equal to:

$$V_{\varphi} = v_{o} \cdot \frac{\cos \alpha}{\cos \varphi} = s \cdot n \cdot \frac{\cos \alpha}{\cos \varphi}$$
(2)

thus

$$v = v_{\alpha} \cdot \cos(\alpha + \varphi) = s \cdot n \cdot (\cos^2 \alpha - \mu \sin \alpha \cos \alpha)$$
(3)

Elementary volume efficiency dV, determined as product of moving elementary surface dS and sped v (Fig. 1b) will be equal to

$$dV = v \cdot dS \tag{4}$$

knowing that

$$dS = r \cdot d\Theta \cdot dr;$$
 $\sin \alpha = \frac{C}{\sqrt{C^2 + r^2}};$ $\cos \alpha = \frac{r}{\sqrt{C^2 + r^2}}$

And introducing the above data to equation (4) we will obtain:

$$dV = S \cdot n \cdot (\cos^2 \alpha - \mu \sin \alpha \cos \alpha) \cdot r \cdot d\Theta \cdot dr = S \cdot n \cdot \frac{r^3 - \mu \cdot C \cdot r^2}{C^2 + r^2} \cdot dr \cdot d\Theta$$
(5)

By carrying out the necessary conversions of the expression (5) and taking into consideration the grain density p Smreczyński [1978] managed to formulate the final formula of the mass efficiency of a screw conveyor:

$$Q = \Pi \cdot S \cdot n \cdot \rho \left\{ R^2 - r^2 - C^2 \cdot \ln \frac{C^2 + R^2}{C^2 + r^2} - 2\mu \cdot C \cdot \left[R - r - C \cdot \operatorname{arc} \operatorname{tg} \frac{C(R - r)}{C^2 - Rr} \right] \right\}$$
(6)

where:

symbols and denotations in expressions (1–6) as in (Fig. 1).

From dependency (6) it results that a screw conveyor's efficiency is influenced by friction μ and the lower the coefficient μ_k is of kinematical friction between grain and screw coil surface, the higher the efficiency. It must be remembered, however, that both the friction between screw coil and grain and the internal one among grain itself are impeding (destructive) factors. Nevertheless friction is indispensable for ensuring the process of relocation between the conveyor and screw coil wall.

This is the hypothesis put forward by Tedder [1974] and other authors [Dreszer 1981, Rademacher 1981].

Tedder [1974], assuming mass (grain) distribution as in (Fig.2), made the efficiency of vertical screw conveyor dependent on angular velocity of mass relatively to wall ω_{l2} and screw coil ω_{23} as well as on adhesive friction among grain mass, screw coil and wall.



Fig. 2. A model of vertical screw conveyor acc. to Tedder [1974]: 1 – wall, 2 – grain mass, 3 – screw coil, the remaining symbols as in the figure.

The values of the above–mentioned parameters are determined by the dependencies $(7\div10)$.

$$\omega_{31} = \omega_{21} + \omega_{23} \tag{7}$$

$$dM_i = \mu_i \cdot \Delta p_i \cdot r_i \cdot dS \tag{8}$$

$$\sum N_i = \sum M_i \cdot \omega_i = 0 \tag{9}$$

$$N = V \cdot \gamma \cdot S = G \cdot S \cdot \omega_{31} \tag{10}$$

where:

 dM_i – elementary moment, N · m,

- Δp_i pressure on working elements (screw coil and wall), Pa = N · m⁻²,
- g = 9,81 gravitational acceleration, m \cdot s⁻²,

G – weight, N,

 M_i – friction force moment, N · m,

- N_{i-} power from moment M_i , W = N· m · s⁻¹,
- $\gamma = \rho \cdot g$ specific gravity of grain mass, N· m⁻³,
- V-volume stream (volumetric efficiency), m³·s⁻¹,
- ω_{l2} relative angular velocity of grain in relation to wall, rad $\cdot s^{-1}$,
- ω_{23} relative angular velocity of grain in relation to screw coil, rad $\cdot s^{-1}$,
- ω_{31} relative angular velocity of grain of screw coil in relation to wall, rad \cdot s⁻¹.

Making necessary mathematical transformations and substituting real values Tedder [1974] determined the dependency defining the volumetric efficiency of a vertical screw conveyor:

$$V = \frac{R^4 \cdot \omega_{23} \cdot \omega_{12}^2 \cdot \cos\alpha}{8g} \tag{11}$$

Exploitation tests showed that the above–mentioned theoretical considerations are valid for a certain, not very big, interval of angular velocities $\omega_{l3} < 20$, rad $\cdot s^{-1}$. For higher angular velocities the results of efficiency calculations are loaded with significant error [Dreszer 1981].

Borisow [1972] accepting a number of conditions and assumptions as [Kanafojski 1963, Fafara 1967] expressed the efficiency of a screw conveyor as the function of its geometrical parameters and the natural slide angle of relocated grain δ , and the coefficient of its filling ψ (Fig. 3).



Fig. 3. An analytical model of a vertical screw conveyor acc. to Borisov [1972]: a) theoretical distribution of material, b) scheme of a screw coil's uncoil and distribution of grain relocation velocity

This researcher, unlike the above–mentioned ones, did not take into account an influence of friction on the relocation process, and expressed the screw conveyor's efficiency as:

$$Q = n \cdot \rho \cdot s \cdot h \cdot \cos^2(\alpha + \delta)$$
⁽¹²⁾

An original approach to the problem as well as an analysis of the work of a horizontal screw conveyor was presented by [Persons *et al.* 1969]. The authors assumed that grain mass behaves as a liquid whose flow (relocation, motion) results from forces caused by pressure, mass and inertia of grain. Dynamic viscosity also plays an important part here. According to the Navier-Stokes equation the value of the force resulting from an influence of dynamic viscosity is equal to:

$$F = 3 \cdot \Pi \cdot \eta \cdot dz \cdot v \tag{13}$$

where:

dz – mean grain relocation, m,

 η – coefficient of dynamic viscosity, Pa · s = N · m⁻² · s ,

F-force, N.

Using a digital computer, by solving a number of complicated motion equations, Persons *et al.* [1969] formulated a dependency describing the mass stream (mass efficiency) for a horizontal screw conveyor:

$$Q = \Pi \cdot \Delta p \cdot (R^{4} - r^{4}) \otimes \eta \cdot l - \frac{\Pi \Delta p \cdot (R^{2} - r^{2}) \cdot R^{2} \cdot l \cdot \lambda \cdot R - r^{2} \cdot l \cdot \lambda \cdot r}{4\eta \cdot l \cdot (l \cdot \lambda \cdot r - l \cdot \lambda \cdot R)} + \frac{\Pi \cdot \Delta p \cdot (R^{2} - r^{2})^{2}}{8\eta \cdot l \cdot (l \cdot \lambda \cdot r - l \cdot \lambda \cdot R)} - \frac{\Pi \cdot \Delta p \cdot (R^{2} - r^{2}) \cdot (r^{2} \cdot l \cdot \lambda \cdot R - R^{2} \cdot l \cdot \lambda \cdot r)}{4 \cdot \eta \cdot l \cdot (l \cdot \lambda \cdot r - l \cdot \lambda \cdot R)} + \frac{\omega_{31} \cdot \Delta p \cdot (r_{k}^{2} - r^{2})}{4}$$
(14)

where:

 λ – coefficient of dynamic viscosity, m²· s⁻¹,

 r_k – limiting radius of grain's self–sliding, m,

l – length of conveyor (relocation path), m.

By analysing the above–mentioned considerations, it is possible to declare that the efficiency of screw conveyors, apart from the parameters accounted for in the dependencies $(1\div14)$, is also influenced by a conveyor's inclination angle, the ratio of a screw coil's diameter to its stroke, clearance between its wall and coil as well as the properties of relocated grain. It is difficult, or even impossible, to express all the above–considered factors in an analytical form. Such attempts were made by [Persons *et al.* 1969, Rademacher 1981], and they resulted in unserviceable, complicated dependencies, rendering calculations loaded with significant error.

MECHANICAL DAMAGE OF GRAIN OCCURRING DURING THE PROCESS OF RELOCATION WITH SCREW CONVEYORS

Application of basically simple and reliable screw conveyors gives rise to considerable doubt in case of materials which should not be damaged or broken-up during relocation. Quasi-static and dynamic loads helping in relocation cause both micro- and macrodamages in grain, lowering its biological and trade value.

The main causes of the above-mentioned damages during grain relocation with the considered conveyors are:

- cutting of grains by wall and screw coil edges in the inlet hole,
- grain damage caused by internal and external friction (with working elements,
- destruction of grains by their crushing between the edges of a screw coil and the conveyor's wall.

Apart from the way of a conveyor's supply (parallel, submersion), there is an adverse pattern of geometrical edge of a conveyor's wall and coil in the inlet hole leading to the working passage (Fig. 4)



Fig. 4. Scheme of work of a screw coil at the inlet to the working passage acc. to Rademacher [1981]: a) the commonly used pattern, b) pattern with an insert eliminating cuting forces, 1 – screw coil, 2 – wall edge, 3 – grain, 4 – insert

Such a location of the working elements edges during the work of a screw conveyor acts like scissors (Fig. 4a) damaging the grain. This adverse pattern of edges can be prevented by an attachement to a screw coil of a properly adjusted insert (4, Fig. 4b), which will replace the angle α by two obtuse ones $\alpha' = \alpha'' = \frac{(\Pi + \alpha)}{2}$.

Another very important factor affecting the number of damages in the relocated grain is the clearance between wall (2) and screw coil (Fig. 5)



Fig. 5. Grain location in the space between screw coil and the wall of screw conveyor: 1 – screw coil, 2 – wall of conveyor, 3 – grain

According to Rademacher the optimum clearance size betwen wall (2) and screw coil (1) can be determined from the dependency:

$$\frac{L}{dz} = \frac{\sqrt{1 - \mu_k^2} - 2\Delta\mu_k^2\sqrt{1 + \varepsilon^2 \mu_k^2}}{(1 - \mu_k^2)\sqrt{1 + \varepsilon^2 \mu_k^2}}$$
(15)

where:

$$\varepsilon = \frac{a}{b}$$
 and $\Delta = \frac{\xi}{dz}$,

a - the longer ellipsoid axis, m,

b – the shorter ellipsoid axis, m,

 ξ – radius of the screw coil edge's rounding, m.

From the practical point of view, using the dependency (15) at the stages of design and construction of screw conveyors for grain relocation seems rather unlikely. These doubts are well justified both economically and technologically.

Apart from special facilities, in which it is necessary to apply precisely constructed, well-cooperating working elements, screw conveyors in agricultural machines and facilities (e.g. cereal combines) are meant for relocation of various kinds of grain with different mechanical properties and varied geometrical shape. Own studies showed that the clearance value depends on the external diameter of a screw conveyor and stays in the range $5\div10\%$. While choosing the clearance the following should be remembered: the greater the diameter of a screw coil, the smaller should be the admissible clearance. The fulfilment of the above condition is a guarantee that grain relocation will occur mainly as a result of internal friction, which will reduce stresses in the mass and will allow to keep the number of mechanical damages of the grain at the minimum level.

ENERGY CONSUMPTION DURING RELOCATION WITH SCREW CONVEYORS

Power intake needed to perform useful work and overcome movement resistances depends on: efficiency, construction parameters, physical-mechanical properties of the material etc.

Taking into consideration the above-mentioned factors [Kanafojski *et al.* 1963, Antoniak 1964, Goździecki and Świątkiewicz 1975, Dmitrewski 1978] presented the dependency to determine input of power to a screw conveyor in the following shape:

$$N = Q_{rr} \cdot g \cdot (l \cdot \aleph + H) \tag{16}$$

where:

Q – efficiency of carrier, kg \cdot s⁻¹,

g – gravitational acceleration, m \cdot s⁻²,

l-length of carrier, m,

H – height of material serving, m,

 \aleph – resistances coefficient dependent on the kind of material.

Analysing distribution of forces and geometry of screw coil in a vertical screw conveyor it is possible to state that the most favourable relocation conditions take place when the angle between the resultant reaction F_R and the axle z is 180°, then $\cos(F_R, z) = -1$ (Fig. 6).

In practice the value $\cos (F_R, z)$ is always different than -1, so the constuctors need to reduce this difference to an unavoidable minimum. This can be done by correct shaping of a screw coil (the generating line of the coil – perpendicularly to the axle z; possibly small C – cf Fig. 1; significant values of the parameter generating the screw surface).



Fig. 6. Distribution of forces in a vertical screw conveyor acc. to Virling and Sinha [1960], Dmitrewski [1978]

Apart from the above-mentioned theoretical considerations, the problem of energy consumption by screw conveyors is the subject of numerous experimental works [Virling and Sinha 1960, Brusewitz and Persson 1969, Tedder 1974, Dreszer 1981, Rademacher 1981].

Beside the aspect verifying the particular theoretical concepts, the research proves that energy consumption during relocation with screw conveyors is also influenced by such parameters as: ratio of diameter to screw coil lift, clearance, inclination angle of the conveyor as well as the properties of the relocated grain, especially its moisture and friction coeficients. Changeability ranges of the above-mentioned parameters, favourably influencing the energy consumption during relocation are mentioned in the reference works.

CONCLUSION

The performed analysis of studies as well as the authors' own research allowed to determine the main factors and parameters influencing the efficiency, energy consumption and quality of grain transport – expressed by a number of damages to it. Considering the fact that screw conveyors for a long time have served as one of the main means of internal grain transport it seems expedient to carry on the research aiming at an improvement of their construction. In view of the accesibility of modern production materials and technologies, the proposed modernization of these facilities can bring substantial benefits such as design of a modern conveyor characterized by high efficiency, low energy consumption and small number of damages to the relocated grain.

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