High-Speed Efficient and Compact Screw Grain Conveyors in Agriculture

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Abstract. Improving the efficiency as well as reliability of reaping threshers results in the enhanced efficiency of cereal harvesting. To make the agroindustrial complex as a whole and agriculture, in particular, more efficient, new advanced technologies are necessary. These technologies are based upon the members of modern machines for soil preparation, seeding, crop tending and all harvesting machinery. However, the implementation of their design program is virtually stagnating due to the lack of funding which restricts the forming and development of market and production relations in the agroindustrial complex in their civilized forms on the basis of the advanced technology and new technique. The article provides the research on the way to improve the efficiency of the screw-type conveyor; this allows building a compact design by means of increasing the number of conveyor rotations. The authors describe a technology of operation of grain conveyors and study their operation mechanism and point to their operation deficiencies consisting, in particular, in the lacking opportunities to transfer grain for long distances along the spatial road or complicates a process flow sheet. In addition, operation at loading directly from the heap requires manual labor or additional equipment.

1. Introduction
The most reasonable way to increase the efficiency of a screw-type conveyor and thus designing a compact structure is to increase the number of its rotations [1]. The screw efficiency also depends on the uniformity of grain feed. When hopper or similar feeders are used, bulk material is delivered to the conveyor through the hole on the top of the intake chamber, and its part is scattered by an ascending screw branch. That is why the material passes to the screw in portions; the quantity of such portions depends on the rotations, screw horizontal tilt and the material internal friction coefficient. However, all these structures do not provide for the opportunity of grain transportation for large distances along the spatial road or complicate the process flow diagram [2]. Most spiral conveyors do not stipulate for the change in the distance and the trajectory of material motion. In addition, the operation at loading directly from the heap requires manual labor or additional equipment. When grain is taken from the bank with the increase of spiral rotation frequency, it is scattered while the axial displacement
resistance is induced inside the casing [3]. As a result of excessive material mixture and grain rotation inside the spring-actuated screw the limit of the efficiency increase at the existing transportation principle.

2. Research purpose
For the purpose of the provision of agriculture sustainable development, reliable provision of the country’s population it is very important to strengthen the material and technical base of the agroindustrial complex (AIC) and to conduct its targeted technical re-equipment. In this connection the article purpose is to provide the research on the cost-effective way to improve the efficiency of the screw-type conveyor for building a compact design by means of increasing the number of conveyor rotations.

3. Research method
The efficiency enhancement with the increase of screw rotations (from 400 up to 1,100 rpm) occurs until some specific moment after which the rotations continue increasing while the efficiency drops (Figure 1). Depending on the screw $D$ diameter the efficiency maximum is displaced. At the horizontal tilt $20^\circ$ and grain humidity 14-15% it can be observed: the screw having the diameter $D = 100$ mm at $900$-$950$ rpm, $D = 125$ mm – $800$-$850$ rpm, $D = 150$ mm – $700$-$725$ rpm.

Using experimental data, make up a parametric equation of the grain motion trajectory:

$$
\begin{align*}
    x &= R \cos \theta, \\
    y &= R \sin \theta, \\
    z &= \frac{S_s}{2\pi} \left( \theta + \frac{\pi}{6} \sin \theta \right),
\end{align*}
$$

where $R$ – average radius of the screw circular projection on the plane $XOY$; $S_s$ – grain screw pitch; $\theta = \omega_z t$ – rotation angle; $\omega_z$ – grain angular velocity; $t$ – rotation time. The equation $\frac{\pi}{6} \sin \theta$ is defined from the conditions: at $z = 0$ $y = 0$, at $z = \frac{S_s}{3}$ $y = R$.

If the requirements are met, the projections of grain motion trajectory on the plane $ZOY$ and $ZOX$ will be asymmetrical and periodical on $z$ (the period equal to $S_s$). The trajectory projection on the plane $XOY$ will have the form of a circumference with the radius $R$. According to the trajectory projection on the plane $ZOY$, and just like in the experiments, it follows that the angular velocities of the ascending and descending arms of the grain screw are different: its velocity at the ascending $\omega_z$ is lower than the one at dropping. In addition, it is not constant and changes from minimum to maximum [4].

At the operation of high-rotation screw the grain axial velocity $v_z$ is behind the screw axial velocity $v_z$. This lagging can be expressed by the coefficient $k_v$ which should be taken into account at the calculation of the efficiency of high-rotation conveyor [5]:

$$
    k_v = \frac{v_z}{v_z}, \quad v_z = k_v \frac{S_n}{60}.
$$

where $S$ and $n$ – screw pitch and the number of rotations. The coefficient $k_v$ can be also obtained through grain angular velocities $\omega_{sep}$ and those of the screw $\omega$:

$$
    k_v = \frac{\omega_{sep}}{\omega}.
$$

The value $k_v$, obtained experimentally for the horizontal screw and grain with the humidity 14-15% ($f = 0.35$-$0.40$) is equal to $0.57$-$0.60$. 

4. Main part
To improve the screw cycle efficiency, it is necessary to expedite the material axial motion, i.e., to stretch the ascending and, particularly, the descending arm of the material trajectory. The efficiency of the 125 mm screw (at the horizontal tilt 50° on the wheat with the humidity 12-13%) with a standard tube equaled 12.6 t/h, with a slotted tube - 14 t/h.

At high rotations of the screw the delivered material forms a screw surface, the ascending \(AB\) and descending \(BC\) the arms of which (Fig.1) have various tilt angles to the screw axis \(Z\) (\(\delta = 57-60°, \ \gamma = 38-40°\)). The ascending arm needs one rotation of a high-speed screw to push the material along the axis by 2/3 of the pitch of the screw \(S_a\) while the descending arm needs one rotation to push it by 1/3 of the pitch. The first arm tends to toss the material up and forward, the second - steeply down under the screw.

![Figure 1](image_url)

**Figure 1.** Change in the efficiency of a high-speed screw depending on the screw rotation and diameter.

It is explained by the fact that at a high speed bulk material (grain) thrown by the centrifugal force to the inside tube surface fills the slots [6]. As they are located quite close to each other (every 30°), a stopping layer forms at the surface under the action of which the circumferential component of the absolute grain motion speed decreases, and the axial one increases [7].

Analyze the grain intake into the screw depending in the screw rotations. Taking some assumption, accept that the condition, under which the largest amount of the material will get into the intake chamber, is expressed [8]:

\[
u_{окр} \leq v_{ист},
\]

where \(\nu_{окр}\) – circumferential speed of the screw edge; \(v_{ист}\) – speed of the grain discharge from the hopper. Providing this, the top screw arm will scatter less grain, and it will pass to the screw mostly by means of the dropping arm [9].

Define the screw rotations corresponding to the optimal conditions of material intake to the conveyor.

Write the expression for speeds:
\[
v_{\text{act}} = \sqrt{\frac{gR_r}{f}}, \text{ m/s},
\]
\[
v_{\text{exp}} = \frac{\pi R_b n}{30}, \text{ m/s},
\]

where \( R_r \) – hydraulic radius of the discharge hole, m; \( f \) – material internal friction coefficient; \( R_b \) – screw thread radius, m.

Equate the right parts of these equations and solve the obtained expression relatively to the number of screw rotations:

\[
n = n_{\text{opt}} = \frac{30}{\pi R_b} \sqrt{\frac{gR_r}{f}}. \tag{2}
\]

Express the condition (1) via the speed ratio:

\[
\frac{v_{\text{act}}}{v_{\text{exp}}} = \varepsilon = \frac{30}{\pi R_b n} \sqrt{\frac{gR_r}{f}} \tag{3}
\]

and name \( \varepsilon \) – coefficient of the ingress probability. Its values, calculated at various screw rotations \( n \) and \( R_r = 0.17 \text{ m}, f = 0.5 \text{ (grain)}, R_b = 0.62 \text{ m}, v_{\text{act}} = 1.8 \text{ m/sec}, \) are provided in Table 1.

**Table 1. Coefficient of the ingress probability.**

| Indicators      | Screw rotations per minute |
|-----------------|---------------------------|
|                 | 300 | 500 | 700 | 900 | 1,100 | 1,300 | 1,500 | 3,000 |
| Screw circumferential speed \( v_{\text{exp}} \), m/sec | 1.8 | 3.14 | 4.4 | 5.6 | 7.0 | 8.2 | 9.5 | 19.0 |
| Ingress coefficient \( \varepsilon \) | 0.94 | 0.57 | 0.41 | 0.32 | 0.26 | 0.22 | 0.19 | 0.09 |
| Charging coefficient \( \psi \) | 0.9 | 0.75 | 0.65 | 0.45 | 0.4 | 0.3 | 0.2 | -- |

It is seen from the Table that the value \( \varepsilon \) decreases with the the increase in the number of rotations. Under this condition the screw grain charging coefficient also decreases which causes the efficiency drop.

Express the efficiency coefficient \( \rho \) as follows:

\[
\rho = k_v \psi.
\]

The value \( \rho \) can be increased making the screw thread with a variable pitch [10]. In this case a screw part located in the intake chamber should have a lesser pitch as compared with the main one (it was double times less in the experiments the authors conducted).

The existing form used to calculate the screw efficiency has a form:

\[
Q = 60 \frac{\pi D^2}{4} Sn \psi \gamma c, \text{ t/h}, \tag{4}
\]

where \( \gamma \) – material volumetric weight, t/m\(^3\); \( c \) – coefficient taking into account the screw tilt.
It is known that the formula (4) do not reflect the nature of change in the efficiency of the screw conveyor during the operation at high (more than 300-400 rpm) speed and thus should be corrected [10]. With the account of the research conducted, the high-speed screw efficiency can be defined as follows:

$$Q = 47.1 \times D^2 S n k_w \psi y c, \ t/h. \quad (5)$$

Using experimental data, express the charging coefficient $\psi$ via $n$:

$$\psi = 1 - A \times \frac{n}{1000},$$

where $A$ – proportionality factor.

For the screw $D = 100$ mm $A = 0.40$, $D = 125$ mm $A = 0.50$ and $D = 150$ mm $A = 0.58$.

Substitute the mean value $k_w = 0.6$ and the value $\psi$, expressed through $n$ to the formula (5):

$$Q = 28.2 \times D^2 S n \left(1 - A \times \frac{n}{1000}\right) y c. \quad (6)$$

5. Conclusion

For the purpose of the provision of agriculture sustainable development, reliable provision of the country’s population it is very important to strengthen the material and technical base of the agroindustrial complex (AIC) and to conduct its targeted technical re-equipment. A reasonable way to increase the efficiency of a screw-type conveyor and thus designing a compact structure is to increase the number of its rotations. To improve the screw cycle efficiency, it is necessary to expedite the material axial motion, i.e., to stretch the ascending and, particularly, the descending arm of the material trajectory. Therefore, further research will provide for new ways of increasing the speed coefficient $k_w$ and the coefficient $\psi$ thus facilitating the design of high-speed and compact screw grain conveyors.

6. References

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