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Grain movement between the cylinders of a semi-automatic rotary dryer during heating

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Abstract. The drying efficiency depends on many factors, in particular, on the movement of grain in the space between the outer cylinder and the inner cylinder during its heating and drying. During these periods, the grain layer in the space between the outer cylinder and the inner cylinder was divided into three sublayers: A, B, C. In sublayer A and sublayer B, not only convective heating of the grain will be carried out, but also heat transfer by the grain during its heating. In sublayer B, only convective heating of the grain is carried out, almost no heat transfer is carried out by the grain. Therefore, the presence of sublayer B is undesirable, or its thickness should be minimal. The only possible way to reduce the thickness of the sublayer B is to increase the width of the blades on the inner cylinder. On the other hand, an increase in the width of the blades on the inner cylinder will lead to an increase in the ratio of air flow velocities along the perimeter of the inner cylinder. Finally, the optimal width of the blades on the inner cylinder can be determined only after calculating the entire grain drying process.

1 Introduction

An essential component of the financial costs of grain production in the conditions of the Non-Chernozem zone of Russia is the cost of drying it. Both theoretical and design developments of many authors [1-8] are aimed at reducing these financial costs. The semi-automatic universal rotary dryer [9] is designed for drying without significant readjustment of all materials and products of agricultural and subsidiary production, in particular, grain. During the loading process, the grain [10] enters the space between the inner cylinder and the outer cylinder when they are at the top, that is, in the first position. In the second position of the cylinders, the grain is heated using the heat of the spent drying agent. In the third, fourth and fifth positions of the cylinders, it is purged by a drying agent. In the sixth position

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of the cylinders, the dried material is cooled by an air flow created by a suction cooling fan. Grain unloading [11, 12] is performed in the first position of the outer cylinder and the inner cylinder.

Many geometric parameters of the semi-automatic universal rotary dryer are obtained structurally. The parameters of unloading and loading grain into a universal semi-automatic rotary dryer were determined [10-14]. Meanwhile, the geometric parameters of some elements of the dryer should be clarified. To do this, let us consider more carefully the movement of the grain located between the inner cylinder and the outer cylinder, when they rotate together in the second position, when the grain is heated. The purpose of the study is to clarify the parameters of the elements of the inner cylinder and the outer cylinder of a semi–automatic universal rotary dryer.

2 Materials and methods

To theoretically determine the parameters of grain movement, we will make the following assumptions:

a) the angle of natural slope of grain decreases linearly with a decrease in its humidity;
b) with an increase in grain moisture by 1%, the angle of natural slope increases by 1°, so, at a humidity of 15%, the angle of natural slope is 30°, at a humidity of 16%, the angle of natural slope is 31°; at a humidity of 17%, the angle of natural slope is 32° and so on, at a humidity of more than 30%, the angle of natural slope 45°;
c) where the thickness of the grain layer between the outer cylinder and the inner cylinder is minimal, and the air flow rate through the holes of the inner cylinder is maximum, the moisture content of the grain when it is purged in the second position is 1% less than the humidity of the surrounding grain.

First, consider the movement of the grain located above the inner cylinder (Figure 1).

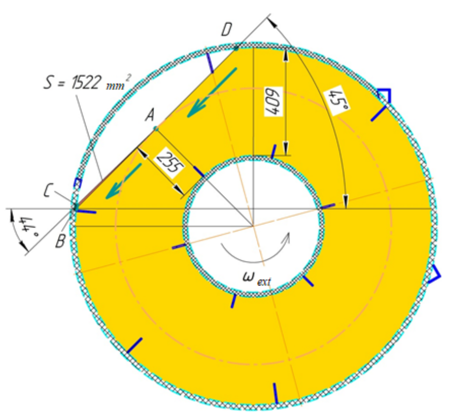

Fig. 1. Movement of the grain located above the inner cylinder.

Let us say the initial moisture content of the grain is more than 30%, the angle of natural slope is 45°. Then, at the beginning of drying, the grain located near point A will have a natural slope angle of 44°. It will move from point A to point B due to gravity. It will fill the ABC sector, the cross-sectional area of which is S=1522 mm^2. This movement will be facilitated by the flow of the drying agent, which reduces friction between the grains, but we will not take it into account. A depression will be created near point A, into which the grain will rush from the inner wall of the outer cylinder, point D. During the rotation of the cylinders, the wetter grain from the wall of the outer cylinder will move to the zone of more intensive drying, the drier grain will move from the zone of more intensive drying to the wall

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of the outer cylinder. Draw a circle through point A with a dashed line. The mass transfer of the grain located above the inner cylinder will occur in the space between this line and the wall of the outer cylinder. Let us determine the intensity of mass transfer at the beginning of drying if the angular velocity at which the cylinders rotate together is ω_{ext}=0.023 rad/s≈1.3 deg/s (Figure 2) [14].

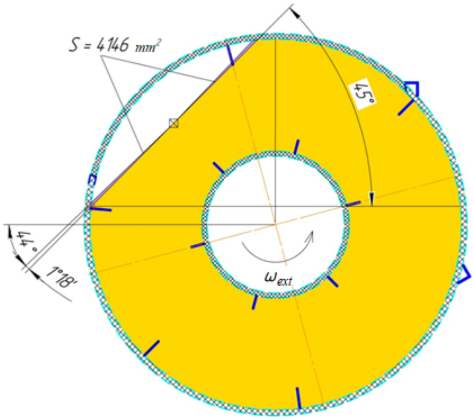

Fig. 2. To determine the volume of the transported grain located above the inner cylinder.

From the figure, the cross-sectional area of the grain being moved S_{wnc}=4146 mm^2= =0.004146 m^2. The length of the working part of the cylinders l_c = 6 m [10], therefore, the volume of the transported grain located above the inner cylinder

$$V_{znc}=S_{znc}l_c;\ V_{znc}=0.004146\text{x}6=0.024876\ \text{m}^3/\text{s}.$$

The mass of the transported wheat, located above the inner cylinder, per unit of time at the beginning of drying

$$m_{znc}=V_{znc}r_p;\ m_{znc}=0.024876\times 850\approx 21.1\ \text{kg/s}.$$

The mass of the transported rye m_{znc}=0.024876×750≈18.7 kg/s.

The mass of the transported barley m_{znc}=0.024876×700≈17.4 kg/s.

The mass of the transported oats m_{znc}=0.024876×550≈13.7 kg/s.

Then consider the movement of the grain located under the inner cylinder (Figure 2). During loading, the space under the inner cylinder is practically filled with grain due to its inertia and elasticity when falling. When the outer cylinder and the inner cylinder begin to rotate, a free space is formed under the inner cylinder due to the angle of the natural slope of the grain (see Figure 3 a, b). This free space is also necessary for cleaning the holes of the inner cylinder with the drying agent flow, into which some puny grains may have got during loading.

Since a free space is formed under the inner cylinder, it would be necessary to reduce the free space above the inner cylinder accordingly, that is, to shift the segments CA and AD up to the left. However, simultaneously with the formation of a free space under the inner cylinder, the position of the grains is ordered during their movement and purging with heated air, as well as the "ascent" of light particles to the surface. Consequently, opposite processes occur that increase the grain level and lower it. Therefore, we assume that the grain level remains unchanged during the initial heating period.

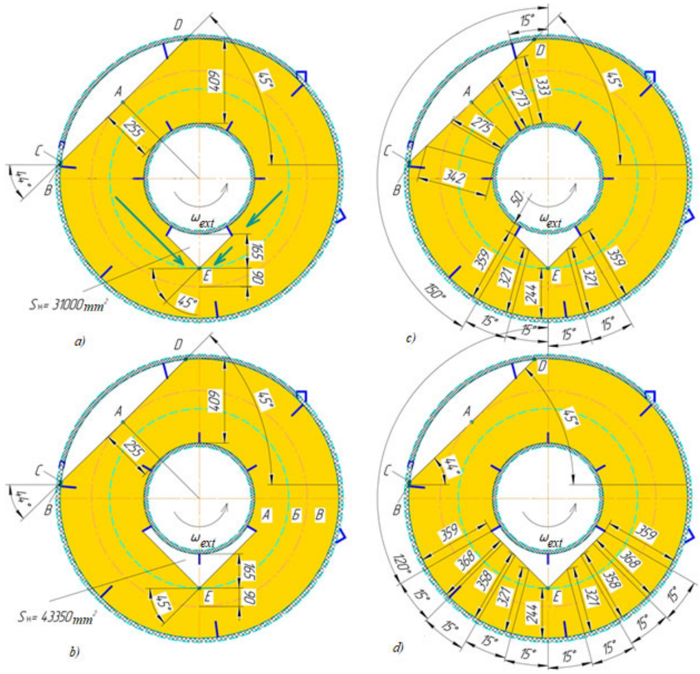

Fig. 3. Movement of grain located under the inner cylinder: a, b) at different positions of the blades of the inner cylinder; c, d) distances covered by warm air in the grain layer.

The amount of free space under the inner cylinder during cylinder rotation periodically changes from $S_{h\ min}$=31000 mm^2 to $S_{h\ max}$=43350 mm^2. However, the distance from the inner cylinder to the point E remains unchanged – 165 mm. It can be seen from Figure 3 that not only the grain located above the inner cylinder will move, but also the grain located under the inner cylinder. When the cylinders rotate, the grain will drain from the blades of the inner cylinder and move to the E point. Since the amount of free space under the inner cylinder changes periodically during the rotation of the cylinders, the grain movement under the inner cylinder will also be periodic. This period corresponds to the angle of rotation of the cylinders by 30°. Since the angular velocity of the cylinders ω_{ext} = 0.023 rad/s, the period of grain movement under the inner cylinder

$$\tau_{under} = \frac{30}{\omega_{ext} \cdot 57.3} \approx 22.76\ sec \tag{1}$$

The volume of grain being moved under the inner cylinder during the period

$$V_{znc\ per}=(S_{h\ max}-S_{h\ min})\cdot l_c; \tag{2}$$

$$V_{znc\ per} = (0.043350-0.031)\cdot 6=0.0741\ m^3/period.$$

Conventionally, per second, the volume of grain being moved under the inner cylinder

$$V_{znc}=V_{znc\ per}/\tau_{under}; \tag{3}$$

$$V_{znc}=0.0741/22.76=0.00325\ m^3/s.$$

The mass of the transported wheat, located above the inner cylinder, per unit of time during heating

$m_{znc}=V_{znc}r_p$; m_{znc}=0.00325×850≈2.8 kg/s.

The mass of the transported rye m_{znc}=0.00325×750≈2.4 kg/s.

The mass of the transported barley m_{znc}=0.00325×700≈2.3 kg/s.

The mass of the transported oats m_{znc}=0.00325×550≈1.8 kg/s.

Where the thickness of the grain layer between the outer cylinder and the inner cylinder is 409 mm, we conditionally assume the air flow rate through the holes of the inner cylinder to be 1. Let's assume that the flow of warm air during grain heating moves strictly radially through the holes of the inner cylinder, the grain layer into the holes of the outer cylinder. Let's also assume that the air flow rate through the holes of the inner cylinder is inversely proportional to the thickness of the grain layer between the outer cylinder and the inner cylinder. Starting counting the radial thickness of the grain layer from the beam coming out of the center of rotation of the cylinders vertically upwards, from Figure 3 a, c, d we determine the relative velocity of the air flow through the holes of the inner cylinder.

3 Results and discussion

The relative dependence of the air flow velocity through the holes of the inner cylinder on the thickness of the grain layer between the outer cylinder and the inner cylinder is shown in Figure 4.

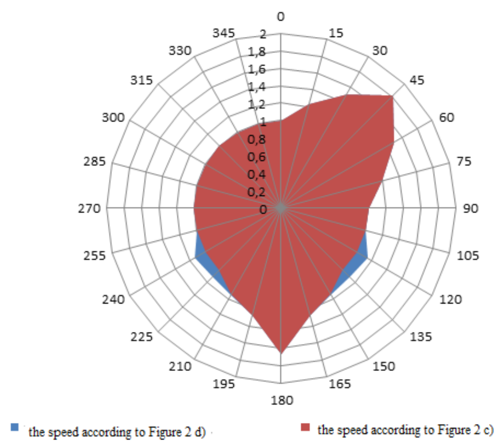

Fig. 4. Diagrams of the air flow velocity through the holes of the inner cylinder (clockwise direction, that is, opposite to the direction of rotation of the cylinders).

The plot of the air flow velocity in accordance with Figure 3b) generally coincides with the plot of the air flow velocity in accordance with Figure 3d, except for the intervals from 105° to 150° and from 210° to 255°. In these intervals, the air flow rate in accordance with Figure 3d) exceeds the air flow rate in accordance with Figure 3 c. In some radial directions, the ratio of air flow velocities along the perimeter of the inner cylinder exceeds 1.8.

Let's draw a circle in Figure 3 through the point E. The grain layer in the space between the outer cylinder and the inner cylinder is divided into three sublayers: A, B, C (see Figure 3b). Some grains of sublayer A are directly in contact with the inner cylinder, so the warm air in the second position of the cylinders will carry out both contact heating of the grain and convective heating in this layer, moving through the pores in the grain. The contact heating of the grain will begin at the moment when it is tightly pressed against the inner cylinder, that is, when the radial beam, in the accepted frame of reference, is located at an angle of 270°. The contact heating of the grain will end at the moment when it is not tightly pressed against the inner cylinder, that is, when the radial beam is located at an angle of 90°. Therefore, the period of contact heating of the grain continues during the rotation of the cylinders at an angle of 180°. Let's determine the time of contact heating of the grain, ωext = 0.023 rad/s (1):

$$\tau_{knz\ A} = 180/(57.3\omega_{ext}) \approx 136.58\ s \approx 2\ min\ 17\ s.$$

when, conditionally terminating only at the point E. The time of convective heating of the grain of the sublayer A during the rotation of the cylinders

$$\tau_{\text{conv n z A}} = 2\times136.58 \approx 273 \text{ s} = 4 \text{ min.}33 \text{ s.}$$

There will be no intensive movement of grains in sublayer B. Their movement both within the sublayer and beyond it will be insignificant. In sublayer B, only convective heating of the grains by warm air passing through the pores will occur. The time of convective heating of the grain of the sublayer B during the rotation of the cylinders

$$\tau_{\text{conv n z B}} \approx 273 \text{ s} = 4 \text{ min } 33 \text{ s.}$$

In sublayer B, there will be intensive movement of grains from point D to point A and from point A to point C (see Figure 2). Convective heating of the grains will occur during the entire rotation of the cylinders. The time of convective heating of the grain of the sublayer during the rotation of the cylinders

$$\tau_{\text{conv n z V}} \approx 273 \text{ s} = 4 \text{ min } 33 \text{ s.}$$

It is known [15-17] that when the grain is heated, there are two opposite trends. On the one hand, the moisture gradient of the outer and inner parts of the grain contributes to the migration of moisture to the outside. On the other hand, the temperature gradient counteracts the migration of moisture from inside the grain to the outside. Therefore, slow heating of the grain is desirable so that the temperature gradient of the outer and inner parts of the grain is minimal. In sublayer A and sublayer B, not only convective heating of the grain will be carried out, but also heat transfer by the grain during its heating. In sublayer B, there is almost no heat transfer by grain. Therefore, the presence of sublayer B is undesirable, or its thickness should be minimal. Its thickness can be reduced by:

a) reducing the diameter of the outer cylinder;
b) reducing the volume of loaded grain;
c) increasing the width of the blades on the inner cylinder.

The diameter of the inner wall of the outer cylinder of 1354 mm is adopted structurally [10] for placing rolls inside the outer cylinders. It cannot be reduced. Reducing the diameter of the outer cylinder will not allow the dryer to be used for drying rolls, so the dryer utilization rate will decrease throughout the year.

Reducing the volume of loaded grain, on the one hand, will reduce the throughput of the dryer. On the other hand, during the drying process, the grain volume may decrease so much that the ratio of air flow velocities (see Figure 4) in some radial directions along the perimeter of the inner cylinder exceeds the permissible values. This will lead to a decrease in the efficiency of grain heating, and possibly to its complete cessation. Therefore, the only possible way to reduce the sublayer B is to increase the width of the blades on the inner cylinder.

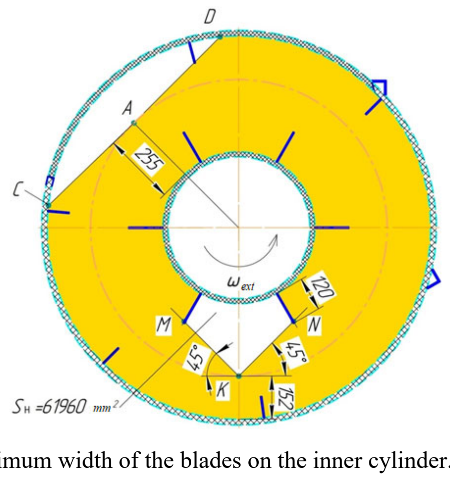

Fig. 5. To determine the maximum width of the blades on the inner cylinder.

The blades on the inner cylinder are designed both to mix the grain and to stiffen the inner cylinder. Their width was adopted constructively [10]. For design reasons, there are no obstacles to increasing their width. Let's determine the maximum width of the blades on the inner cylinder by plotting (Figure 5).

From the point K of the intersection of the vertical passing through the center of rotation of the cylinders and the circle passing through point A, we will draw two rays at an angle of 45° and -45°. Let's draw the rays, continuing the directions of the blades. Let's put the points M and N at the intersections of the rays. The maximum blade width will be at least the distance from the outer wall of the inner cylinder to the points M and N, that is, 120 mm. In this case, the distance from the inner wall of the outer cylinder to the point K, that is, the minimum thickness of the layer of raw grain, 152 millimeters.

4 Conclusion

With an increase in the width of the blades on the inner cylinder, the volume of the minimum free space under the inner cylinder increased from $S_{h\,min}$=31000 mm^2 to $S_{h\,min}$=61960 mm^2, that is, almost doubled. Accordingly, the volume of the maximum free space under the inner cylinder $S_{h\,max}$ has increased. An increase in the amount of free space under the inner cylinder will cause the grain to be displaced into the free space above the inner cylinder. Moving down the point K (see Figure 5) will cause an upward-left shift of point A, respectively, a decrease in the sublayer B. Therefore, the minimum thickness of the raw grain layer will be less. A decrease in the minimum thickness of the raw grain layer will cause an increase in the ratio of air flow velocities along the perimeter of the inner cylinder, since the air will meet little resistance near the K point. Therefore, the increase in the width of the blades on the inner cylinder should be moderate. The optimal width of the blades on the inner cylinder can be determined only after calculating the entire grain drying process.

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