Experimental substantiation of the effective height of a grain falling by a stream of liquid in an ergot release device

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Abstract. The bunker grain mass coming from the combines to the purification points contains, in addition to grain, weed and harmful impurities, which include toxic sclerotia of ergot, causing disease in people and animals, and even death. Existing grain cleaning machines do not provide for a single technological process the complete release of ergot sclerotium due to the similarity of their properties and the properties of the culture being cleaned. Ergot sclerotia are less dense than grains of rye, wheat, oats and barley, which are mostly affected by ergot. Therefore, the complete isolation of ergot sclerotia from grain in one process can be carried out in aqueous solutions of inorganic salts. In order to mechanize the separation of sclerotium ergot from the grain by the wet method and to develop a device for cleaning the grain material that is not complicated in design with low energy intensity of the technological process in comparison with the existing grain cleaning machines, practical experiments were carried out on immersion of winter rye grain of the Falenskaya 4 variety into the water and in the aqueous salt solution sodium chloride (NaCl). It has been established that the effective height of the location of the loading bin relative to the surface of the aqueous solution of salt in the bath of the device for extracting harmful impurities from the grain material by the wet method is 40.0–60.0×10⁻³ m, at which undesirable capture of the air bubble by the grains does not occur. This determines the improvement of the quality of the technological process of cleaning the grain from harmful impurities of the developed machine for the separation of ergot.

1. Introduction

People from ancient times used food products from grain. With an increase in labor productivity, an increase in the yield of grain crops through the use of fertilizers, surplus grain was used to prepare food for farm animals [1, 2].

Currently, the bunker grain mass, delivered from the fields from combine harvesters to post-harvest processing facilities, also contains various weed impurities, which are divided into mineral (sand, lumps of earth, pebbles) and organic (particles of stems, leaves, spikelets and inflorescences of various plants). Weed impurities also include the seeds of the broom, gorchak, mouse, chaff, cockle, and also, in particular, poisonous sclerotia of ergot [3-5].

Ergot sclerotia are excessively poisonous. When eating food contaminated with ergot, people experience dizziness, weakness, convulsions, and narcotic hallucinations, and in some cases can even be fatal as a result of paralysis of the respiratory center [6, 7].
Therefore, high-quality cleaning of the bunker grain mass from all impurities is required. The cleaning of the bunker grain mass from various impurities is carried out by grain cleaning machines, which have a complex structure, are laborious in technological adjustments and maintenance. These machines do not provide for a single process a complete separation of impurities from the grain due to the proximity of their properties and the properties of the culture to be purified [8-10].

At present, photoelectronic separators have been developed for cleaning grain, which are used to isolate weed impurities from the grain material, distinguishing them by color. However, such harmful weeds of grain material as sclerotia of ergot mutate, the color of which becomes similar to the color of the grains of the main crop. Accordingly, modern photoelectronic separators are also not able to isolate toxic sclerotia ergot, similar in color to the grain of the main crop [11].

The ergot sclerotia, which are poisonous impurities in the grain material, have a lower density ($\rho_s = 0.9–1.15\times10^3$ kg/m$^3$) than the grain of rye, wheat, oats and barley ($\rho_r = 1.2–1.5\times10^3$ kg/m$^3$), which are mainly affected by ergot. Therefore, the complete isolation of sclerotium ergot from grain in one process can be carried out in aqueous solutions of inorganic salts, for example, sodium chloride or potassium salt [12, 13].

For the mechanization of the separation of sclerotia of ergot from grain by the wet method, an urgent task is to develop a device for cleaning grain material that is not complicated in design and should have a low power consumption of the technological process compared to existing grain cleaning machines. When developing such a device, it is necessary to determine the effective height $h$ of the location of the loading bin relative to the surface of the aqueous solution of salt in the device’s bath when the grain is immersed in the flow. Determination of the effective height $h$ is necessary for the qualitative execution of the technological process of cleaning grain from harmful impurities by this device.

In this work, the purpose of the research is to determine the effective height $h$ of the location of the loading bin relative to the surface of the aqueous salt solution in the bath of the device for extracting harmful impurities from the grain material by the wet method when the grain is submerged by the flow.

2. Materials and methods
In order to achieve the goal of the research, practical experiments were performed on feeding 10000 seeds of winter rye of the Falenskaya 4 variety with 14% humidity [14] into water ($\rho_w = 1000$ kg/m$^3$) and in an aqueous solution of sodium chloride (NaCl) with density $\rho_{zh} = 1090$ kg/m$^3$. For this purpose, an experimental setup was made, shown in Figure 1, which consisted of a laboratory tripod 1, a bunker 3, a bath 6, a grid 8 for removing grains floating on the surface of a liquid and a sieve 7 for separating the grains from water or an aqueous salt solution.

The laboratory tripod 1, consisting of a stand and a vertical stand, is additionally equipped with a counterweight 9 for stability. The holder 2 is fixed on the vertical stand with the help of a coupling with clamping screws, on which the bunker 3 is suspended.

The bunker 3 consists of vertical side, rear and end walls, sloping bottom. The end wall at the level of the fracture of the vertical rear wall and the inclined bottom mates with an additional inclined bottom, equipped with an outlet and an adjusting valve 4. The sloping bottom from the outlet is made in the form of a sloping plane 5. The bunker 3 is made with the sides of 0.1 m and height 0.23 m. The angle of inclination of the bottom and the additional bottom, equipped with an outlet, was 60°. The capacity of the bunker 3, under which the bath 6 is installed, allowed to hold 1.5 kg of grain.

Bath 6 is made of transparent glass, the side walls and the bottom of which are glued together with a silicone-based sealant. Bath 6 is a glass vessel having a length of 0.35 m, a width of 0.20 m and a height of 0.15 m. The volume of water poured or an aqueous solution of salt in this vessel was 9.0 liters.

For removal of grains floating on the surface of an aqueous solution of salt grains, a metal grid 8 with apertures of cells $1.2\times10^{-3}$ m was used. The metal grid 8 was made of a square shape with sides of 0.15 m.

Sieve 7 for separating grains from water or an aqueous solution of salt is a colander made of a metal grid with apertures of $1.2\times10^{-3}$ m. The external dimensions of the sieve 7 corresponded to the internal...
dimensions of the bath 6. The walls of the sieve 7 on top are equipped with small ones «ears» that fix this fixture on top of a glass bath 6.

Figure 1. General view (a) and scheme (b) of an experimental setup for the study of the effective height of the immersion of grain stream of aqueous salt solution: 1 – laboratory tripod; 2 – holder; 3 – bunker; 4 – adjusting valve; 5 – sloping plane; 6 – bath; 7 – sieve; 8 – grid; 9 – counterweight

The process of immersing the grain in water or an aqueous solution of salt is as follows. Grain material is loaded from above into the accumulative part of the bunker 3. The material moves under the action of gravity along the surface of the side, rear and end vertical walls down. Further along the sloping bottom and an additional sloping bottom, the grain is directed to the outlet. Two inclined bottom, symmetrically located relative to each other, provide uniform resistance to the movement of the grain material across the entire width of the outlet of the bunker 3. As a result, the grain material from the storage part of the bunker 3 along the width of the outlet is uniformly fed into the bath 6 with an aqueous solution of salt, in which the sieve 7 is previously placed.

When the grain material gets into the aqueous salt solution, grains that have a higher density $\rho_z$ than the density $\rho_{zh}$ of the solution fall to the bottom of the bath 6, and other grains with a lower density $\rho_z$ float to the surface of the aqueous salt solution. Drowned grains can also float on the surface of an aqueous solution of salt with trapped air bubbles. Grains that were not submerged and floated with air bubbles and were on the surface of an aqueous solution of salt, are removed using grid 8 to count the number of grains. Removing the sieve 7 from the bath 6, the grain is filtered from the aqueous solution of salt, and then placed on a flat platform for drying. The sieve 7 is again placed in the bath 6 and the process of studying the immersion of grain in an aqueous salt solution is repeated at different specific grain loading, feed height $h$ and fluid density $\rho_{zh}$.

The variation of the specific load $g_{zd}$ of the outflow of grain material from the bunker 3 is carried out by adjusting the valve 4 by changing the flow area of the outlet opening of the bunker 3. The height $h$ of the grain supply relative to the surface of the aqueous salt solution is set by changing the position of the bunker 3 by shifting the coupling with the holder 2 along the height of the vertical rack of the laboratory tripod 1.

The proportion of $P_z$ not sunk and floated with air bubbles grains on the surface of water and an aqueous solution of salt to the number of abandoned grains was determined by the formula (%):

$$P_z = \frac{n_z}{n_1} \times 100\%,$$  \hfill (1)
where \( n_1 \) – the amount supplied to the water and the aqueous solution of salt grains, \( n_1 = 10000 \) units; 
\( n_z \) – the number of grains on the surface of water and an aqueous solution of salt, units.

The specific load \( g_{ud} \) the flow of a sample of winter rye grains of the Falenskaya 4 variety out of the bunker was determined by the expression:

\[
g_{ud} = \frac{1}{B_P} \sum_{i=1}^{n} \frac{m_i}{t_i}
\]

where \( B_P \) – the width of the cross section of the hopper, m; \( m_i \) – the mass of the \( i \)-th hitch of the grains, kg; \( n \) – the number of repeated unloading of the sample of grains, units; \( t_i \) – the duration of the \( i \)-th experience, s.

The variation of the specific grain load \( g_{ud} \) was carried out with values of 0.67, 1.47, 2.87, 4.45 and 7.22 kg/(s×m), which corresponded to the opening of the outlet window of the experimental unit by the values 10.0, 15.0, 20.0, 25.0 and 30.0×10\(^{-3}\) m. To obtain more reliable information, the experiments were carried out in triplicate. The temperature of ambient air, water and an aqueous solution of sodium chloride (NaCl) was 20 degrees Celsius.

The processing of the obtained experimental data was carried out on a personal computer using a special program for the statistical processing of information SigmaPlot 11 [15].

3. Results and Discussion

To determine the effective height \( h \) of the location of the loading hopper relative to the surface of the aqueous solution of salt in the bath of the device for extracting harmful impurities from the grain material by the wet method, practical tests were carried out when the grain was submerged by the flow.

The results of experiments on the immersion of a stream of winter rye grains of the Falenskaya 4 variety into water with density \( \rho_{zh} = 1000 \text{ kg/m}^3 \) and into an aqueous solution of sodium chloride (NaCl) with density \( \rho_{zh} = 1090 \text{ kg/m}^3 \) are shown in Figure 2.

**Figure 2.** The dependence of the share \( P_z \) of grain, which does not sink and also floats with air bubbles when immersed in water (a) and an aqueous solution of sodium chloride (b) grains of winter rye varieties Falenskaya 4 from the feed height \( h \) at different specific grain load \( g_{ud} \)

The dependences of the share of \( P_z \) grain, which is not drowned and also floated with air bubbles to the surface of water and an aqueous solution of grain salt, from the feed height \( h \) at different specific grain load \( g_{ud} \) are described by equations (%): [16]:

\[
P_{zd} = 0.4799 - 0.0074 h - 0.0106 g_{ud} + 0.000078 h^2 + 0.0019 g_{ud}^2.
\]
From the obtained equation (3) it follows that the value \( P_{g_{ud}} \) are more influenced by the specific grain load \( g_{ud} \) than the height \( h \) of the grain feed. The response surface (Figure 2a) shows that when the grain height \( h = 20.0 \times 10^{-3} \) m, the maximum value \( P_{g_{ud}} = 0.45\% \) is at the smallest specific grain load \( g_{ud} = 0.67 \) kg/(s×m). This is due to the fact that a significant amount of grains, when falling from such a height, cannot overcome the force of the surface tension of water \( (\rho_s = 1000 \) kg/m\(^3\)). Minimum values \( P_{g_{ud}} = 0.2–0.9\% \) are observed with a specific grain load \( g_{ud} = 1.47 \) kg/(s×m) for varying parameters \( h \) from 20.0 to 140.0×10\(^{-3} \) m. Moreover, the smallest values \( P_{g_{ud}} \) when varying \( g_{ud} \) from 0.67 to 7.22 kg/(s×m) are determined at the height of the grain supply \( h = 40.0 \times 10^{-3} \) m, which is 0.2–0.26%. An increase in the specific grain loading \( g_{ud} \) from 1.47 to 7.22 kg/(s×m) and an increase in the height \( h \) of the grain supply causes an increase in value \( P_{g_{ud}} \), which is caused by the capture of air bubbles by the grains and their ascent to the surface of the water. In this case, with an increase in the height \( h \) of the grain supply and the specific grain load \( g_{ud} \), the number of grains entraining air bubbles increases. In addition, when the heights \( h \) of the grain supply 100.0, 120.0 and 140.0×10\(^{-3} \) m and a specific grain load \( g_{ud} = 4.449 \) and 7.221 kg/(s×m) grains with air bubbles are grouped into lumps that float to the surface of the water, thereby causing an increase share \( P_{g_{ud}} \).

From the expressed equation (4) it follows that the specific grain load \( g_{ud} \) has a significant effect on the indicators \( P_{g_{ud}} \), the height \( h \) of the grain supply affects to a lesser extent. The response surface of the quantity of \( P_{g_{ud}} \) not sunk and surfaced grain to the surface of the aqueous salt solution with density \( \rho_s \) = 1090 kg/m\(^3\) (Figure 2b) carries identical information that the surface of the response of the quantity of \( P_{g_{ud}} \) of sunk and surfaced grain to the surface of water (Figure 2a).

When a grain moves in a fluid flow, the speed of individual grains will be averaged. Therefore, we can talk about a separate average grain, to which forces are applied. The values \( P_{g_{ud}} \) for the solution increase by an order of magnitude compared with the values \( P_{g_{ud}} \) for water, due to an increase in the surface tension coefficient of the aqueous salt solution in comparison with water. In addition, the density \( \rho_s \) of the liquid increases by 9 %, and, consequently, the Archimedean force \( F_A \) and the hydrostatic resistance force \( F_C \) applied to the averaged weevil increase. These forces impede the movement of the kernels when they pass the surface tension of the solution, for overcoming which the kernels need a large kinetic energy \( E_k \), and hence a large potential energy \( E_p \). The potential energy \( E_p \) of the kernels linearly depend on the height \( h \) of the location of the bunker above the liquid level. Therefore, to effectively overcome the grain surface tension of the solution, it is necessary to increase the height \( h \) of the location of the bunker. The greater the density \( \rho_s \) of the salt solution as compared to the density \( \rho_s \) of the water leads to an increase in the proportion of defective grains that float to the surface of the liquid. All the above explains the increase in values \( P_{g_{ud}} \) compared to values \( P_{g_{ud}} \).

However, in this case, the \( P_{g_{ud}} \) values increase by an order of magnitude due to an increase in the surface tension coefficient of the aqueous salt solution in comparison with water, to overcome which the grain flow requires a high feed height \( h \). Accordingly, the smallest \( P_{g_{ud}} \) values with varying \( g_{ud} \) from 0.67 to 7.22 kg/(s×m) are observed at a height of feeding the grain \( h = 60.0 \times 10^{-3} \) m, which is 2.2–3.0%. This is due to the fact that when feeding grain from such a height \( h \), no air bubble is caught by the grain. The maximum value of \( P_{g_{ud}} = 7.0\% \) is observed with a grain feed height \( h = 20.0 \times 10^{-3} \) m and a grain load \( g_{ud} = 0.67 \) kg/(s×m), as well as with a grain feed height \( h = 140.0 \times 10^{-3} \) m and grain load \( g_{ud} = 7.22 \)

\[
P_{g_{ud}} = 5.6488 - 0.0810h - 0.1352g_{ud} + 0.00054h^2 + 0.0410g_{ud}^2.
\]
kg/(s×m) value \( p_{\text{iso}} \) = 7.5%. This is due to the fact that a significant amount of grains from the feed height \( h = 20.0 \times 10^{-3} \) m cannot overcome the surface tension force of an aqueous salt solution, and at the feed height \( h = 140.0 \times 10^{-3} \) m, air bubbles are captured by the grains, grouping them into lumps and active ascent to the surface of the solution.

4. Conclusion
Thus, based on the experimental studies of the immersion of winter rye grain Falenskaya 4 variety with 14% humidity in a liquid at a temperature of 20 degrees Celsius, the following conclusion can be drawn: the effective height \( h \) of the location of the hopper relative to the water surface with density \( \rho_{h} = 1000 \) kg/m\(^3\) will be \( 40.0–60.0 \times 10^{-3} \) m, and relative to the surface of an aqueous solution of sodium chloride (NaCl) with density \( \rho_{h} = 1090 \) kg/m\(^3\) – \( 40.0–60.0 \times 10^{-3} \) m. With these values of height \( h \) does not occur unwanted air bubble entrapment. This determines the improvement of the quality of the technological process of cleaning the grain from harmful impurities of the developed machine for the separation of ergot [17].

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