Prospects and method of seed grain storage in a container with gas-regulating medium

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Abstract. The quality of seed grain storage is an important factor in increasing crop yields. Sowing with poor quality seeds even in favorable weather conditions leads to reduction in yields by more than 10 %. During storage, grain loses its weight and quality. The main causes of such losses are biological losses (resulting from grain respiration, the intensity of which depends on the temperature and humidity of the environment); losses from insect pests, rodents that can penetrate the grain mass. The existing storage methods are labor-intensive and low efficient; therefore, this paper describes the method of seed grain storage in a container with gas-regulating medium. It presents the design of the container and the results of laboratory tests to determine the effect of structural and technological parameters of the container on seed grain germination and the change of the vital activity of insect pests of cereals.

1. Introduction

At the current stage of development of the Russian agro-industrial complex grain producers traditionally provide themselves with seeds of the recognized varieties of grain crops thus creating the necessary seed stock. As a result, the seeds are mainly stored directly at grain producers’ facilities after being processed on grain cleaners to meet the standards established by the State Standard for Seeds.

Grain preparation and storage is a complex and labor-intensive task for grain producers. Nevertheless, the advantages of using high quality seeds in sowing are evident. Sowing with poor quality seeds even in favorable weather conditions leads to reduction in yields by more than 10 % [1, 2].

The storage period is characterized by complex biochemical processes. At the beginning of storage, they are connected with the transition of low-molecular organic substances accumulated during plant photosynthesis and grain filling into high-molecular ones: polysaccharides, proteins and fats. At the end of the storage period – to increase seeds germination from dormant state due to air-thermal heating of seeds before sowing.

The main danger for grain is increased moisture, which affects the intensity of biochemical processes in grains. In dry grain the processes proceed slowly, the grain is dormant. With high moisture and sufficient oxygen in the intergrain space, the grain breathes intensively (aerobic
respiration). Aerobic respiration is the main type of grain respiration accompanied by the losses of dry matter (weight loss), the increase in the amount of hygroscopic moisture (moisture increase), the change in the air composition of intergrain spaces and the formation of a large amount of heat in the grain mass. Attention should be paid to the fact that carbon dioxide (CO₂) formed as a result of respiration gradually displaces the air containing oxygen from the grain mass and forces the grain cells to switch to anaerobic respiration. In anaerobic respiration, there is the reaction of oxygen formed from grain carbohydrates. This triggers the processes similar to alcohol fermentation in grain, because of which its quality is deteriorated [2–4].

The moisture of the grain mass also has a direct impact on the development of grain storage pests. For the life of most cereal pests, it is advisable to have the grain moisture of at least 14 %. However, it was revealed that mites can live and develop at a moisture content of grain products below 14 %, grain weevils – 12–13 %, rice weavers and grain borers – 11 %, drugstore beetles – 6 % [5, 6].

Life processes occurring in grain are also affected by the room temperature: when the temperature decreases, the processes slow down, and when the temperature increases, the respiration of grain increases. Temperature increase and high moisture of grain contribute to the development of various microorganisms – bacteria and mold, which under favorable conditions multiply very quickly and can completely damage the grain.

At present, the methods of grain storage in oxygen-free environment have begun to be used, where the main storage regime is the storage of grain with the moisture content of 8–10 % [4, 7].

Grain, the moisture of which was below the critical value, in the conditions of oxygen-free storage completely retains its technological advantages (including milling and baking) and fodder properties (nutritional value), but partially or completely loses its germination. Therefore, the method of storage in oxygen-free environment is not acceptable for seed grain storage.

The scientists of Ryazan State Agrotechnological University developed a method of seed grain storage in gas-regulating medium. It is aimed at slowing down aerobic respiration of grain and preventing anaerobic respiration. The reduction of aerobic respiration rate is achieved due to partial air dilution in a sealed volume where the grain is stored. To avoid anaerobic respiration, the preventive aeration of grain heap is implied with subsequent removal of excess air through the vacuum.

Preventive aeration is necessary because even when the moisture content of grain is below the critical value, it continues to breathe. By absorbing oxygen from the air, the grain releases carbon dioxide into it and when the amount of this gas in the air reaches the limit at which the grain can switch to adiabatic respiration, the grain mass shall be aerated.

The method of grain storage in gas-regulating medium will also allow fighting harmful insects and microorganisms, as the bulk of them consists of aerobes.

In order to implement this method, the structure of the sealed container is created as shown in Figure 1 [7–10].

The purpose of the study is to increase the efficiency of seed grain storage by designing a container for grain storage in gas-regulating medium and justifying its design and operating parameters.

2. Materials and methods

Earlier theoretical studies [7] revealed that the main structural and technological parameters of a sealed container with gas-regulating medium, which can affect the grain safety include the pressure of gas mixture inside the container, filling degree of the container with grain mass, moisture content of grain and oxygen content of gas mixture, as well as the volume of carbon dioxide storage tank.

The first four factors can be determined in the course of laboratory studies; the capacity of carbon dioxide tank can be determined in the course of theoretical studies.

Analyzing the volume and mass of gases in the air it is noted that about 99 % is nitrogen, oxygen, argon and carbon dioxide. The average value of the molecular weight of gas mixture, based on the composition of the mass components, can be determined from the following equation:

$$M_{av} = \frac{1}{M_{r}(N)} \frac{\alpha_{(N)}}{M_{r}(O)} \frac{\alpha_{(O)}}{M_{r}(Ar)} \frac{\alpha_{(Ar)}}{M_{r}(CO)} \frac{\alpha_{(CO)}}{M_{r}(CO)}$$  \hspace{1cm} (1)
where \( \omega_{(N_2)}, \omega_{(O_2)}, \omega_{(Ar)}, \omega_{(CO_2)} \) – mass fraction of four main air components (nitrogen, oxygen, argon and carbon dioxide), \%;

\[ M_r(N_2), M_r(O_2), M_r(Ar), M_r(CO_2) \] – molar mass of \( i \) component of a mixture [g/mol].[1]

Figure 1. Sealed container for seed grain storage with regulating air medium

It was found that during anaerobic respiration of seeds in the container, the percentage of carbon dioxide in the air increases and oxygen decreases. Given that the volume of the intergrain space is relatively small compared to the total volume of the sealed container, respiration depends significantly on the content of oxygen and carbon dioxide in the air. The presence of grain-free air in the container may to some extent affect the intensity of air composition change in the intergrain space. Then the volume occupied by air in the sealed container will be made up of the volume of the container free of grain mass and the volume of air in the intergrain space and is defined based on the following expression:

\[ V_{free} = \beta \cdot S \cdot V_k + 100\% \] (2)

where \( V_{free} \) – free volume occupied by air inside the container, m\(^3\);

\( \beta \) – filling degree of the container with grain mass, \%;

\( S \) – porosity of grain mass;

\( V_k \) – container volume, m\(^3\).

The grain mass porosity characterizes the intergrain space ventilation and can be determined from the following expression:

\[ S = \frac{V_{n-V}}{V_n} \cdot 100 \% \] (3)

where \( V_n \) – total volume of grain mass, m\(^3\);

\( V \) – grain volume, m\(^3\).

If oxygen flows freely into the grain mass and carbon dioxide is removed, at anaerobic respiration the respiratory coefficient will be equal to one, the proportion of carbon dioxide and oxygen will be equal, i.e.

\[ V_{CO_2} = V_{O_2} \] (4)

In enclosed volume the aerobic respiration of grain is accompanied by oxygen decrease with increase of carbon dioxide concentration, because of which the average molar mass of air mixture increases. Since carbon dioxide is heavier than other air components, it is lowered into the carbon dioxide storage tank, from which it can be removed during aeration of the grain mass. The beginning
of the aeration process can be the moment when the limit of oxygen content in the bulk grain is reached, at which the grain can switch to anaerobic respiration.

A vacuum pump connected to carbon dioxide storage tank may be used for aeration of the grain mass, and the vacuum oxygen monitoring sensor may be used for monitoring. In order to calculate the volume of the carbon dioxide storage tank, the following assumption is taken into account: as the conventional air mixture is located inside the container with ambient temperature and has a small volume, it can be considered an ideal gas. Then, using the Mendeleyev-Clapeyron equation for ideal gas, it is possible to write the following:

\[
P_{xp} \cdot V_c = m_{CO_2,C} \cdot RT_{xp},
\]

where \(P_{xp}\) – pressure of the gas mixture inside the sealed container, Pa; \(R\) – universal gas constant, \(J/(mol \cdot K)\); \(T_{xp}\) – temperature of gas mixture, \(^0K\); \(m_{CO_2,C}\) – molar mass of gas mixture, kg/mol; \(m_{CO_2,C}\) – gas mixture in the sealed container, kg.

Using the expression (3) from the expression (5) we determine the mass of the gas mixture \(m_{CO_2,C}\):

\[
m_{CO_2,C} = \frac{(P_{xp} \cdot \beta \cdot S \cdot V \cdot M_{CO_2,C})}{(RT_{xp} \cdot 100 \%)}
\]

It can be seen from formula (6) that at constant container volume and storage temperature depending on external climatic conditions, the process of grain respiration in the container will be influenced by gas mixture pressure inside the container and the filling degree of its grain mass. The weight content of carbon dioxide in the gas mixture can be determined from the expression:

\[
m(CO_2) = \frac{m(CO_2)}{m_{CO_2,C}} \cdot \left(\frac{P_{xp} \beta \cdot S \cdot V \cdot M_{CO_2,C}}{RT_{xp} \cdot 100 \%}\right)
\]

It is known that the porosity of wheat grain mass is 35–45 % at a bulk density of 750–850 kg/m\(^3\) [11]. Then the tank volume to accumulate carbon dioxide can be determined from the equation:

\[
V_{CO_2} = \frac{m(CO_2) \cdot R \cdot T_{xp}}{M_{CO_2} \cdot P_{xp}}
\]

3. Research methodology

The laboratory studies were carried out to confirm the theoretical prerequisites for seed grain storage in a sealed container under gas-regulating conditions. The studies determined optimal structural and technological parameters of grain storage in a sealed container and the effect of the cleared air on the life of cereal pests. The original experimental facility was created for the study, the general view of which is shown in Figure 2 [12].

Figure 2. General view of experimental facility
The experimental facility consists of a container (1) with a sealed cover (2), on which the reference vacuum meter GSGJ 27100 (4) is installed. On the tank walls there are slide valves with gates (3) for air supply from the environment to the container, removal of contaminated air from it and creation of cleared atmosphere inside with the help of a vacuum pump MNR – A998A through a slide valve with gate (5). The oxygen content in the air inside the tank was controlled by SK-2 gas analyzer (7) operating in O₂ mode. The battery of the gas analyzer was recharged by means of a device (8) from the 220 V electrical network. The grain moisture was controlled by means of a moisture meter IVDM-2-01. Avalon spring wheat seeds were chosen as a model material. Seed germination after the seasonal storage period was taken as the optimization parameter.

The following design and process parameters of the sealed container affecting the optimization parameter were studied using the laboratory facility.

Gas mixture vacuum pressure in the container (P) with variants:

\[ P_{-1} = 0.9 \text{ MPa}; \quad P_{0} = 0.5 \text{ MPa}; \quad P_{+1} = 0.1 \text{ MPa}. \]

Filling degree of container volume with grain (\( V_p \)) with variants:

\[ V_{p-1} = 0.8; \quad V_{p0} = 0.9; \quad V_{p+1} = 1.0. \]

The limit oxygen content in the gas mixture in the intergrain space (\( C_k \)) with the following variants:

\[ C_{k-1} = 14 \%; \quad C_{k0} = 17 \%; \quad C_{k+1} = 20 \%. \]

Moisture of grain for storage (W) with variants:

\[ W_{-1} = 12 \%; \quad W_{0} = 16 \%; \quad W_{+1} = 20 \%. \]

In order to avoid the possibility of external climatic factors, such as temperature and relative moisture, sharp fluctuations in air temperature, laboratory tests were carried out in the climate heating and cooling chamber KTK 3000. The temperature in the chamber was constantly maintained at 50°C and the relative moisture – at 90 %. The storage period amounted to 90 calendar days.

The laboratory studies were conducted in the following sequence. After cleaning and sorting the seed grain was filled into the container and sealed with a cover. Air was then pumped out by means of a vacuum pump and a cleared atmosphere was created with a value corresponding to the test matrix. The storage conditions of grain in the container were checked daily. During the control, the oxygen content of the gas mixture inside the container was recorded, the gas pressure inside the container was monitored by means of the gas analyzer (7) and the gas pressure inside the container was monitored by the control vacuum meter (4). When the limit value of oxygen content determined by the test matrix was reached, the grain mass was aerated. For this purpose, the vacuum slide valve (5) was opened, the vacuum pump (6) was used to pump gas with reduced oxygen content from the container. The vacuum slide valve was then closed, and the atmospheric slide valves opened through which fresh air penetrated the container, filling the entire container space. After that, the atmospheric slide valves were closed, the vacuum slide valve was opened, and the vacuum pump created a vacuum of fresh gas mixture in the container to the value determined by the test matrix [12]. At the end of the experimental storage period the grain seeds were tested for germination according to the requirements of the state standard [13].

Germination and seed vigor were calculated in percentage. The result of the experiment was the arithmetic mean value of germination results of all analyzed samples, if when determining the germination of seeds for four samples the deviation of the analysis of some samples from the arithmetic mean value did not exceed the permissible value established by GOST.

The impact of gas-regulating medium on the life of cereal pests was studied on the basis of the state standard [14, 15].

The method of determining the change of life activity of harmful insects that infected grain depending on the vacuum of the gas medium in the intergrain space is based on the accelerated testing method. The method consists in that the rate of reactions of metabolism (respiration) of grain, especially dry, is very low, in comparison with the rate of exchange reactions of insects, so that according to state standards the increase of carbon dioxide concentration in the intergrain space is considered both a sign of life activity of insects and the degree of grain contamination [14].
The carbon dioxide content of the air in the intergrain fill was monitored by SK-2 gas analyzer. Before the beginning of the experiments, the grain mass with a humidity of 16% was supplied to the container of the laboratory facility in the amount of three kilograms. The grain was then artificially contaminated by adding 50 grains contaminated with the larvae of grain weevil (Sitophilus granarius) or grain moth (Sitophilus zeamais) to the grain mass.

After that, the container with contaminated grain was closed with a non-sealed cover and mixed in the climatic chamber, where favorable conditions were created for insect development (temperature – 30°C and air moisture – 65%). Under such conditions, the grain was held until the released carbon dioxide over 24 hours of insect incubation made 0.5% per kilogram of the grain mass, which according to GOST corresponds to the average contamination of grain by insects [15].

Then the container was closed with a tight cover, and the gas medium was discharged to value of 0.9 MPa, 0.7 MPa, 0.5 MPa, 0.3 MPa and 0.1 MPa.

The carbon dioxide concentration was determined in 24, 48 and 72 hours after the beginning of the experiment.

The repeatability of measurements was ensured where for each experimental group there were three repetitions of carbon dioxide measurements in the intergrain space.

4. Results and discussion
Four factor experiments were carried out to confirm the results of theoretical studies on the possibility of storing seed grain in a sealed container with gas-regulating medium and to determine the optimal parameters of grain storage [16, 17].

The results obtained in the course of experiments made it possible to determine the multiple regression equation, to establish a connection between the germination of seeds Y and the parameters of seed grain storage in a sealed container.

The processing of experimental results was limited to the calculation of regression coefficients, which was carried out by mathematical statistics using Statistica v8. Based on the obtained coefficient values, a regression equation was compiled:

\[ Y = 97.42 - 3.70X_1 - 3.30X_2 - 1.90X_3 - 1.92X_4 + 0.24X_1X_2 + 1.1X_1X_3 - 1.16X_1X_4 + 0.8X_2X_3 - 0.12X_2X_4 - 1.1X_3X_4 - 8.2X_1^2 - 4.22X_2^2 - 5.12X_3^2 - 3.81X_4^2 \]

where Y – grain germination; \(X_1\) – moisture content of grain placed in a container for storage; \(X_2\) – critical oxygen content in air at which it is necessary to start the aeration of the grain mass; \(X_3\) – pressure of discharged gas atmosphere inside the container (vacuum pressure); \(X_4\) – degree to which the container is filled with grain.

The reliability of the obtained regression equation and experimental data is characterized by the determination coefficient \(R^2=0.9169\) and the regression coefficient \(R=0.9575\) [18].

On the basis of regression equation (9) the graphical dependence of seed grain germination on technological parameters of container storage under conditions of discharged gas medium was built. The dependencies are shown in Figures 3 and 4.

**Figure 3.** Dependency graph of spring wheat germination on grain moisture when placed for storage and oxygen content in the discharged gas medium of the container

**Figure 4.** Dependency graph of spring wheat germination on grain moisture and pressure of discharged gas medium of the container
The analysis of obtained graphical dependencies allowed concluding the following:

- the moisture of grain to be stored in the container shall be 15.2 %, i.e. the grain storage in the container under discharged atmosphere conditions does not require grain drying to critical moisture value, thereby reducing the residence time of the grain in a dryer, which will reduce energy and time costs, as well as reduce grain damage during drying by creating a more sparing drying mode;
- the maximum germination of grain after storage in the container under the condition of a discharged atmosphere was observed at a maximum oxygen content of 14 %;
- in order to preserve the germination of grain, it is necessary to maintain the vacuum pressure in the container equal to 0.66 MPa during storage;
- the filling degree of the container with grain does not affect germination [19, 20].

The results of the calculation of the volume of the carbon dioxide storage tank according to formula 8 showed that the cubic meter of the container volume, the carbon dioxide tank volume should not be less than 0.008 m$^3$.

The results of the study of the effect of the discharged gas environment inside the container on the life of insect pests are presented in the form of histograms (Figures 5, 6).

![Figure 5. Histogram of the effect of discharged atmosphere on life of a grain weevil](image1)

![Figure 6. Histogram of the effect of discharged atmosphere on life of a grain moth](image2)

The analysis of histograms showed that in the absence of a sparse gas environment, the grain weevil continues to develop. Its life activity in grain becomes more active, as evidenced by the increase in carbon dioxide concentration in the intergrain space from 1.5 to 1.65 %.

As the vacuum pressure of gas environment increased, the insect life is reduced. Thus, at a vacuum pressure of 0.9 MPa, the amount of carbon dioxide released by insect pests decreased by 0.2 % on average, and at a vacuum pressure of 0.7 MPa by 0.8–0.9 %. When the insects were kept in the gas medium at a vacuum pressure of 0.3 MPa, on the second day their life activity was completely stopped.

Besides, the possibility of insect pests to restore their vital functions after being in a discharged gas environment was studied during laboratory tests.

In order to create normal incubation conditions for insect pests the tanks with contaminated grain were closed with a non-sealed cover. The control measurements of carbon dioxide content in the air were made on the fifth, tenth and fifteenth days of the experiment.

The results of the measurements are presented as histograms in Figures 7 and 8.
Series 1 – 5 days of insect incubation; Series 2 – 10 days of insect incubation; Series 3 – 15 days of insect incubation

Figure 7. Histogram of recovery of vital functions of a grain weevil after its presence in discharged gas environment

Series 1 – 240 hours of insect incubation; Series 2 – 480 hours of insect incubation; Series – 720 hours of insect incubation

Figure 8. Histogram of recovery of vital functions of a grain moth after its presence in discharged air atmosphere

The histograms show that the insect pests are able to recover their life functions when they are in normal atmospheric conditions if they have previously been in a discharged gas environment with a pressure of more than 0.5 MPa. The rate of restoration of life functions of insect pests was higher, the lower was the vacuum pressure of the atmosphere. After three days in a tank with a vacuum pressure of 0.3 MPa and below the vital functions of pests were not recovered, as evidenced by the absence of an increase in carbon dioxide content in the air, which is likely to suggest that the insect pests died due to lack of air.

Therefore, the technology of seed grain storage in a container in a discharged gas environment should contain a preparatory mode thus creating conditions for the destruction of pests in the grain mass. The duration of this mode is 48–72 hours with the vacuum pressure not exceeding 0.3 MPa.

5. Conclusion

According to results of laboratory studies the method of seed grain storage in the container under gas-regulating medium condition allows preserving its germination. At the same time, it is necessary to store grain in the container with the moisture content of at least 15%; to create and maintain the gas vacuum in the container within 0.6 MPa during storage; to ensure the aeration of the grain mass at the oxygen content in the carbon dioxide storage tank below 14%. In order to control insect pests after laying the grain mass for storage in a sealed container with a gas-regulating medium, it is necessary to keep it for 48–72 hours under the pressure of not more than 0.3 MPa.

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