KnE Life Sciences

DonAgro
International research conference on Challenges and Advances in Farming, Food Manufacturing, Agricultural Research and Education
Volume 2021

Conference Paper

# Processes of Heat and Mass Transfer During Grain Mass Storage in Metal Silos of Large Capacity

**Ivan Kechkin[1], Vladimir Ermolaev[1], Marina Belyaeva[1], Valentina Tarakanova[2], Elena Gurkovskaya[2], and Konstantin Buzetti[2]**

[1]Department of Commodity Science and Expertise, Plekhanov Russian University of Economics, 36, Stremennyi prov., Moscow, 117997, Russian Federation
[2]K.G. Razumovsky Moscow State University of technologies and management (the First Cossack University), 109004, Moscow, Russia

**ORCID:**
*Vladimir Ermolaev: http://orcid.org/0000-0002-1450-2517*
*Ivan Kechkin: http://orcid.org/*

Corresponding Author:
Ivan Kechkin
kechkin87@mail.ru

Published: 5 April 2021

Publishing services provided by Knowledge E



Selection and Peer-review under the responsibility of the DonAgro Conference Committee.

## Abstract

This study showed that there were some changes in the temperature and humidity parameters of wheat grains during the storage year. The grain moisture content in both the near-wall and central parts of the metal silo largely did not change, remaining at a level of 10-11%. Moisture values were recorded monthly, and grain temperature was recorded in accordance with seasonal changes, thus, the range of temperature changes was from 20 to 32°С at a minimum outdoor temperature of 5°С. The moisture content of the grain in the surface layer increased by 0.4-1.2% and the final moisture content of the grain was 11.6%. Experiments on grain temperature and humidity changes with active ventilation in large-capacity metal silos have shown that the rate of change (decrease) in temperature depends on the specific air flow rate, and the difference in air and grain temperature. Experimental storage showed that a grain with the moisture content up to 13.6% can be stored for up to nine months without deterioration in quality. A longer shelf life is possible for wheat grains with a moisture content of up to 12%. This article pays special attention to the processes occurring in the under-roof space of large-capacity metal silos and suggests methods for solving this problem.

**Keywords:** long-term storage, active ventilation, metal silos, heat and mass transfer processes.

OPEN ACCESS

## 1. Introduction

A lot of scientific papers have been devoted to studying the features of grain storage in large-capacity metal silos, including long-term storage without significant changes in quality and commodity value [1]. They pay considerable attention to changes in grain quality at different storage periods, determining the effectiveness of active ventilation of the grain mass in order to cool the grain in various climatic conditions [2].

Metal silos of large capacity (MSLC) create the most unfavorable storage conditions in the upper part of the grain embankment [3].

Grain harvesting, formation of grains, lots of uniform quality, post-harvest ripening of the grain mass in the south of the Russian Federation (for example, the Krasnodar Territory) are carried out in summer from June to September. The average daily air temperature during this period varies from 15 to 30℃, while the average values of night air temperatures (according to the Climate Statistics website of Russia, statistical data are given for the last ten years) range from 10 to 25℃, and daily temperatures vary from 15 to 35°C [4]. It is obvious that the temperature of the grain mass during storage corresponds to the average air temperature during harvesting, and the grain requires cooling. Given that night air temperatures are statistically likely lower than the grain temperature, ventilation for cooling should be carried out at night. In relation to the use of outdoor air for active ventilation of grain, its relative humidity is important [5]. When the air temperature is below 20°C, it is actually advisable to cool the grain mass in silos; the relative humidity reaches values of 70–75%. It is known that at such humidity values, the moisture content of wheat and barley grain is critical, that is, 14.0 - 14.5%. In other words, there is a danger of grain moistening when cooling the grain mass with a temperature of 25–29℃ due to sorption of moisture from the air if the grain moisture was at the level of 12–13% [6].

The need for grain cooling is justified by the results of studies of the wheat quality stored in MSLC with a diameter of 15.2m. It is established that at a temperature of 10℃ with a humidity of 11-15%, wheat can be stored for up to twelve months without changing its quality indicators. At a temperature of 20℃ it can be stored without changing the quality for twelve months only with a moisture content of not more than 12%. The grain with a moisture content of 13-14%, after three months of storage, shows some indicators of deterioration (sowing properties, a decrease in the activity of dehydrogenases, an increase in the acid number of fat), and after nine months, the respiration rate increases approximately twice. At a temperature of 30°C, grain storage without deterioration was observed for two months with a moisture content of not more than 13%. At humidity from 13 to 14%, quality deterioration occurred already in the first month of storage. By the time of three months, the quality indicators have significantly worsened: the natural mass, germination energy and germination rate have decreased [7], the acid number of fat, the respiration rate have increased, and the quality of gluten has decreased.

## 2. Methods and Equipment

At night the grain is ventilated with outside air. In the study there were the air parameters characteristic of late September and early October: temperature AT = 10°C, relative air humidity $\phi$B=60%. With these parameters, the moisture content of air is dA = 5.58 g/m$^3$, (Table 1), compiled on the basis of the I-d diagram [8].

For practical calculations, taking into account the current values of temperature (t) and relative humidity (φ), we can use the following formulas that we obtained based on the data in Table 1.

$$d = k \times e^{0,07 \times t}, \tag{1}$$

where d - moisture content of air, g/m$^3$;

k – coefficient, taking into account the value of the relative humidity of the air for which the moisture content is calculated;

e – base of the natural logarithms;

t – current value of air temperature, °C.

$$k = 0,045 \times \varphi - 0,02. \tag{2}$$

The standard deviation in the temperature range from 35 to minus 15°C is 0.9887 for *d*, and 1.0000 for *k*, which confirms the accuracy of the approximation and the formulas can be used for practical calculations.

Instructions for the active ventilation of the grain and oil seeds (machinery and technology), for wheat with a moisture content of up to 14%, recommend a specific air flow rate q = 10 m$^3$/h per a ton of grain. The rate of decrease in grain temperature Vt = 0.2°C for one hour of ventilation, this parameter is taken on the bases of the results of the all-Russian Research Institute of Grain and its Processed Products (VNIIZ) studies when ventilating wheat in a metal container with a diameter of 22.8 m and a mound height of 17 m.

## 3. Results

Experiments on changes in grain temperature and humidity with active ventilation in metal silos showed that the rate of change (decrease) in temperature depends on the specific air flow rate, the difference in air and grain temperatures. Analyzing the data shown in the graphs, we can conclude that the average hourly rate of decrease in grain temperature (initial temperature 22°C) varies from 0.20 to 0.12°C/h, and the first day

Table 1: Moisture content of air.

| Moisture content of air *d* g/m$^3$ at various values of temperature and relative humidity | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air temperature *t*, °С | at atmospheric pressure of 745 mm Hg | | | | | | | |
| | relative humidity φ, % | | | | | | | |
| | 100* | 90 | 80 | 70 | 60 | 50 | 40 | 30 |
| -15 | 1,25 | 1,13 | 1,00 | 0,88 | 0,75 | 0,63 | 0,50 | 0,37 |
| -10 | 1,96 | 1,76 | 1,57 | 1,37 | 1,18 | 0,98 | 0,78 | 0,58 |
| -5 | 3,02 | 2,72 | 2,42 | 2,11 | 1,81 | 1,51 | 1,21 | 0,91 |
| 0 | 4,62 | 4,16 | 3,70 | 3,23 | 2,77 | 2,31 | 1,85 | 1,39 |
| 5 | 6,61 | 5,95 | 5,29 | 4,63 | 3,97 | 3,31 | 2,64 | 1,97 |
| 6 | 7,16 | 6,44 | 5,73 | 5,01 | 4,30 | 3,58 | 2,68 | 1,78 |
| 7 | 7,70 | 6,93 | 6,16 | 5,39 | 4,62 | 3,85 | 3,08 | 2,31 |
| 8 | 8,25 | 7,43 | 6,60 | 5,78 | 4,95 | 4,13 | 3,30 | 2,47 |
| 9 | 8,79 | 7,91 | 7,03 | 6,15 | 5,27 | 4,40 | 3,52 | 2,64 |
| 10 | 9,34 | 8,41 | 7,47 | 6,54 | 5,58 | 4,67 | 3,74 | 2,81 |
| 11 | 10,08 | 9,07 | 8,06 | 7,06 | 6,05 | 5,04 | 4,03 | 3,02 |
| 12 | 10,82 | 9,74 | 8,66 | 7,57 | 6,49 | 5,41 | 4,33 | 3,25 |
| 13 | 11,55 | 10,40 | 9,24 | 8,09 | 6,93 | 5,78 | 4,62 | 3,46 |
| 14 | 12,29 | 11,06 | 9,83 | 8,60 | 7,37 | 6,14 | 4,92 | 3,70 |
| 15 | 13,03 | 11,73 | 10,42 | 9,12 | 7,82 | 6,52 | 5,21 | 3,90 |
| 20 | 18,00 | 16,20 | 14,40 | 12,60 | 10,80 | 9,00 | 7,20 | 5,40 |
| 25 | 24,60 | 22,14 | 19,68 | 17,22 | 14,76 | 12,30 | 9,84 | 7,38 |
| 30 | 33,34 | 30,00 | 26,67 | 23,34 | 20,00 | 16,67 | 13,34 | 10,01 |
| 35 | 44,84 | 40,36 | 35,87 | 31,39 | 26,90 | 22,42 | 17,94 | 13,46 |
| 40 | 59,98 | 53,98 | 47,98 | 41,99 | 35,99 | 29,99 | 23,99 | 17,99 |
| 45 | 79,98 | 71,89 | 63,90 | 55,92 | 47,93 | 39,94 | 31,95 | 23,96 |

of ventilation corresponds to a higher value. These figures correspond to a difference of air and grain temperatures of 10°С and a specific air supply during ventilation - 10 m$^3$/h×t. With a temperature difference of 20°C, the indicated values of the decrease rate in the temperature of the grain mass are slightly higher, up to 0.24°C/h. For the conditions of the south of Russia, the temperature difference between the outside air and the grain mass of more than 10°C is unlikely. On this basis, the average hourly rate of decrease in grain temperature with active ventilation for calculation can be taken in the range of 0.12 ÷ 0.18°C/h with a specific air flow rate of 10 m$^3$/h×t [9].

The analysis of the specific cost of electricity for grain ventilation at different specific air flow rates was conducted. It was established that at a specific air flow rate of 10 m$^3$/h×t, the energy consumption is 0.12 kW/h×t; and at 20 m$^3$/h×t, they increase by 0.18 kW/h×t. The given values correspond to a temperature difference of 10°С. With large values of the temperature difference, the specific energy consumption is reduced more than two times.

When the grain is stored in metal containers, daily temperature change of 10°C or more can occur in the wall layer with a thickness of up to 0.05 m. Moreover, in a silo with a capacity of up to 4000 tons this layer accounts for less than 1% of the grain mass [10].

The shelf life of freshly harvested grains with a moisture content of 14%, according to the general technological regulations for elevators and grain receiving enterprises, for wheat, rye, barley, oats and rice without ventilation, is predicted up to 12 months (at a temperature range from 5 to 25°C) [11].

The condensate formation in the super-grain space of a metal silo is possible with a sharp drop in temperature (more than 10°C) even at a grain temperature of 10°C in the embankment and at a relative humidity of intergranular spaces of 65%. In this case, the relative humidity of the air in the upper part of the embankment increases when air enters the super-grain space up to 90%, which leads to the transition through the dew point and the formation of condensate. It should be noted that in the cross section of the silo, the density of the grain mass is different (in the center it is higher, to the periphery - lower). In the center, grain cooling is slower. The temperature field along the silo section is uneven, in the center it is from 10 to 14°C, in the zone closer to the walls - from 2 to 8°C. At the same time, the moisture content of wheat grains did not exceed 14%.

Experimental storage showed that the grain with a moisture content of up to 13.6% without deterioration in quality can be stored for up to nine months. A longer shelf life is possible for wheat grains with a moisture content of up to 12% [12].

The existing approaches to the analysis of the reasons for the lower technological suitability of metal silos in comparison with reinforced concrete containers for long-term grain storage do not give proper attention to the processes taking place in the under-roof space of a metal silo, and, as a result, do not consider all possible measures that can correct this situation.

It should be emphasized that the grain-filled inner surfaces of the metal silo are practically not exposed to the risks of condensation of moisture contained in the intergranular air, which is explained by the specifics of phase balancing between the surfaces of the grains and the intergranular air [13].

It is from the last statement in this part that the simplest and least costly way to improve the conditions for ensuring the grain quality preservation during its long-term storage in a metal silo is as follows: it is necessary to load such silo with the grain completely, preferably under the neck, leaving as little free grain space as possible. This minimizes the area of the inner surfaces of the metal silo, on which moisture condensation is possible to occur and to contact with the grain subsequently. It should be borne in mind that not all designs of metal silos allow loading grains under the neck [14].

## 4. Discussion

An effective method of reducing the possible moisture condensation on the inner surface of the roof is a proper organization of its convective ventilation. In house-building technologies, such a problem is well known and has proven solutions that can very well be applied to provide ventilation of the under-roof space of a metal silo. The essence of these decisions is to provide an under-roof space with specially directed movement of convective ascending flows of external air.

Such free air convection in the under-roof space can be achieved by installing a set of special air supply and air discharge aerators, moreover, air discharge aerators should be installed at the upper marks of the roof, and air supply aerators are closer to its lower cut. In some roof constructions, manufacturers declare an annular gap along the lower perimeter of the roof - it could be considered as a distributed air supply aerator. The outer surface of the roof supplied with a design set of aerators - inlet and outlet ones. However, this is a task for manufacturers of silos as aerators' installation cannot be fully implemented by the operating organization. Manufacturers of silos do not pay enough attention to this problem. The standard air distribution devices installed on the roof of the silo, in essence, solve the problem of air inlet and outlet into and out the silo when loading or unloading grain, as well as with active ventilation of grain in the silo. Numerous data and materials at our disposal confirm that the practiced arrangement of such air-distributing devices on the silo roof does not provide full convective ventilation of the inner surfaces of the silo roof and, accordingly, does not help to reduce the risks of grain moistening with moisture condensation [15].

Another passive technique that can reduce the risks of the described condensation of moisture is the thermal insulation of surfaces [16]. Moreover, it is advisable to carry out such insulation first of all at the silo roof. Thermal insulation of the walls of the silo, apparently, will give a much smaller economic effect due to its significantly higher costs (because of large area) and lower technological efficiency. The indicated trick also belongs to the category of recommended design solutions for manufacturers of silos [17, 18].

## 5. Conclusion

Ways to improve conditions to ensure high-quality grain preservation during its long-term storage in metal silos are as follows.

1. It is necessary to load the metal silo with grains completely, preferably under the neck, leaving as little free grain space as possible.

2. It is necessary to organize properly the convective roof ventilation by installing a set of special air supply and air discharge aerators.

3. It is necessary to provide thermal insulation of the roof surface of metal silos.

4. When the values of the temperature difference of the stored grain mass in metal silos and outdoor air are less than 10°C, the specific energy costs are doubled.

## Funding

This work was carried out as part of the state assignment for topic No. 0585-2018-0003 “Development of the flour and cereals technology with the aim to increase the degree of raw material use and to expand the assortment by developing products of advanced processing and integrated criteria for evaluating grain and flour for its intended purpose”.

## Acknowledgement

We greatly appreciate assistance in conducting the study of the employees of the elevator laboratory of the all-Russian Research Institute of Grain and its Processed Products (VNIIZ) - a branch of the FSBIU “Federal Food Science Center named after V.M. Gorbatiy” RAS.

## Conflict of Interest

The authors have no conflict of interest to declare.

## References

[1] Vassiliev, V., *et al*. (2012). Impact of the 3d Flow Effects on the Silo Combustor Thermal State. *Proceedings of the ASME Turbo Expo,* pp. 881–890.

[2] Toffolo, M., *et al*. (2018). Microarchaeology of a Grain Silo: Insights into Stratigraphy, Chronology and Food Storage at Late Bronze Age Ashkelton. *Journal of Archaeological Science*, pp. 177–188.

[3] Bonner, M. and Alavanja, M. (2017). Pesticides in Human Health and Food Security. *Food and Energy Security*, vol. 6 issue 3 pp. 89–93.

[4] Davies, W. and Ribaut, J. (2017). Stress Resilience in Crop Plants. Strategic Thinking to Address Local Food Production Problems. *Food and Energy Security*, vol. 6 issue 1 pp. 12–18.

[5] Pollock, C. (2016). Sustainable Farming: Chasing a Mirage? vol. 5 issue 4 *Food and Energy Security*, pp. 205–209.

[6] Cervelin, B., *et al*. (2017). A Computer Model for Particle-Like Simulation in Broiler Houses Computers and Electron. *Computers and Electronics in Agriculture* vol. 141 pp. 1–14.

[7] Oates, M., *et al*. (2017). Low Cost Sunlight Analyser and Data Logger Measuring Radiation Computers and Electron. *Computers and Electronics in Agriculture*, vol. 141 pp. 38–48.

[8] Gilmore, C., *et al*. (2017). Industrial Scale Electromagnetic Grain Bin Monitoring *Computers and Electronics in Agriculture*, vol. 136 pp. 210–220.

[9] García-Nieto, P., *et al*. (2017). Modeling Pressure Drop Produced by Different Filtering Media in Microirrigation Sand Filters using the Hybrid ABC-MARS-Based Approach, MLP Neural Network and M5 Model Tree *Computers and Electronics in Agriculture*, vol. 139 pp. 65–74.

[10] Huang, Y. and Li, C. (2017). Real-Time Monitoring System for Paddy Environmental Information based on DC Powerline Communication Technology *Computers and Electronics in Agriculture*, vol. 134 pp. 51–62.

[11] Stone, G. and Glover, D. (2017). Disembedding grain: Golden Rice, the Green Revolution, and heirloom seeds in the Philippines. *Agriculture and Human Values*, vol. 34 pp. 87–102.

[12] Bhatta, M., *et al*. (2018). Genome-Wide Association Study Reveals Novel Genomic Regions for Grain Yield and Yield-Related Traits in Drought-Stressed Synthetic Hexaploid Wheat. *International Journal of Molecular Sciences,* vol. 19(10) pp. 34-39.

[13] Kechkin, I., *et al*. (2020) Dependence of Fat Acidity Value on Wheat Grain Storage Conditions. *BIO Web of Conferences*, vol. 17 issue 3 pp. 34-39.

[14] Kechkin, I., *et al*. (2020). Management of Air Flows Inside Steel Silo During Grain Storage. *BIO Web of Conferences*, vol. 17 issue 3, pp. 22-25.

[15] Li, X., *et al*. (2018). Role Of Mid- and Far-Infrared for Improving Dehydration Efficiency in Beef Jerky Drying. *Drying Technology*, vol. 36 issue 3 pp. 283-293.

[16] Sritongtae, B., Duangmal, K. and Morgan, M. R. A. (2017). Drying Kinetics, Physico-Chemical Properties, Antioxidant Activity and Phenolic Composition of Foam-Mat Dried Germinated Rice (Vigna Umbellata) Hydrolysate. *International Journal of Food Science and Technology*, vol. 52 issue 7 pp. 1710-1721.

[17] Farias, V. S. O., *et al*. (2018). Drying Study of Ceramic Tiles using Three-Dimensional Analytical Solution of yhe Diffusion Equation. *JP Journal of Heat and Mass Transfer*, vol. 15 issue 2 pp. 409-432.

[18] Alves-Filho, O. (2018). Energy Effective and Green Drying Technologies with Industrial Applications. *Chemical Engineering Transactions*, vol. 70 pp. 145-150.