Modelling grain active ventilation process in the silos

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Abstract. Changes in grain raw material properties in a complex thermophysical process are presented in the article, and a multifactorial mathematical model for developing engineering solutions for active ventilation is obtained. A numerical study of non-stationary changes in temperature and moisture content in a one-dimensional grain layer along with the height of a metal silo depending on environmental conditions is carried out. The simulation of the temperature and moisture fields in siloses is important for assessing the state and determining the parameters of the active ventilation system. The results show a significant air velocity effect on cooling and the speed of the drying process. The overall duration of drying and cooling of the grain top layer depends slightly on the initial parameters of the air such as the temperature and the moisture content. The obtained model is reliable to predict the drying kinetics for different storage conditions and different grain types. With the help of the presented model, it is possible to substantiate the safe grain storage modes in conditions of heterogeneity and temporal variations of standard parameters (temperature, air humidity).

1. Introduction
In the process of post-harvest processing of grain crops, storage occupies a special place. As a rule, the dried grain is stored for a long time in metal silos. Therefore, a careful monitoring of the grain mass parameters during this time is required. The importance of grain storing is also justified by economic factors. For farms and agricultural complexes, the main period of grain sales is the harvest period, when the grain price is the lowest. If quality storage is organized, then grain can be sold for an extended period of time, when the prices increase and the products acquire extra commercial appeal. The overall time of grain storage depends on the moisture content: during the long-term storage it should never exceed 6-12% depending on the type of grain products. The storage period time for quality products is reduced with humidity increase. Thus, it is necessary to create the temperature mode that accords with the regulatory requirements for various types of storage of cereals or legumes. This is also solved with the help of ventilation systems, by maintaining the necessary parameters of the grain (humidity and temperature). The main objective of proper storage organization is to determine the modes of periodic layer blowing to prevent spontaneous grain combustion and moisture condensation that may appear on the inner surfaces of the walls and silo roof [1]. To preserve the grain quality efficiently, the problem of internal heat and moisture exchange modeling in metal silos during grain storage in a dense bed is solved.
2. Mathematical model

The states of the system are described by the system of non-stationary differential heat and mass transfer equations. The mathematical model presented in this article contains linear differential equations of the first order with two independent variables: \( \tau \) is the grain cooling time and \( z \) is the height of the granary refilling. The calculations used the numerical Euler method. The simulation was performed using the Matlab Simulink software. The described processes occur in the air flow and in the grains during the active ventilation while the grain moisture content changes.

The developed mathematical model allows determining parameters of the heat and mass transfer kinetics of thermal-moisture treatment of the grain mass. These parameters influence the choice of the air parameters with active ventilation. The model also predicts the air temperature at the exit of the grain layer as well as the grain temperature after cooling. The influence of various factors – air velocity, initial air temperature, and granary refilling height – on the layer warm-up time is shown.

The system consists of differential equations that describe the temperature distribution \([2]\) and the moisture content over the grain height in time. This system is based on the thermal and mass balance for air and for grain in an elementary grain layer of height \( dz \). It also includes the equations that describe the relationship between the temperature \( t_w \) and the moisture content \( x_a \) on the saturation line, i.e., on the surface of the grain mass. The system of equations (1) - (7) is composed for a single layer of grain of height \( dz \), where \( f \) is the surface area of the grain of one layer related to the volume of grain in it, \( f_1 \) is heat exchange area in layer \( dz \), and \( G \) is the flow rate of air .

The main assumptions of the mathematical model are as follows:
- the movement of air in the grain layer is one-dimensional; flow parameters (temperature and moisture content of air) and grain parameters (temperature and moisture content) in a layer change only in time and over the vertical coordinate \( z \).
- thermophysical properties of grain and air are taken approximately constant.

Initial and boundary conditions:
- \( \Theta_0 = 30 \, ^\circ\text{C} \); \( t_{a0} = 10 \, ^\circ\text{C} \);
- \( \omega_0 = 0.14 \, \text{kg H}_2\text{O/kg dry grain} \); \( x'_a = 0.008 \, \text{kg H}_2\text{O/kg dry grain} \);

Figure 1. The scheme of modelling grain active ventilation in silos: \( dz \) – elementary grain layer, \( z \) – the silo height, \( t_a \) – air temperature, \( t_2 = \Theta (\tau) \) – grain temperature, \( \omega \) = absolute grain humidity, \( x_a \) = absolute air humidity, \( u \) = air velocity.
where the heat transfer coefficient is calculated taking into account the internal thermal resistance of individual grains:

\[ K = \frac{1}{\frac{1}{\alpha} + \frac{d_{eq}}{2} \cdot \lambda_g} \]  

The heat transfer coefficient \( \alpha \) from the grain layer to the air is determined by the Nusselt number calculated by the following criterial relation:

\[ Nu_t = 1.38 Re^{0.5} Pr^{0.33} \]  

The mass transfer coefficient in the grain layer \( \beta \) based on the Lewis ratio, related to the moisture content of air, is:

\[ \beta = \frac{\alpha}{c_{pa}} \]  

### 3. Results and Discussions

The graphs represented in figure 2, 3 show the change of parameters during the heat and mass transfer process for 10 grain mass layers. The thickness of each layer is \( dz = 1 \text{ m} \) for wheat grains, and the air velocity is \( u = 0.1 \text{ m/s} \). The initial conditions for this calculation of the moisture content of grain are \( \omega_0 = 0.14 \text{ kg H}_2\text{O} / \text{ kg of dry grain} \); moisture content of air at the entrance to the first layer \( x_1' = 0.008 \text{ kg H}_2\text{O} / \text{ kg of dry air} \); air temperature at the entrance to the 1st layer \( t_1' = 10 \degree \text{C} \); and the initial grain temperature in the whole volume \( \Theta = 30 \degree \text{C} \).

It can be seen that during the ventilation process that the grain temperature gradually decreases towards the temperature of the cold air supplied to the first layer from the outside. At the same time, higher layers cool down more slowly due to air saturation in the lower layers of the grain mass. Similarly, the total moisture content of the grain layers decreases due to the moisture transfer from the upper hotter areas down to the colder ones. The graphs in figure 4 show changes in temperature and moisture content of wheat over time depending on the height of the metal grain storage facility for different values of the cooling air velocity.

The lower the air temperature, the drier it is and the more intense the mass exchange between the air and the grain is. Accordingly, figure 5 shows the change in moisture content of the grain \( \omega \) [kg H\(_2\)O / kg dry grain] over time in the last grain layer (10 m) for different initial air parameters (\( t_1' = 10 \degree \text{C}, t_1' = 15 \degree \text{C}, t_1' = 5\degree \text{C} \)).
Figure 2. The grain temperature $\Theta$ [$^\circ$C] distribution over the height of the metal silo in time.

Figure 3. The grain moisture content $\omega$ [kg H$_2$O/kg dry grain] distribution, over the height of the metal silo in time.
4. Conclusion

The effect of the air velocity and initial temperature on the duration of the layer cooling to ambient temperature has been studied. It is shown that the most notable effect on the duration of cooling is exerted by the air velocity.

Thus, an increase in the air velocity from 0.5 m / s to 0.1 m / s accelerates the layer cooling by 92%. A further increase in speed up to 2 m / s leads to 2.6 times faster cooling compared with that at the speed of 0.5 m / s. The obtained quantitative data demonstrate the effect of the air velocity and initial temperature on the grain cooling and drying time. The lower the initial air temperature, the drier it is and the more prominent the decrease of the moisture content of the grain is. However, these factors do not affect the process timing.

Based on the data obtained, it is also possible to conclude that the effect of the air heating and humidifying while it passes through the layers of grain is quite considerable. The temperature difference between the lower and upper layers of the grain mass is about 10-15 degrees. An increase in the air temperature in the upper layer during the process of ventilation above the values of the critical temperatures of moisture loss leads to the formation of condensate on the inner surfaces of the metal.
Thus, in the absence of additional preparation of parameters of air (dehydration, dehumidification) [4] supplied to aeration, control over the air parameters for active ventilation is necessary when building the system.

In the case when the air temperature rises above the critical temperature of the outside air, it is necessary to apply compensatory measures to preserve the products, one of which may be an increase of the air velocity for ventilation.

References
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