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MODELING OF AIRFLOW DISTRIBUTION IN A STATIONARY POROUS BULK

Arlauskas D.[1], Zvicevičius E.[1], Paskačimas K.[2]
[1] Faculty of Engineering, Vytautas Magnus University, Kaunas, Lithuania.
[2] Faculty of Natural Sciences Vytautas Magnus University, Kaunas, Lithuania.

This paper investigates the airflow distribution in a stationary porous grain bulk. The aim of the study was to develop a mathematical model for a ventilated stationary porous layer, analyze airflow dispersion, and compare the results of CFD (Computational Fluid Dynamics) simulations with experimental data. The modeling was performed using SolidWorks software, while experimental measurements were conducted in a specially designed test stand. To assess the accuracy of the developed model, a statistical analysis was carried out using an independent two-sample t-test and Fisher's criterion. The experimental and simulation results showed strong agreement, with no statistically significant difference detected between their variances ($p < 0.05$). The findings confirm that the developed mathematical model accurately represents airflow behavior in the stationary porous grain bulk. The simulation results allow for a more detailed visualization of airflow distribution, identifying zones of excessive flow and stagnation. These insights contribute to optimizing ventilation system efficiency, reducing energy consumption, and improving grain storage conditions.

Keywords: grain, ventilation, airflow, CFD modeling, SolidWorks.

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Introduction

Wheat is one of the primary sources of food and livestock feed worldwide, therefore the research of their processing and cultivation is of great importance as it could lead to a greater quality and quantity of yield and reduce storage losses. During vegetation crop yield and quality is affected by diseases, pests and environmental conditions, while during storage, proper use of technologies ensures optimal conditions, prevents spoilage and reduces quantitative and qualitative losses (Khatchatourian et al., 2009; Raila et al., 2019). Wheat grows during only warm seasons, but their consumption continues throughout the whole year, therefore maintaining their quality during storage is equally important as their cultivation. During storage, the quality of grain bulk can change due to natural processes and environmental factors. Mass losses can reach 1-2% or even more (Khatchatourian et al., 2009; Mateen et al., 2025). While it is not possible to avoid quantitative and qualitative losses of yield, these losses can be considerably reduced if proper and effective ventilation systems are used (Khatchatourian et al., 2009; Liang et al., 2020).

Many researchers are conducting studies related to grain drying and heat-mass exchange in grain bulks (Petruševičius et. al., 2009; Katchatourian et. al., 2009; Horabik et al., 2020; Xiaoliang et al., 2025). It is stated that to reduce mass and quality losses during storage, it is essential to keep grains at low temperatures. If dried grains are not cooled before storage, their biological activity increases along with the risk of grain pests and mold occurrence (Katchatourian et al., 2009; Liang et al., 2020). Additionally, temperature differences between layers of the grain bulk can lead to condensation formation and increase in grain moisture content (Novošinskas et al., 1999; Liang et al., 2020). To cool the grains and mitigate the mentioned risks, ventilation systems are used in grain storage facilities.

Currently, the most widely used grain ventilation systems are active ventilation ducts and screw-in grain aerators. Both systems are simple in design, however their operation requires knowledge of ventilation and drying processes. Otherwise, the desired results may not be achieved, or the grain may even be damaged.

During ventilation, the uniformity of the cooling process in the grain bulk depends on the installed system and its arrangement within the bulk. Since airflow distribution in the grain layer and the efficiency of the cooling process are directly influenced by the cross-sectional form of the bulk and its other properties, it is often challenging to apply generalized duct layout schemes (Raila et al., 2019; Eichheimer, 2020, Xiaoliang et al., 2025). To accurately select ventilation systems, ducts, their placement and airflow, it is essential to consider the specific characteristics of the storage facility and the grain bulk (Kantzas et al., 2015; Liang et al., 2020). If the airflow distribution within the bulk is uneven, grains in different locations in the bulk will be ventilated at varying intensities, thus the temperature uniformity of the bulk will be disrupted and lead to formation of different temperature gradients (Xiaoliang et al., 2025). Consequently, the viability of the grain and intensity of biochemical and microbiological processes will differ across various zones of the bulk (Khatchatourian et al., 2009; Raila et al., 2019). The digital simulation and analysis of airflow in bulk materials provide the basis for designing, implementing and managing ventilation technologies in agricultural production storage facilities (Kantzas et al., 2015; Liang et al., 2020; Xiaoliang et al., 2025).

The aim of the study: to develop and validate the adequacy of mathematical model that enables the simulation of the distribution duct-grain bulk system and the analysis of airflow distribution patterns in the ventilated grain layer.

Goals:

1. To develop a mathematical model of the distribution duct-grain system.
2. To conduct experimental aerodynamic studies of the distribution duct-grain bulk system.
3. To evaluate the adequacy of the developed mathematical model.

Object and methods

This study presents a simulation of airflow distribution and experimental investigations to evaluate the adequacy of the model. The mathematical model of the equivalent cross-section of the grain bulk was developed using 3D modeling software SolidWorks. The dimensions and geometric shape of the modeled equivalent cross-section were proportionally selected based on a real storage facility and the grain bulk stored within it, scaled down by a factor of 10 (Fig. 1).

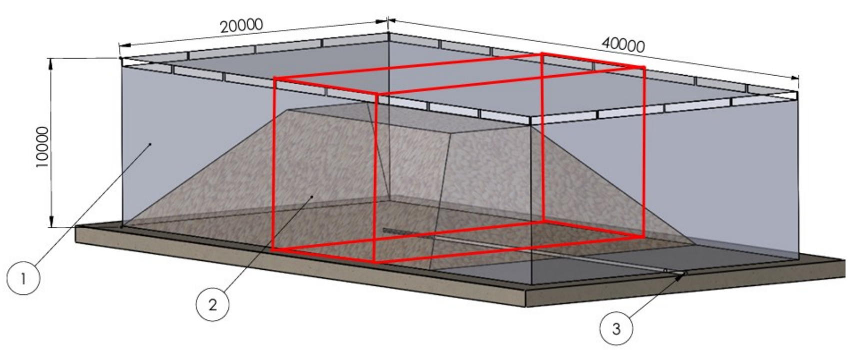

Fig. 1. Modeled grain storage facility and its equivalent cross-section: 1 – storage facility; 2 – grain bulk; 3 – ventilation duct.

The geometric model of the equivalent cross-section of the grain bulk was treated as a homogenous solid body with porous medium properties. In reality, a grain bulk consists of a large number of small solid particles, making individual particle modeling an inefficient process (Eichheimer, 2020). Therefore, a simplified modeling approach was chosen: the grain bulk was treated as a porous medium (Novošinskas et al., 1999) with aerodynamic properties approximating those of an actual grain bulk. In the CFD (Computational Fluid Dynamics) simulation, the pressure drop of airflow through the grain layer is evaluated based on the porosity and equivalent pore diameter (Eichheimer, 2020; Xiaoliang et al., 2025). The porosity of the grain can vary between 0.4 and 0.5 (Dan Agro center, 1999; Novošinskas et al., 1999; Petruševičius, Raila 2009), in further calculations and simulations, a value of 0.5 is used. The equivalent pore diameter can range from 1 to 2 mm (Novošinskas et al., 1999; Petruševičius, Raila, 2009), to determine its exact value, this parameter was calculated using the Ergun equation (Eichheimer, 2020) (equation 1). This equation is used to predict gas pressure drop as it flows through the medium, filled with uniformly sized spherical particles.

$$\Delta P = \frac{150 \cdot L \cdot (1-\epsilon)^2}{d_p^2 \epsilon^3} \mu \upsilon + \frac{1.75 \cdot L \cdot (1-\epsilon)}{d_p \epsilon^3} \rho \upsilon^2 , \quad (1)$$

where: ΔP – pressure drop, Pa;

ϵ – porosity of medium, accepted value 0.5;

d_p – equivalent pore cross-section, mm;

υ – velocity of air exiting the supply duct, m/s;

μ – dynamic air viscosity, accepted value $1.52 \cdot 10^{-5}$ Pa·s;

ρ – air density, accepted value 1.2 kg/m³;

L – distance between pressure measurement points, accepted value 1.145 m.

Air pressure drop was determined through experimental studies conducted on a specially designed test stand. To prepare for the study, a test stand identical in shape and dimensions to the equivalent cross-sectional model of the grain bulk was constructed (Fig. 2). The test stand is assembled from OSB boards. To ensure tightness, the joints of the boards were sealed with silicone. The inside of the stand was lined with foam to minimize air gaps between the grain bulk and the OSB boards. A flange was attached to the side panel of the stand, to which the fan's air supply duct was connected. The airflow supplied to the grain bulk was measured using an Almemo FVAD15 anemometer by determining the air velocity at the fan inlet. By adjusting the rotational speed of the fan's impeller, an airflow rate of 118 m^3/h was determined. 200 kg of grain was poured into the test stands. At the highest point, the grain bulk reached a height of 550 mm with a natural angle of repose of 23°.

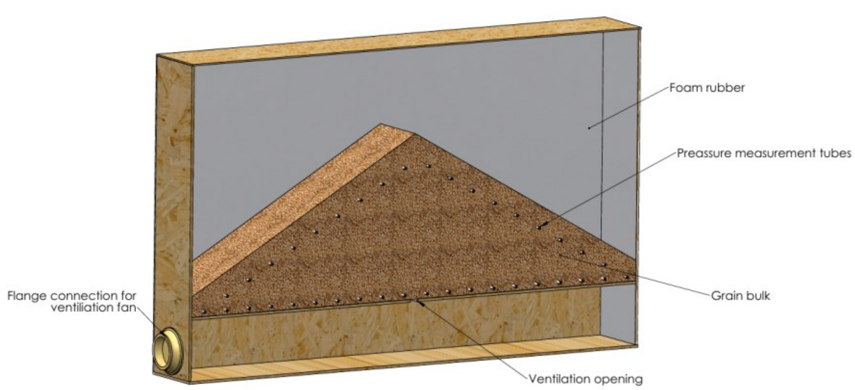

Fig. 2. Schematic diagram of experimental test stand

To measure the air pressure, 40 pressure measurement nozzles were installed along the perimeter of the grain bulk, spaced 100 mm apart on the side panel of the stand. Static pressure measurements were carried out using two different devices: the Almemo FDA602S1K and the MMG-2240 micromanometer. Each measurement was repeated twice. Given that the grain bulk had an isosceles triangular shape and was symmetrical, and the static pressure measurement points were symmetrically positioned along its central axis, the results from corresponding symmetrical points were averaged. The mean static pressure values and associated errors were calculated based on a total of eight individual readings.

By measuring the static pressure of the airflow passing through the grain layer at various locations within the bulk and evaluating the differences and distribution in the cross-section, the air pressure drop was determined (equation 2):

$$\Delta P = P_{max} - P_{min}, \tag{2}$$

where: P_{max} – the highest measured airflow pressure value, Pa;

P_{min} – the lowest measured airflow pressure value, Pa.

After calculating the pressure drop value, all equation values are determined except for the equivalent pore diameter. The Ergun equation (Eichheimer, 2020) is rearranged so that it can be solved as a quadratic equation (equation 3):

$$\frac{150 \cdot L \cdot (1-\epsilon)^2}{\epsilon^3} \mu v + \frac{1.75 \cdot L \cdot (1-\epsilon)}{\epsilon^3} \rho v^2 d_p - \Delta P d_p^2 = 0. \tag{3}$$

The equivalent cross-sectional model of the grain bulk in SolidWorks software was assigned the same parameters as those used in the experimental studies: an airflow rate of 118 m^3/h and the bulk geometry. In the simulation results, measurement sensor zones were assigned, from which four values were extracted. The highest value, the lowest value and 2 most commonly occurring values. The accuracy of the CFD model was validated with independent two-sample t-test and Fisher's criterion, with a significance level of $p < 0.05$.

Results and discussion

Experimental studies were conducted using an airflow of 118 m^3/h while the grain bulk height at the midpoint was 550 mm with a repose angle of 23°. Since the air was supplied through a 30 mm wide duct located at the center of the test stand, and the grain bulk had an irregular shape, the airflow distribution was uneven. The following figure (Fig. 3) presents the pressure distribution at the bottom and surface of the grain bulk.

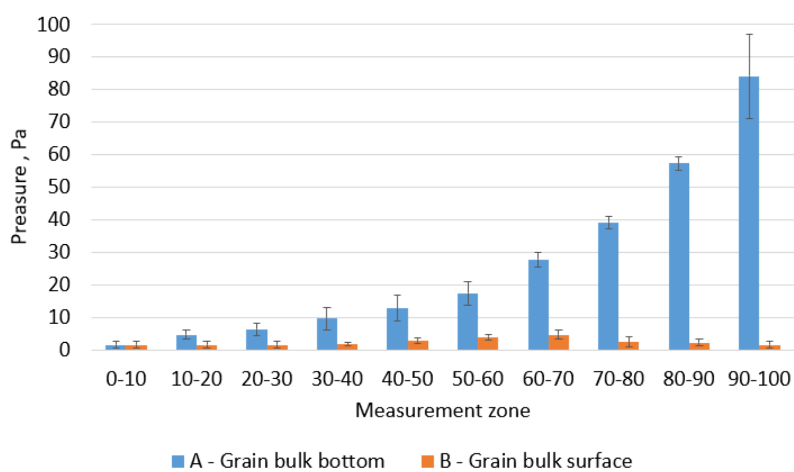

Fig. 3. Airflow pressure distribution in the grain bulk with a 23° repose angle

During the experimental study, it was determined that the highest pressure of 84.06 ± 12.8 Pa forms in the 90-10 measurement zone, parallel to the bottom of the grain bulk (Fig. 3). As the distance from the ventilation opening increases, the pressure decreases parabolically and drops to 1 ± 0.9 Pa in the 0-10 measurement zone, which is the farthest from the opening. Analyzing the reading from the surface pressure sensors of the grain bulk, a mound-shaped pressure distribution was observed along the entire length of the bulk. The lowest pressure of 1.5 ± 0.9 Pa was recorded at the points farthest from the air supply located at the top of the bulk near the test stand edge. The highest pressures were recorded in the 50-60 and 60-70 measurement zones, at 3.2 ± 0.9 Pa and 3.4 ± 1.4 Pa, respectively. Therefore, it can be concluded that airflow is concentrated through the center of the grain bulk and exits from the top in the 50-70 cm measurement zones.

A CFD simulation in SolidWorks was conducted under identical conditions. The following section presents the results of the airflow pressure distribution simulation (Fig. 4). As shown in Figure 4, the highest airflow pressure value was determined to be 85 ± 4.7 Pa. Similar to the experimental study, the lowest pressure was recorded at points farthest from the ventilation opening, in the 0-10 measurement zones. Through simulation, the pressure in this area was found to be 2.2 ± 0.69 Pa. In the measurement zones parallel to the top of the grain bulk, the highest pressure values were recorded as 3.95 ± 0.63 Pa (50-60 measurement zone) and 4.6 ± 0.79 Pa (60-70 measurement zone). Although both the experimental study and the simulation allow for the determination of pressure at sensor locations, the pressure distribution map provided by the simulation reveals stagnation zones that form above the 0-10, 10-20, and 90-100 sensors.

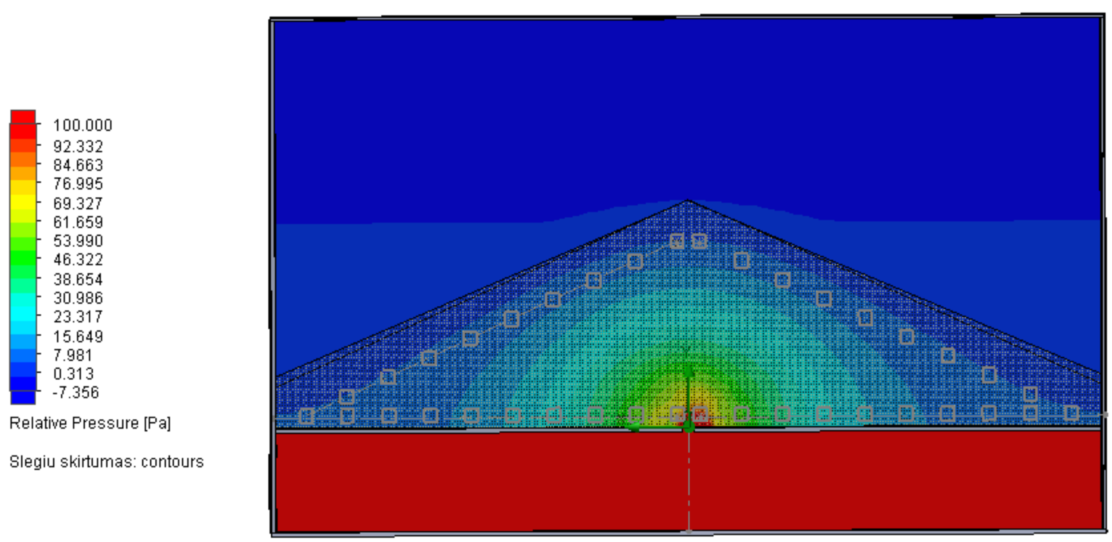

Fig. 4. CFD simulation of the grain bulk with a 23° angle of repose

To assess the adequacy of these simulation results, they are compared with the experimental study. The comparisons are presented in Figures 5 and 6.

The measurements from the simulation and experimental study (Fig. 5 and Fig. 6) were statistically compared using two methods. The first method (Fisher's F-test) involved paired group comparison, where each set of eight measurements within a group was compared with another set of eight measurements from the same group. The second method (the independent two-sample t-test) involved comparing the mean values, where the average values from all measurement zones in the experimental study were compared with the corresponding simulation averages.

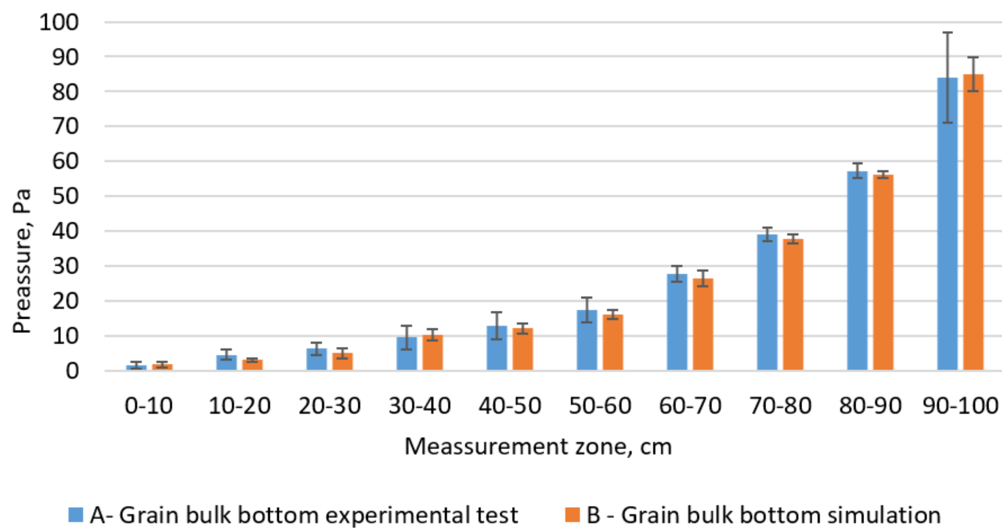

Fig. 5. Measurement and simulation results at the bottom of the grain bulk with a 23° repose angle under an airflow of 118 m^3/h

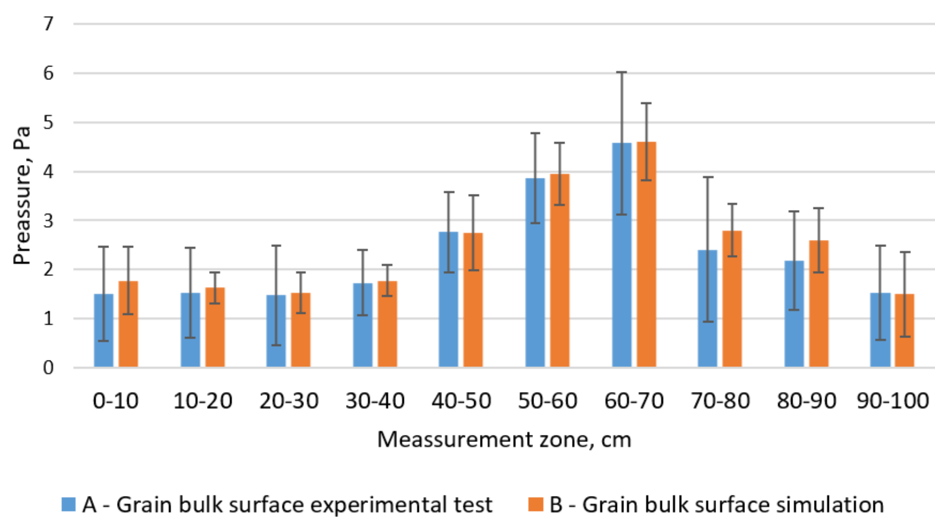

Fig. 6. Measurement and simulation results at the surface of the grain bulk with a 23° repose angle under an airflow of 118 m^3/h

Initially, Fisher's criterion was applied to determine whether the variances of the two groups were equal. The critical value for the F-test was calculated as follows (equation 4):

$$F_{crit} = \frac{S_1^2}{S_2^2}, \tag{4}$$

where: F_{crit} – critical value of the F-test, calculated as the ratio of the variances of two groups;

S_1, S_2, – variance of the first and the second group.

When comparing variances statistically, a significance level of 0.05 is used (Table 1). If no statistically significant difference between the variances is found, the analysis proceeds with an independent two-sample t-test assuming equal variances. The *p*-value for this test is calculated using the following formula (equation 5):

$$p = \frac{\bar{X}_1 - \bar{X}_2}{s_p \cdot \sqrt{\frac{1}{n_1} - \frac{1}{n_2}}}, \tag{5}$$

where: p – represents the test statistic used in the two-sample Student's t-test. It is used to determine whether there is a statistically significant difference between the means of two independent samples;

$\bar{X}_1$, $\bar{X}_2$ – the means of the two samples;

n_1 ir n_2 – sample sizes of the two samples;

s_p – pooled standard deviation.

The results of the statistical comparison are presented in Table 1.

Table 1. Comparison of means and paired groups

Paired group comparison												Overall mean comparison	
Grain bulk bottom												Grain bulk bottom	
Measurement zone	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Critical value	Calculated value	Critical value
F Test	1,949	8,132	1,584	4,947	6,312	8,367	1,135	2,188	4,930	7,390	9,276	1,017	3,179
T Test	0,437	0,014	0,119	0,478	0,567	0,276	0,233	0,071	0,112	0,810	0,05	0,959	0,05
Grain bulk surface												Grain bulk surface	
Measurement zone	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Critical Value	Calculated value	Critical value
F Test	1,949	8,681	6,248	4,475	1,141	2,101	3,346	7,373	2,402	1,236	9,276	1,019	3,179
T Test	0,437	0,733	0,885	0,829	0,970	0,780	0,962	0,390	0,248	0,923	0,05	0,786	0,05

Note: values highlighted in red denote statistically significant differences at the 0.05 significance level ($p < 0.05$). Values highlighted in green indicate no statistically significant difference.

According to Table 1, when comparing individual measurement zones based on variance differences, none of the Fisher's test values exceeded the critical value (9.276): no statistically significant differences between the simulation and experimental results were observed. Therefore, the independent two-sample t-test for equal variances was applied. At a significance level of $p < 0.05$, no statistically significant difference was found in 19 out of 20 zones. Statistical analysis comparing the means of all zones showed no statistically significant difference between the simulation and experimental results, based on both Fisher's test ($F_{crit} = 1.017$) and the independent two-sample t-test ($p < 0.05$). These two statistical methods confirm the adequacy of the developed model.

Conclusions

1. A mathematical model of the airflow distribution system–grain bulk was developed, enabling CFD simulations by modifying the duct position, airflow rate, and grain bulk size and shape.

2. Experimental studies demonstrated that the highest pressure of 84.06 ± 12.8 Pa formed near the ventilation opening, while the lowest pressure of 1.5 ± 0.9 Pa was recorded at the bulk edge and surface.

3. Statistical analysis indicated that 1 out of 40 measurement points was inconsistent, but in the overall mean comparison, no statistically significant difference was observed. Statistical methods confirmed that the developed model is adequate; only one measurement zone showed a significant difference between the measured and simulated results.

4. The simulation-generated graphs facilitate the identification of airflow distribution patterns, detection of excessive flow and stagnation zones, and allow for faster and more cost-effective optimization of ventilation systems. The use of simulation-generated graphical representations of the grain bulk duct system model enables easier identification of airflow distribution patterns, detection of high-flow and stagnation zones, and allows for faster and more cost-effective optimization of ventilation systems.

References

1. Dan Agro centras. Kaip džiovinti grūdus aruodiniuose sandėliuose (How to Dry Grain in Storage Warehouses). Vilnius: Sapnų sala, 1999. 62 p.
2. Eichelheimer, P. Fluid flow in porous media: A combined numerical and experimental approach. Bayreuth University Repository, 2020.
3. Horabik J., Wiacek J., Parafiniuk P., Banda M. Calibration of discrete-element-method model parameters of bulk wheat for storage. Biosystems Engineering, 2020, 200(6), 298-314.
4. Kantzas, A., et al. Fluid flow in porous media: Experimental and numerical approaches. Journal of Agricultural Engineering, 2015, 58(2), 123–136.
5. Khatchatourian, O. A., Toniazzo, N. A., Gortshoy, Y. F. Simulation of airflow in grain bulks under anisotropic conditions. Biosystems Engineering, 2009, 104, 205–215.
6. Liang, X., et al. Fundamentals of Fluid Flow in Porous Media. 2020. 408 p.
7. Mateen, M., Khan, Z. A., Minli, Y., Wenqiu, M., Tola, A. A. Enhancing wheat storage efficiency: A microcontroller-based environment control system for silo. Smart Agricultural Technology, 2025, 11, 100865. ISSN 2772-3755.
8. Novošinskas, H., Raila, A., Steponaitis, V. Augalininkystės produktų laikymo technologijos, sandėliai ir įrenginiai (Storage Technologies, Warehouses, and Equipment for Crop Products). Kaunas: Lietuvos žemės ūkio universitetas, 1999. 59 p.
9. Petruševičius, V., Raila, A. Augalininkystės produktų džiovinimas storame nejudančiame sluoksnyje (Drying of Crop Products in a Thick Static Layer). Akademija: Lietuvos žemės ūkio universitetas, 2002. 262 p.
10. Raila, A., Zvicevičius, E., Čipienė, A. Grūdų sandėlių ventiliacija ir laikymo sąlygų stebėjimas. Mano ūkis, 2019.
11. Xiaoliang, W., Ying, Z., Wang, Y., Yanbo, H., Haiyang, D. Permeability prediction of bulk wheat for storage using micro-computed tomography and lattice Boltzmann method. Biosystems Engineering, 2025, 253, 104124. ISSN 1537-5110.
12. Xiaoliang, X., et al. (2025). Advances in grain storage modeling: A comprehensive review. Journal of Cereal Science, 100, 103274.

Author for contacts

Dovydas Arlauskas

Vytautas Magnus University, Faculty of Engineering, Kaunas, Lithuania.

Tel.: +370 625 15362

E-mail: dovydas.arlauskas1@stud.vdu.lt