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AIRFLOW MODELING IN A GRAIN SILO

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K e y w o r d s: silo, airflow, distribution of airflow velocity, discretization, model, process simulation.

A b s t r a c t

Grain storage in a silo requires the passage of a forced air stream through grain layers for the purpose of airing, cooling and drying the stored product. The intensity of the observed processes is determined by, among others, the distribution of airflow velocity throughout the silo which, in turn, is affected by the silo's structural characteristics and the parameters of the plant material. The objective of this study was to develop a model of airflow through the grain layer, subject to the above parameters. The study involved the development and the formal presentation of a mathematical model and its implementation in a chosen programming environment. For the needs of the modeling process, the part of the silo filled with grain was divided into a finite number of elements with the use of strictly formalized discretization principles.

MODELOWANIE PRZEPŁYWU POWIETRZA W SILOSIE ZBOŻOWYM

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S ł o w a k l u c z o w e: silos, przepływ powietrza, rozkład prędkości przepływu, dyskretyzacja, model, symulacja procesu.

A b s t r a k t

Podczas przechowywania ziarna w silosach zbożowych wskazane jest wymuszenie przepływu strumienia powietrza przez warstwę. Wymuszony przepływ powietrza jest wykorzystywany do wietrzenia, schładzania lub dosuszania magazynowanego ziarna. Intensywność zachodzących procesów zależy między innymi od rozkładu prędkości przepływu strumienia powietrza w całej objętości silosu. Ta z kolei zależy od parametrów konstrukcyjnych silosu i parametrów materiału roślinnego.

Celem pracy było opracowanie modelu przepływu powietrza w warstwie ziarna w zależności od tych parametrów. Zakres pracy obejmował opracowanie i formalizację modelu matematycznego oraz jego implementację w wybranym środowisku programistycznym. Na potrzeby modelu wypełnioną ziarnem objętość silosu podzielono na skończoną liczbę elementów, stosując własne ściśle sformalizowane zasady dyskretyzacji.

Symbols

D	– silo diameter	m
F	– area	m^2
H	– silo height	m
J, N, K	– discretization parameters	
Re	– Reynolds number	
T. ΔT	– temperature	K
V	– volume	m^3
c	– drag coefficient	
p, Δp	– pressure, pressure loss	Pa
t. Δt	– time	s
Q	– fan output	$m^3\ s^{-1}$
q	– volumetric flow rate	$m^3\ s^{-1}$
v	– velocity	$m\ s^{-1}$
κ	– local drag coefficient (empirical constant)	
θ	– porosity	
ρ	– density	$kg\ m^{-3}$

Introduction

Theory and practical experience indicate that the storage of grain in a silo requires the passage of a forced air stream through grain layers. Subject to the volume and the temperature of the airflow, the purpose of this procedure is to air, cool or dry the stored grain. The intensity and quality of the observed processes are determined by, among others, the distribution of airflow velocity throughout the silo which, in turn, is affected by:

- structural parameters of the silo, such as: shape, dimensions, perforation of the walls, point and method of airflow supply;
- parameters of plant material, such as: shape and size of seeds, moisture content, layer porosity (KUSIŃSKA 2006), non-homogeneity of parameter distribution as the result of self-segregation during silo filling (ŁUKASZUK 2005).

In view of the number and the variability of the discussed parameters, their effect on the distribution of airflow velocity is very difficult to determine by way of a natural experiment in an actual site as such a procedure would be very time consuming, costly and impossible to replicate. The effect of those factors could be minimized by performing the experiment in a laboratory, yet this would lead to dimensional analysis problems related to the scale of the experiment (MÜLLER 1983). In view of the above, a simulation experiment based on the mathematical model of the process and a formalized description of partial phenomena seems to offer a sound solution.

Objective and scope of the study

The objective of this study was to develop a model of airflow through the grain layer, subject to the discussed parameters. The model should:
– provide information on the velocity and direction of flow at any point of the stored grain volume;
– support the selection of an optimal airflow supply method;
– provide input data for modeling grain airing, cooling and drying in a silo.

As part of the study, a mathematical model has been developed, formalized and implemented in a selected programming environment. A process simulation has been performed, and the obtained data was validated in view of the results of published empirical studies.

Mathematical model

The mathematical model has been formulated on the following assumptions:
– the modeled process takes place in a set environment;
– to account for the purpose of the modeling process, the characteristic parameters of the studied plant material were layer porosity and the drag coefficient;
– the value of the investigated parameters varies in the volume of stored grain;
– the grain silo has a cylindrical shape with a circular cross-section.

Discretization

For the purpose of discretizing the silo volume filled with grain, this region is divided into thin, horizontal layers, subject to the purpose of modeling and the adopted simplifications (CARVALLO et al. 2006). Alternatively, the layers may be further sub-divided into concentric rings (IGAUZ et al. 2004). Both methods are deployed on the assumption that the observed phenomena and processes are axially symmetric. In the proposed solution, the silo volume filled with grain was regarded as a cylinder with diameter equal to the silo diameter D and height equal to bed height H. Silo volume was divided into a finite number of elements on the following discretization principles:

– the cylinder was equally divided by horizontal planes into a K number of layers;
– each layer was divided into an N number of rings, with a J number of elements in each ring;
– it has been assumed that the core of the layer is divided into four elements, and the number of elements in each successive ring is doubled;

$$\bigwedge_{n=1,N} J = (n + 1)^2 \tag{1}$$

– the radii r_n of successive rings were selected to ensure that the upper and lower areas of all elements, including their volume, are identical.

$$\bigwedge_{n=1,N} r_n = \frac{D \cdot \sqrt{(2^n - 1)}}{2 \cdot \sqrt{(2^N - 1)}} \tag{2}$$

A model division at $N = 4$ and $K = 8$ is presented in Figure 1.

Element

The identified element $E_{i,j,k}$ is part of a ring with flat upper, lower and side walls which are sections of the cylinder's internal and external walls. Unless limited by boundary conditions, airflow takes place through those walls from or in the direction of all adjacent elements (Fig. 2).

Having made the assumption that under the established conditions, air pressure inside the element does not change over time ($p(t)$ = const.), and that relative temperature change $d(\Delta T/T)/dt$ is irrelevant for instantaneous airflow density, the balance equation for the volumetric flow rate in the region of any element takes on the following form:

$$\Sigma\, q_i = q_d + q_g + q_l + q_p + q_w + q_{zl} + q_{zp} = 0 \tag{3}$$

where the applied symbols indicate the following flows: d – lower, g – upper, l – left, p – right, w – internal, zl – external left, zp – external right.

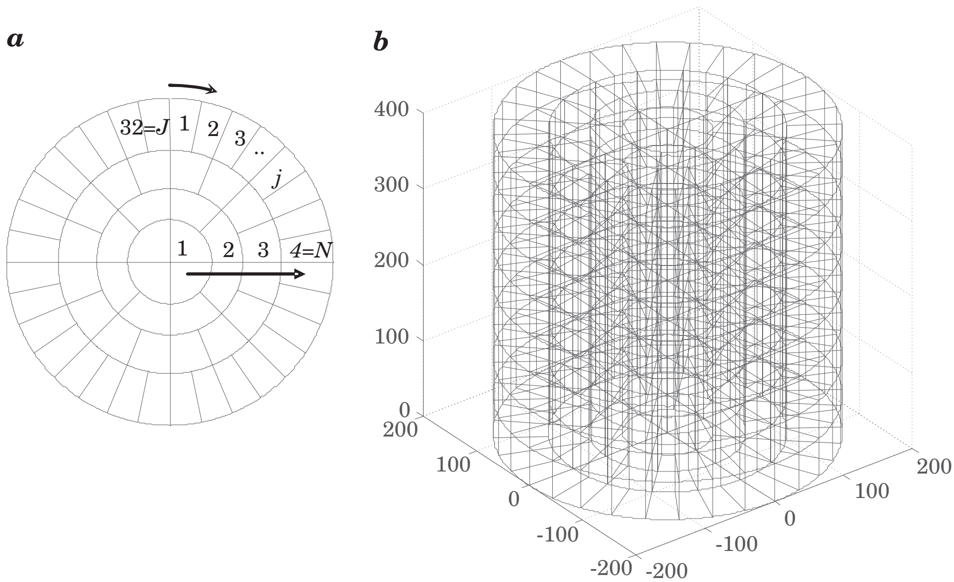

Fig. 1. Discretization of a silo with a diameter of $D = 4$ m and height of $H = 4$ at $N = 4$ and $K = 8$: a – division into elements in a layer, b – division into layers

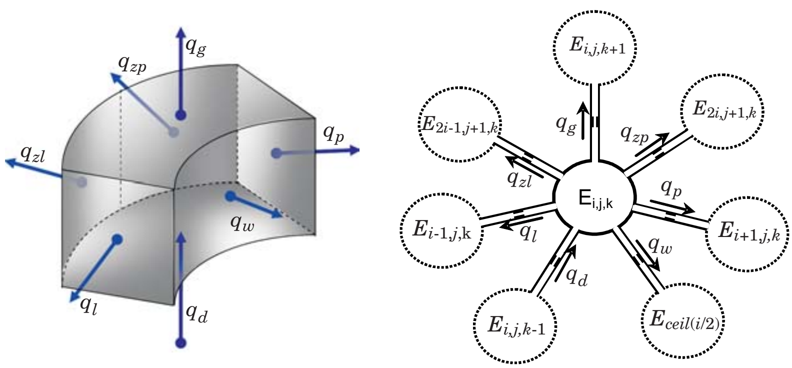

Fig. 2. Airflow model: a – geometric model, b – physical model

Each flow can be expressed in the form of a product of average airflow velocity v_i and effective airflow area F_{ei}:

$$q_i = v_i \cdot F_{ei} \tag{4}$$

The effective airflow area is the product of the area of the i^{th} wall of the element and the porosity θ of the grain layer for the element tangential to the element analyzed in the region of that wall.

$$\theta = \frac{V_e}{V} \qquad \rightarrow \qquad F_{ei} = \theta_i^{\frac{2}{3}} \cdot F_i \tag{5}$$

The geometric surface area of element walls will reach, respectively:

$$F_d = F_g = \frac{\pi \cdot D^2}{16 \cdot (2^N - 1)} \tag{6}$$

$$\bigwedge_{n=1,N} F_w = \frac{\pi \cdot \sqrt{2^{(n-1)} - 1}}{2} \cdot \frac{D}{2 \cdot \sqrt{2^N - 1}} \cdot \frac{H}{K}$$

$$\bigwedge_{n=1,N} F_l = F_p = (\sqrt{2^n - 1} - \sqrt{2^{(n-1)} - 1}) \cdot \frac{D}{2 \cdot \sqrt{2^N - 1}} \cdot \frac{H}{K}$$

$$\bigwedge_{n=1,N} F_{zl} = F_{zp} = \frac{\pi \cdot \sqrt{2^n - 1}}{2^{(n=1)}} \cdot \frac{D}{2 \cdot \sqrt{2^N - 1}} \cdot \frac{H}{K}$$

Flow split

The splitting of the airflow that reaches the element into evacuated flows is determined by the value of the drag coefficient Δp and the correlation between individual drags. The drags are directly proportional to the square of average flow velocity:

$$\Delta p_i = \frac{c \cdot \rho}{2} \cdot v_i^2 = \frac{c \cdot \rho}{2} \cdot \left(\frac{q_i}{F_{ei}}\right)^2 = \frac{c \cdot \rho}{2} \cdot \frac{q_i^2}{\theta_i^{\frac{4}{3}} \cdot F_i^2} \tag{7a}$$

where: c – drag coefficient

The results of measurements of the actual air drag in a grain layer (KUSIŃSKA 2006, 2007) indicate that for low flow velocity (laminar flow), i.e. for low Reynolds numbers Re, the loss will be proportional to velocity:

$$\Delta p_i = \kappa \cdot \rho \cdot v_i = \frac{\kappa \cdot \rho \cdot q_i}{F_{ei}} = \frac{\kappa \cdot \rho \cdot q_i}{F_i} \cdot \theta_i^{-\frac{2}{3}} \tag{7b}$$

where: κ – is an empirical coefficient whose value can be estimated with the use of the Ergun equation (ERGUN 1952) or Shedd's equation (SHEDD 1953).

The splitting of the evacuated flows can be described in view of the system's specific properties – the incoming flows will be split in such a way as to minimize hydraulic flow loss in an element. Having assumed that density ρ is constant and that coefficient κ is not modified, this function will take on the following form:

$$\min \left[f(\Sigma \Delta p_i) = f\left(\Sigma \left(\frac{q_i}{F_i} \cdot \theta_i^{-\frac{2}{3}} \right) \right); \quad q_i \geq 0 \right] \tag{8}$$

Boundary conditions

In the analyzed model, boundary conditions concern the region where the silo is supplied with air, the walls of the silo, including any perforated wall sections, as well as the free, upper surface of the grain layer. In all cases, those conditions were determined by identifying the porosity θ of the grain layer and the effective area of airflow F_{ei} through the walls of the boundary zone element. As regards the elements in the air supply zone (Fig. 3), boundary conditions are expressed by the following equation:

$$q_i = Q \cdot \frac{F_{ei} \cdot \theta_i^{-\frac{2}{3}}}{\Sigma \left(F_{ei} \cdot \theta_i^{-\frac{2}{3}} \right)} \tag{9}$$

where Q is the fan output.

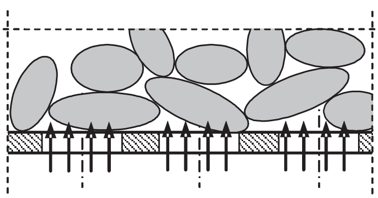

Fig. 3. Silo supply zone

Operating model

Three groups of variables have been determined in the operating model:
- the geometric dimensions of the silo and the filling method,
- selected attributes of plant material and its spatial distribution in a layer,
- the method of supplying the silo with air and airflow volume.

The calculations were preceded by a silo filling simulation to account for the distribution of plant material values (MYHAN 2003). The model has been implemented in the MATLAB 7.1 (MathWorks) programming environment using the sparse matrix presentation option which lowers the memory requirement and significantly speeds up calculations.

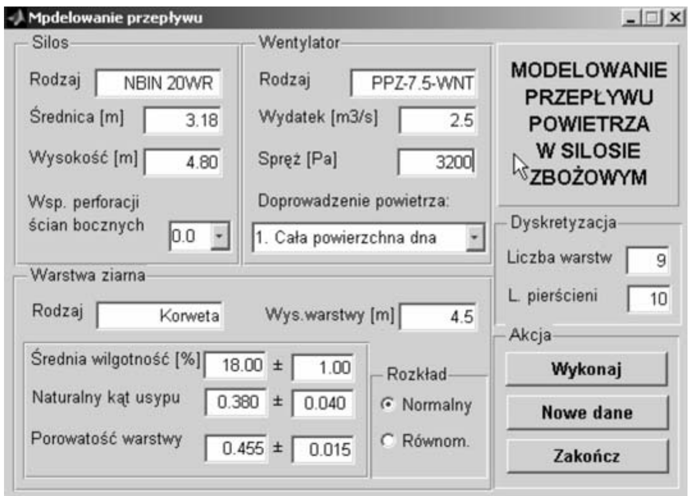

Fig. 4. Input data interface

Preliminary verification of the model

Full model verification requires a complex and a costly experimental procedure. Since the objective of modeling was not only to determine the distribution of airflow velocity but also the effect of that distribution on the evenness of grain drying in the silo, the preliminary verification relied on the results of an experiment carried out by GU et al. (2000). The experiment was performed in a laboratory, and the cited results concern moisture distribution in a grain bed after grain with initial moisture content of 22.5% had been air dried for 91 h at the temperature of 25.3°C and relative humidity of 32%. The average velocity of the supplied airflow was 0.04 m/s. A simulation experiment was carried out under identical initial conditions and in accordance with the proposed model. The results of both experiments are presented in Figure 5. A comparison of the obtained data indicates that when the remaining process parameters are constant, moisture distribution in a grain bed is highly correlated with the distribution of airflow velocity.

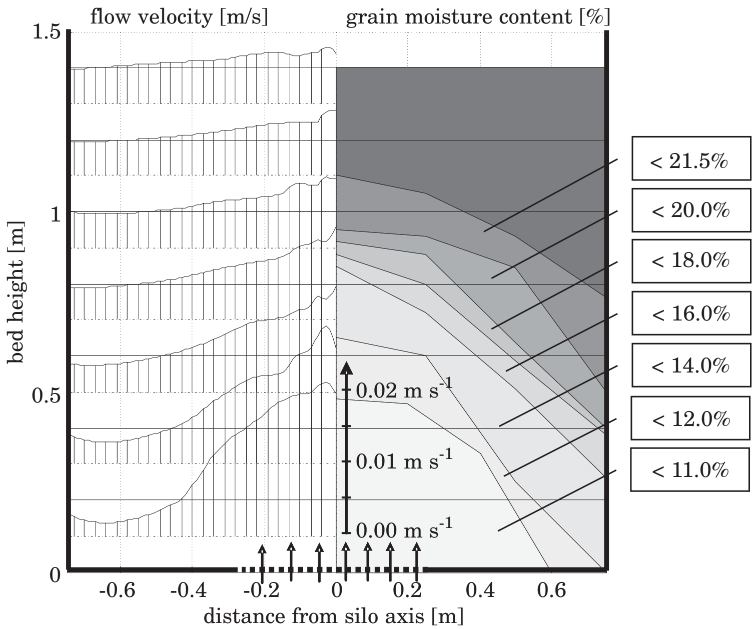

Fig. 5. Comparison of airflow velocity distribution in a silo (simulation) and the distribution of grain moisture content (GU 2000)

Process simulation – examples

The process of airflow through a grain layer in an NBIN 20WR silo with the diameter of D = 3.18 m (www.bin.agro.pl) was simulated. It was assumed that the silo was filled with wheat grain to the height of 4.5 m using the center, gravitational fill method. Bed porosity was set at 0.455 ± 0.015 (ŁUKASZUK et al. 2004) and the natural dumping angle was adopted at 0.38 ± 0.04 (HORABIK et al. 2000). In line with the manufacturer's recommendations, it was assumed that airflow through the grain layer was forced by a fan with volumetric output of 2.5 m^3/s, and air was supplied evenly through the silo's perforated bottom.

The distribution of velocity components in the entire layer volume is presented in Figure 6.

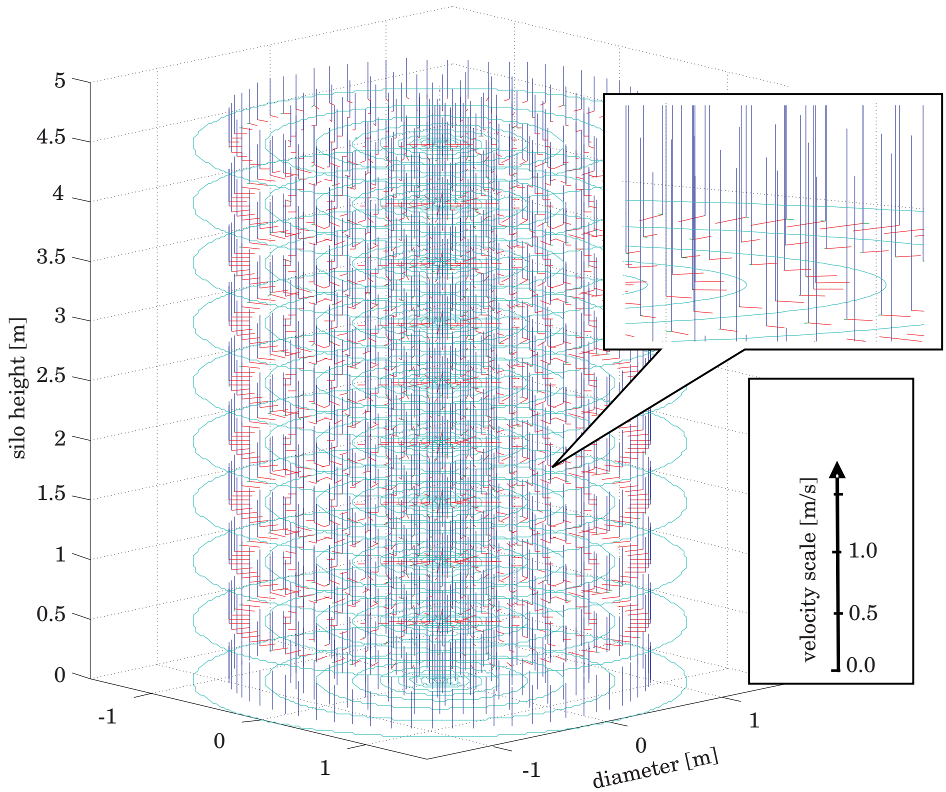

Fig. 6. Distribution of airflow velocity in a grain bed

The experiment was replicated. The only modified parameter was the method of air supply which was changed to:

– axial to $^1/_2$ D of the silo bottom;
– ring shaped to $^1/_2$ $D \div D$ of the silo bottom;
– a central duct with the diameter of 0.4 m, immersed in the bed at the depth of 1.75 m.

Each variant was analyzed with solid and perforated side walls of the silo. Averaged values of airflow velocity distribution in the bed are presented in Figure 7.

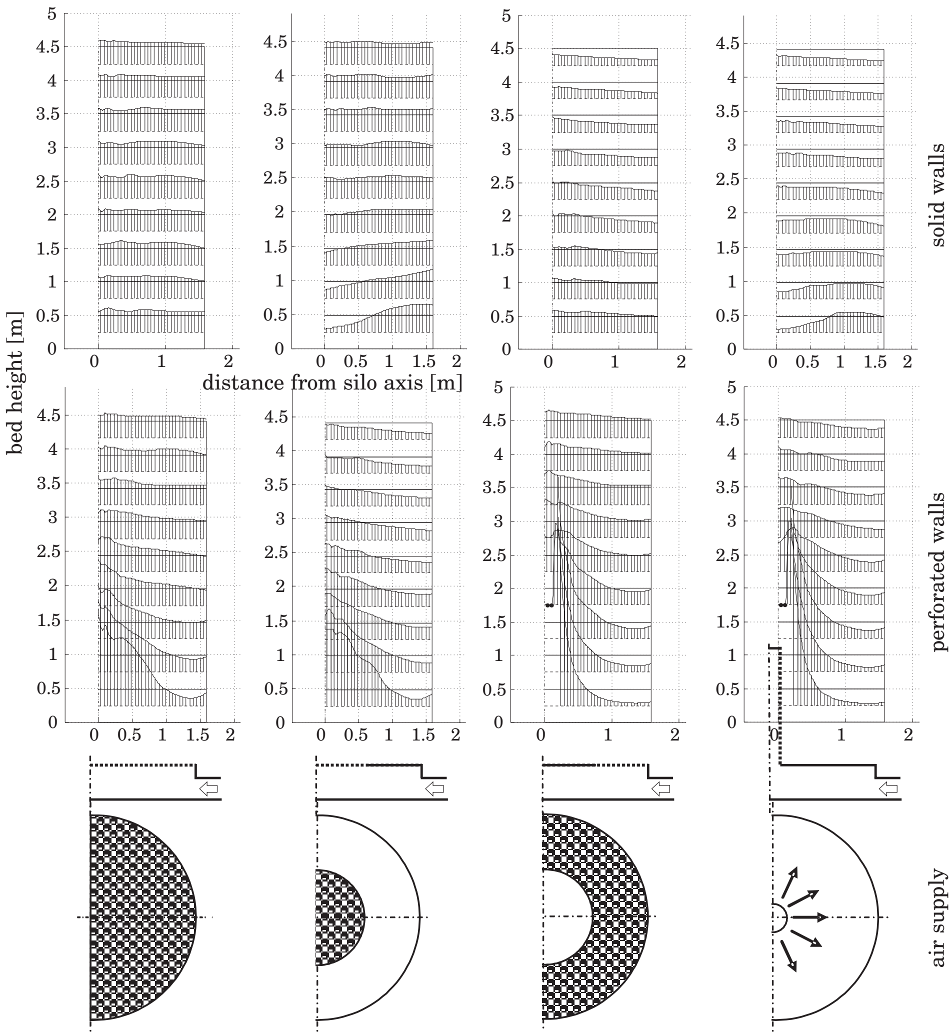

Fig. 7. Averaged distribution of the axial airflow velocity component subject to the supply method and the perforation of the silo's side walls

Conclusions

1. A preliminary verification and the performed simulations indicate that the proposed method and the resulting model may be applied to simulate the distribution of airflow velocity in a silo.

2. The obtained results suggest that the distribution of airflow velocity is strongly correlated with the method of air supply and the ratio of the silo's

diameter to bed height, and it is weakly correlated with fan output when airflow is laminar.

3. The presented model should be regarded as a preliminary stage in modeling the process of grain airing, drying and cooling in a silo. It can be fully verified after heat and mass exchange processes have been modeled in the region of finite elements discretizing the grain bed.

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