MATHEMATICAL MODELING AND NUMERICAL SIMULATION OF THE DRYING PROCESS OF SEEDS IN A PILOT PLANT
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MODELAREA MATEMATICĂ ȘI SIMULAREA NUMERICĂ A PROCESULUI DE USCARE A SEMINȚELOR ÎNTR-O INSTALAȚIE PILOT

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ABSTRACT

The artificial drying of grain seeds is widespread to ensure that they are preserved, as reducing the water content allows products to be stored for long periods of time without the need for complex storage facilities. The proposed drying installation is a low-capacity pilot one, which can change and monitor in real time a series of important parameters of the drying process. By means of the CFD simulation the construction of the cylindrical box and of the deflectors was optimized. This leads to reaching a uniform drying and to reducing the energy consumptions.

REZUMAT

Uscarea artificială a semințelor de cereale este larg răspândită pentru a asigura condiții de conservare a acestora, deoarece prin reducerea conținutului de apă se permite păstrarea produselor pe perioade lungi de timp fără a fi nevoie de instalații complexe de depozitare. Instalația de uscare propusă este una pilot, de capacitate mică, prin care se pot modifica și monitoriza în timp real o serie de parametri importanți ai procesului de uscare. Cu ajutorul simulării CFD a fost optimizată construcția casetei cilindrice și a deflectoarelor. Aceasta conduce la obținerea unei uniformități a uscării și la o reducere a consumurilor energetice.

INTRODUCTION

The experimental laboratory investigations of cereal seed drying precede the CFD simulation process, because the simulation involves the use of physical parameters (porosity, volume mass, specific heat, conductivity) for both the product and the air used as drying agent.

By CFD simulation of the cereal seed drying process, it is possible to graphically visualize the evolution of temperature and humidity fields at any point in the product layer. Calibration of the simulation is performed by comparison with the experimentally obtained data, measured in the median area of each product layer.

The degree of precision of the mathematical model, obtained by CFD simulation, is given by the differences in temperature and humidity of grain seeds determined under laboratory conditions. An important weight in these differences is also the simplifying assumptions on which the mathematical model of convective drying was built, considering that this process is complex by the large number of physical parameters, as dependent variables, which vary simultaneously over short time.

The use of the Computational Fluid Dynamics technology has made it possible to design and simulate a drying baffled unit for agricultural seed, to achieve uniform seed temperature distribution and to reduce the energy demand.

Franks believes that mathematical models are based on three rules: for physical processes, there must be a number of independent equations equal to the number of unknown sizes; from any equation, the solution leads to the value of an unknown; equations are systematized so that each one obtains one of the most significant quantities (*Franks, 1961*).

Many mathematical models have been developed to simulate the heat and the moisture transfer in the aerated bulk stored grains. A lot of them were obtained at low temperatures and low seed humidity.

Iguaz et al. (2004) developed a model for the storage of rough rice during periods with aeration. *Andra* (2001) and *Devilla* (2002) simulated the temperature changes in a wheat storage bin, but, without moisture changes.

Chang et al. (1993) and *Sinicio et al.* (1997) also developed a rigorous model to predict the temperature and the moisture content of wheat seeds during storage with aeration.

The aim of this paper is to propose the mathematical model of mass and heat transfer and to simulate the air flow in a cylindrical drying unit with deflectors, using the FLUENT software.

MATERIALS AND METHODS

CFD analyses can provide complex information on the drying phenomenon that cannot be obtained under experimental conditions. Table 1 presents the capability and limits of the experiment and the CFD numerical simulation by comparative analysis.

Table 1

Comparative analysis between experiment and simulation

Elements	Experiment	CFD Numerical Simulation
	Quantitative description of the drying phenomenon using measurements	Quantitative prediction of the drying phenomenon using mathematical models and CFD simulation programs
Model scale	normal	real
Number of analyzed problems	limited	unlimited
Conditions of deployment	laboratory	real conditions
Sources of errors	measurements errors	modeling, meshing, implementation

The mathematical model of the convective drying process is based on fluid dynamics, mass balance and energy dynamics theory.

The equations of the mathematical model of the air flow are: the differential equation of continuity, Navier – Stockes equations, mass transfer equation, heat transfer equation and moment transfer equation.

The system of the equations described above is the general mathematical model. This system is solved by numerical procedures, using solving algorithms. Numerical solving by CFD simulation of the equation system in the mathematical model is accomplished by the iterative method using the Gauss-Seidel model.

CFD simulation, based on the proposed mathematical model, involves the following steps:

- numerical meshing of the calculation area by the finite volume method (centered difference approximation) in the pre-processing stage;
- imposing boundary conditions to obtain a determined system of equations, which is done in the pre-processing stage for geometry;
- solving the system of equations in each domain node by the interactive method until obtaining the convergence in the processing stage;
- graphical representation of the solutions obtained at each node in the studied field, for parameters of speed, temperature, humidity and current lines, in the post-processing stage.

During the pre-processing stage are presented the numerical meshing techniques and the limit conditions for obtaining a determined system of equations.

Approximation by meshing is a fundamental concept based on several numerical methods such as finite difference method, finite volume method, finite element method and spectral method.

The numerical discretization of the computation domain in this simulation is done by the finite volume method (centric approximation). Control volume discretization applies to a three-dimensional domain divided into a finite number of adjacent volumes of parallelepipedal shape chosen to contain a single node of the network represented by the coordinates i, j, k and side faces intersecting the lines of the network in points located halfway between two neighbouring nodes (fig. 1).

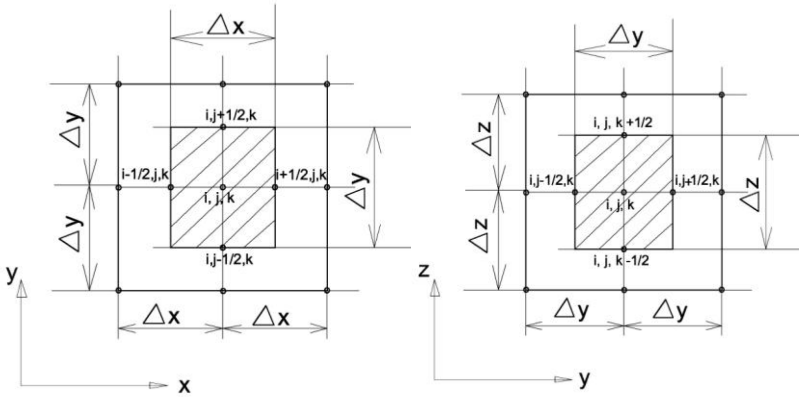


Fig. 1 - Defining the control volume

At the basis of this method are the solutions for the integration of an equation on each volume, by choosing a certain distribution law of *u* (*u* may be a function of temperature, humidity, displacement of a fluid or product) so that it can be evaluated integrally. The meshed form of the equation contains the function values for a group of nodes of the network, adjacent to the central node.

The areas of separation between the adjacent control volumes are in this case discontinuous surfaces. The values of the function *u* on these surfaces are considered equal to the arithmetic mean of the values corresponding to the volumes placed on one side and the other, being represented by the relations:

$$u_{i+\frac{1}{2},j.k} = \frac{u_{i+1,j,k} + u_{i,j,k}}{2} \; ; \; u_{i-\frac{1}{2},j.k} = \frac{u_{i,j,k} + u_{i-1,j,k}}{2} \tag{1}$$

$$u_{i,j+\frac{1}{2}.k} = \frac{u_{i,j+1,k} + u_{i,j,k}}{2} \; ; \; u_{i,j,-\frac{1}{2}.k} = \frac{u_{i,j,k} + u_{i,j-1,k}}{2} \tag{2}$$

$$u_{i,j,k+\frac{1}{2}} = \frac{u_{i,j,k+1} + u_{i,j,k}}{2} \; ; \; u_{i,j,k-\frac{1}{2}.} = \frac{u_{i,j,k} + u_{i,j,k-1}}{2} \tag{3}$$

where: *i*, *j*, *k* as the index represents the natural number.

By integrating the partial derivative equations on the finite control volume V (V=Δx·Δy·Δz), the first and second order integrals appear, which will take a discretised form respecting the values of the function in the neighbouring volumes. The discretized form on the three directions will be:

$$\int_{\Delta V} \left(\frac{\partial u}{\partial x} \right) dxdydz = \left(\frac{u_{i+1,j,k} - u_{i-1,j,k}}{2\Delta x} \right) \Delta V \tag{4}$$

$$\int_{\Delta V} \left(\frac{\partial u}{\partial y} \right) dxdydz = \left(\frac{u_{i,j+1,k} - u_{i,j-1,k}}{2\Delta y} \right) \Delta V \tag{5}$$

$$\int_{\Delta V} \left(\frac{\partial u}{\partial z} \right) dxdydz = \left(\frac{u_{i,j,k+1} - u_{i,j,k-1}}{2\Delta z} \right) \Delta V \tag{6}$$

where: V represents the volume.

The expressions of the integrals of the mixed derivatives can be obtained using the integration of second-order mixed derivatives:

$$\int_{\Delta V} \left(\frac{\partial^2 u}{\partial x \partial y} \right) dxdydz = \frac{u_{i+1,j+1,k} - u_{i+1,j-1,k} + u_{i-1.j-1,k} - u_{i-1,j+1,k}}{4\Delta x \cdot \Delta y} \tag{7}$$

Finite volume discretization involves an analysis of the working range that is volumetric represented by the cylindrical unit. It has the form of a cylinder that has three slots where the cereal seeds are introduced for drying. The hot air enters this cylindrical box through the central region, being guided by cylindrical tubing that connects to the dryer.

The geometry of the three-layer cylindrical unit is shown in fig. 2, and the mesh geometry is shown in fig.3.

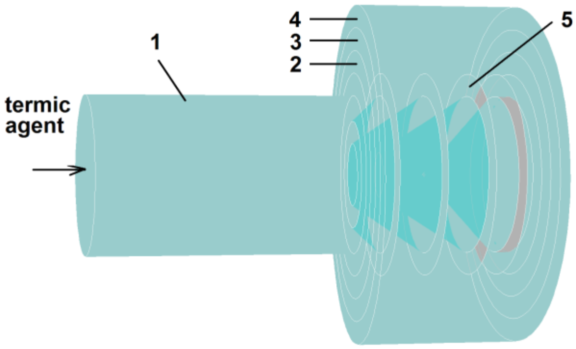


Fig. 2 - Defining the control volume

1 – heat duct, 2 – first seed layer, 3 – second layer, 4 – third layer, 5 – deflectors; thermal agent – heated air.

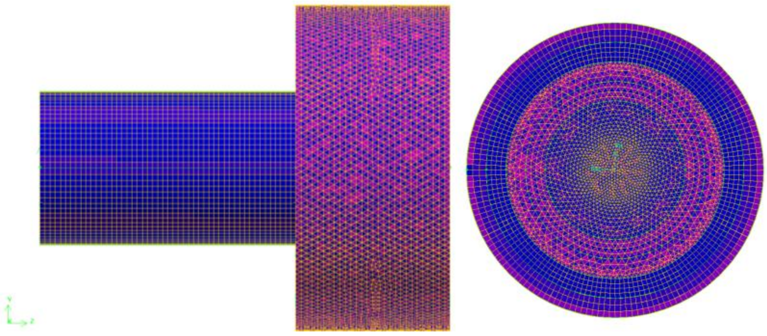


Fig. 3 - Cylindrical box meshing

The cylindrical unit geometry is hybridized. The mesh of the cylindrical introduction of the drying agent is structured, and in the region of the three slots where the seeds are introduced, the mesh is unstructured.

The air inlet and outlet area in the free volume and the four vertical surfaces define the free volume and are shown in table 2.

The processing imposed conditions for the drying agent were:

- for simulation version I – air velocity (2 m/s), inlet surface temperature and adiabatic wall temperature (313 K), air humidity (0.008 kg water vapour / kg dried air), air density (1.225 kg / m^3), exit pressure (0 Pa), specific heat (1011 J / kg K), thermal conductivity (0.0454 W / m K);
- for simulation version II – air velocity (2 m/s), inlet surface temperature and adiabatic wall temperature (343 K), air humidity (0.020 kg water vapour / kg dried air), air density (1.325 kg / m^3), exit pressure (0 Pa), specific heat (1001 J / kg K), thermal conductivity (0.0244 W / m K).

Table 2

Cylindrical unit imposed initial conditions

Cylindrical box areas	Contour conditions
Entry	Speed
Exit	Pressure
Surfaces	Wall
Volume	Fluid

At the discretization of the pressure and other conservation equations, the upwind mesh scheme of the first order was used (Ansys-Fluent-User Guide, 2012). The value of the velocity *u* is transported to the edge of the volume element relative to the local speed direction. A linear (first order) scheme was used to simulate the pressure equation in order to maintain the stability of the final solution. The quadratic scheme is more sensitive to pressure deformations, resulting in instability of the calculation, of the solution for the multiphase flow (air plus humidity) and of the density (of nodes) imposed by the mesh. All the simulations were unstated.

The initial conditions imposed for corn seed processing were: 25% relative humidity, 0.156 kg water vapour/kg dried product absolute humidity, 615 kg/m^3 product density, 1679 J/kg K specific heat, 0.158 W/m K thermal conductivity.

The porosity index was determined experimentally by scanning a determined volume (68.7 cm^3) of 78 corn seeds with a mass of 42.3 grams with a 3D SKYSCAN 1172 micro CT scanner at a resolution of 27.224 μm, resulting a porosity index of 34.5%.

For the stability of the calculation, the following coefficients of sub-relaxation were applied: pressure - 0.3; moment - 0.7; energy - 1. The convergence criteria used for all solution variables was set at 0.001. The total number of iterations for the processing stage was 180. The time step at which the simulation data was retrieved and recorded at the processing stage was 120 seconds.

The flow regime for simulation is tested to obtain a convergent equilibrium state in the evolution of residuals (fig. 4).

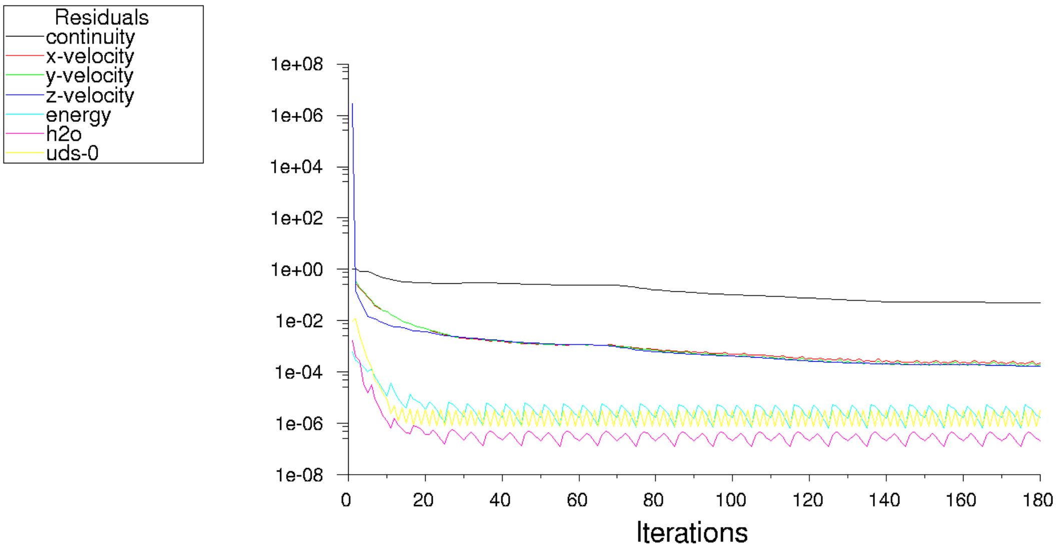


Fig. 4 – Convergence plot of the simulation

Following the mathematical modeling of the drying process, CFD simulations were made in two variants for the three-layer cylindrical unit with corn seeds from the DKC 4751 hybrid.

In the simulation, the residual was imposed at 1e-4 and the graph shows the trend of decreasing the speed on the three directions and the continuity, but the convergence check was also required and it was obtained after 180 iterations.

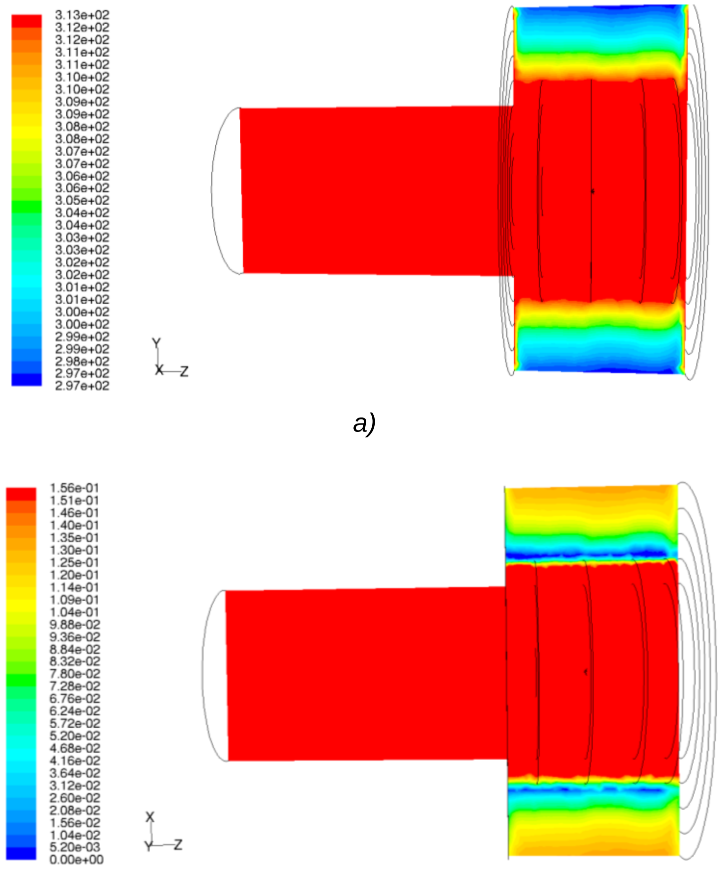
It can be said that the numerical solution converges when it tends towards the analytical solution, when the network step tends to zero. A numerical solution converges if the values of the variables in the computing domain nodes tend to approach the exact solution. Also, the numerical solution process is considered stable if errors in the discrete solution do not increase so much that the result becomes not real.

The post-processing step aims to present in colours the main parameters of interest in the process of drying the corn seeds. Parameters are rendered for each computational node in the form of temperature, humidity fields, or by showing the flow of air through current lines depending on its velocity and temperature. The post-processing was done for the three layers of corn seed following the distribution of temperature and humidity in the seed layers.

RESULTS

The field of the current lines obtained in the three-layered cylindrical unit has a laminar flow of the drying agent at the unit entrance, and in the region of the baffles, one can see a uniform distribution of the hot air over the entire surface of the corn seeds to be dried. In the simulation version I, with a thermal velocity of 2 m/s and its inlet temperature of 313 K (40°C), a speed increase of up to almost 8 m/s is observed in the deflector region as a result of the reduction of the section and afterwards it reaches uniformly again the value of 2 m/s on the surface of the first seed bed. Passing the three layers of corn seeds, the speed of the current lines drops to 0.3 m/s at the exit of the last layer (fig. 5). The surface temperature of the first seed coat is 313 K (40°C) with a uniform distribution of current lines, and in the seed layers the temperature decreases, yielding heat for drying and lowering to the last layer up to 300 K (27 °C).

In the CFD simulation variant II at an air velocity of 2 m/s and its inlet temperature of 343 K (70°C), the same speed increase in the deflector region is observed as a result of the section reduction, which will be uniformly reached again at 2 m/s on the surface of the first grain seed bed. Passing the three layers of corn seed, the current line speed drops to 0.3 m/s at the exit of the last layer. The distribution of air velocity in the three-layer cylindrical box is preserved as in variant I, with very small variations, as the geometry remains unchanged (fig. 6).

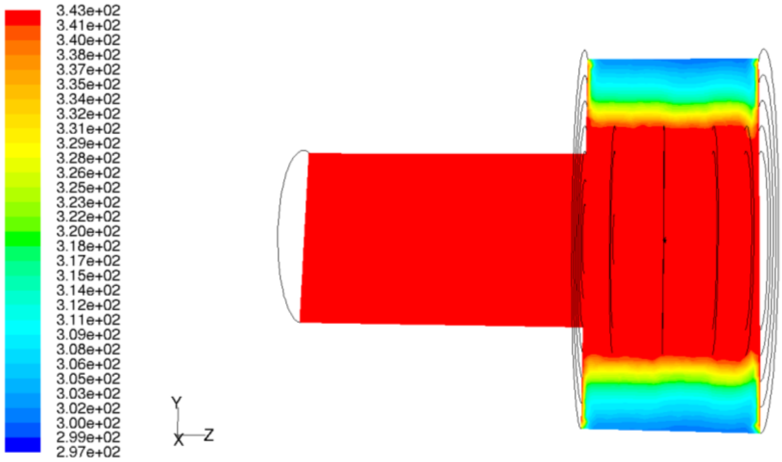


a)

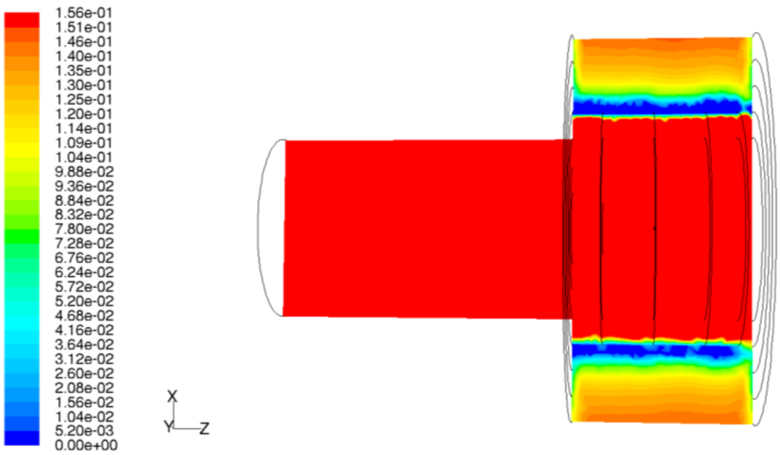
b)

Fig. 5 - The longitudinal section representation of the temperature field (K) and the absolute humidity field (kg water vapors/kg dry product) for the first version (temperature of 313 K = 40°C):
a – temperature; b – absolute humidity.

The temperature at the surface of the first seed bed is 343 K (70°C) with a uniform distribution of the current lines, and in the seed layers, the temperature decreases giving off their heat for drying and lowering to the last layer to 311 K (38°C). As shown in fig. 5 and fig. 6, regardless of the working regime of the drying unit, the same uniformity of the current lines is maintained over the whole surface of the first layer of seeds. In the design phase of the three-layer cylindrical unit, the distance between the baffles and sections was optimized by repeated CFD simulations to achieve this uniformity of spreading of the drying agent at the layers of corn seeds. In order to obtain the seed temperature and humidity parameters CFD simulation was performed at two different temperatures of the hot air.



a)



b)

Fig. 6 - The longitudinal section representation of the temperature field (K) and the absolute humidity field (kg water vapors/kg dry product) for the second version (temperature of 343 K = 70°C):
a – temperature; b – absolute humidity.

CONCLUSIONS

After the drying process mathematical modeling, CFD simulations have been made in two variants for the cylindrical box with three corn seeds layers.

The results regarding the distribution of the corn seed humidity, in the three layers of the cylindrical box in the second variant, had medium values that varied from the first to the last layer as it follows: the medium value reached was 11.5% in the first layer, 17% in the second and 21% in the third one.

By means of these CFD simulations calibrated with the experiment, one can make a sufficiently exact model, so that it could be used for other types of seeds too. The main condition is that the entry data introduced in the simulation and obtained experimentally should be as exact as possible. By means of the CFD simulation one can optimize the working process in the cereal seed drying.

Also, by means of the CFD simulation the construction of the cylindrical box and of the deflectors was optimized so that one could obtain a uniform distribution of the air currents and of the temperature fields in the three cereal seed layers. This leads to reaching a uniform drying and to reducing the energy demand.

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