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46. SIMPOZIJ AKTUALNI ZADACI MEHANIZACIJE POLJOPRIVREDE

Izvorni znanstveni rad
Original scientific paper

CFD SIMULATION OF AN INNOVATIVE VERTICAL DRYER FOR AGRICULTURAL SEEDS DRYING

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SUMMARY

Artificial drying of agricultural seeds ensures conditions for their preservation while by reducing the water content of seeds, it is possible to keep them for long periods of time, without the need of complex storage facilities. During the drying process, both moisture and a significant amount of heat are lost, resulting in high energy consumption. Recovery of lost heat from the used drying agent was achieved in an innovative model of the vertical dryer so that the energy consumption of the drying process was reduced.

The development of the Computational Fluid Dynamics (CFD) technology and software has made it possible to design and simulate an innovative vertical dryer model with heat recovery for agricultural seed, to achieve uniform seed temperature distribution and to reduce energy consumption. CFD simulation has the advantage of testing the flow of heat agent and assessing the temperature distribution within the vertical dryer before introducing the agricultural seeds into it.

The paper presents a comprehensive method of CFD simulation in the heat recovery dryer, where the mathematical models of heat transfer and the hot air flow, the distribution of the temperature of the drying agent and the temperature in the seed layer are presented simultaneously in two or three dimensions.

The results obtained by the CFD simulation of the dryer have an error of ± 5% against the experimental determinations, which is an accepted level in the heat transfer field.

Keywords: drying, vertical dryer, agricultural seeds, CFD simulation.

INTRODUCTION

Grain seeds are a component part of human nutrition and global production growth, as a result of market demand, makes them an important product. Each year about 60 million tonnes of grain are damaged by environmental factors. According to the FAO (Food and Agriculture Organization of the United Nations), there is an annual loss of over 20% of the world's grain harvest, most of it due to the spread of fungi, mildew and insect activity.

Drying is the most widely used method of preserving grain seeds. Drying reduces the water content and increases the concentration of soluble substrates to values that ensure the stability and preservation of cereal seeds. During the drying process, both moisture and a significant amount of heat are lost, resulting in high energy consumption (Dieter and Karl, 2006; Incopera et al., 2007). The recovery of the heat lost from the drying agent used in the cereal seed drying process is a means by which the total energy consumption can be reduced.

The development of the Computational Fluid Dynamics (CFD) technology and software has made it possible to design and simulate an innovative vertical dryer model with heat recovery for agricultural seed, to achieve uniform seed temperature distribution and to reduce energy consumption. CFD simulation has the advantage of testing the flow of heat agent and assessing the temperature distribution within the vertical dryer before introducing the agricultural seeds into it.

Over time, several mathematical models have been developed for heat and mass transfer in porous media such as grain seed layers. Many models were obtained at relatively low temperatures and low humidity to grain. The partial differential equation models for wheat storage with aeration were developed by (Metzger and Muir, 1983) and (Wilson, 1988). The models simulated forced convective heat and moisture transfer in vertical direction, but the model was not validated. Other authors (Chang et al., 1993; Chang et al., 1994; Sinicio et al., 1997) developed a rigorous model to predict the temperature and moisture content of wheat during storage with aeration, and found that prediction result is in reasonable agreement with observed data. The authors Sun and Woods, (1997), Jia et al., (2001), Andrade (2001) and Devilla (2002) simulated the temperature changes in a wheat storage bin respectively, and however, the moisture changes were not done. The authors Iguaz et al. (2004) developed a model for the storage of rough rice during periods with aeration. Two models of the phenomenon of mass and heat transfer in a bed of grains was developed and analyzed (Thorpe, 2007; Thorpe, 2008).

The paper presents a comprehensive method of CFD simulation in the heat recovery dryer, where the mathematical model of heat transfer, the distribution of the temperature of the drying agent and the temperature in the seed layer are presented simultaneously in two or three dimensions.

MATERIALS AND METHODS

Designing the innovative vertical dryer for agricultural seeds requires several steps: sketch, CFD simulation, 3D drawing, execution and functional testing.

If the results of the process correspond to the initial requirements of the project (a high energy efficiency vertical grain dryer), the project is implemented. If these requirements are not met, the process is resumed from the start.

The CFD simulation method aims to solve the problems of the flow of heat and the heat transfer inside the vertical drier. Numerical CFD simulation papers offer three stages: pre-processing, processing and post-processing (Hirsch, 1992; Tannehill et al., 1997). In the pre-processing step the 3D modeling of the vertical drier is carried out, followed by the meshing of the dryer volume in a finite number of elements (volumes) and the introduction of boundary conditions. At the processing step, the flow model is chosen according to Navier-Stokes equations and the heat transfer energy equation. The calculations are done in this stage as well. In the post-processing step the results obtained after the model calculations are processed and the results are obtained in graphical form. According to the described steps, CFD simulation of the vertical drier requires definition of geometry. The innovative vertical dryer model with heat recovery for seed grain drying has complex execution geometry (Fig. 1), but for CFD simulation it is simplified so that it is possible to define and visualize the internal flow regions of the drying, and heat transfer (Fig. 2).

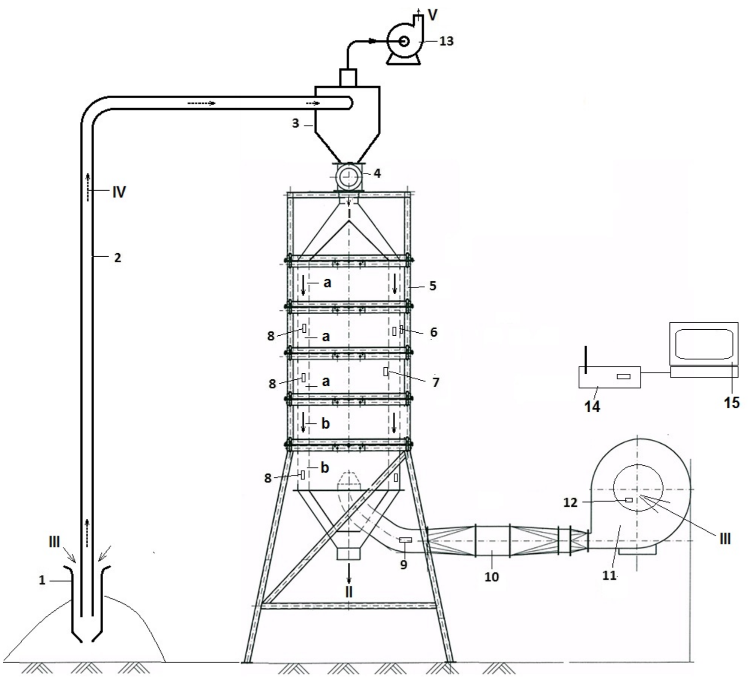

Figure 1. Innovation vertical drier with heat recovery
1 seed feed device; 2 pipe; 3 seed-air separator, 4 air lock, 5 vertical drier, 6 wireless sensor agent used; 7 wireless sensor agent; 8 temperature sensor inside the dryer; 9 velocity sensor; 10 air heater battery, 11 fan; 12 wireless sensor; 13 pneumatic fan; 14 wireless device; 15 PC; I wet seeds; II dried seeds; III air; IV mixed air seeds; V air; a drying section; b cooling section.

The dimensions of the dryer used in CFD simulation are identical to those in the actual model to be built, and the simplifications to the vertical drier geometry do not influence the physical phenomena that occur during the drying process. The detailed dimension are shown in Table 1.

Table 1. Dimensions of the vertical dryer model with heat recovery used in the CFD simulation

Dimensions	Unit - m
Height dryer	3
Diameter dryer	1
Grain layer thickness	0.1
Height drying/cooling sections	0.4
Diameter warm air inlet for drying	0.2

A grid independence study was carried out with three different mesh densities with mesh sizes varying from 1,500,000; 5,670,000 to 8,358,000. A mesh density of 5,670,000 cells (volumes) was optimal for good simulation and reasonable computational time. The optimizing of the meshing has the purpose to avoid errors occurring in calculation stage. Meshing of the vertical dryer model with heat recovery was of the unstructured type with tetrahedral elements at quality 0.8, developed with Gambit v. 2.2.30 software, shown in Fig. 3.

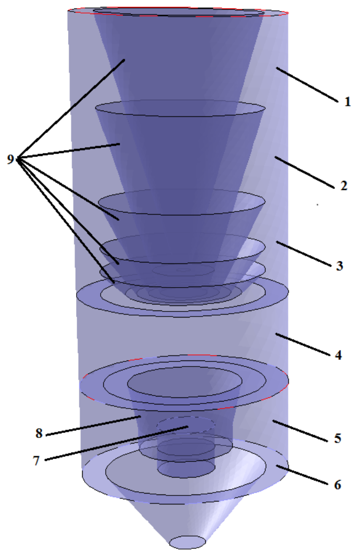

Figure 2. Vertical drier geometry for CFD simulation
1, 2, 3 drying sections; 4, 5 cooling sections; 6 grain seed layer; 7 warm air inlet for drying; 8 nozzle; 9 deflector cones.

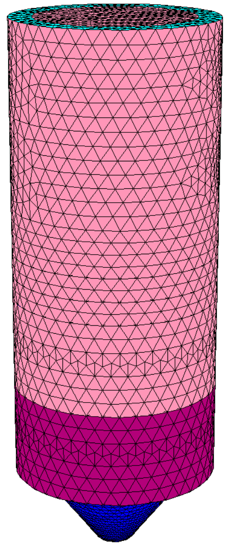

Figure 3. Tetrahedral mesh model of the vertical drier geometry.

In the step of processing the turbulent k-ε model was used, which is a standard model in CFD simulation for modeling hot air flow within the vertical dryer. The k-ε standard model is the "full" of turbulence simplest model. It is turbulence shape with two transport equations, which allows independent assessment of the turbulent velocity and length scale of turbulence. This model works well technically in a wide variety of fluid flow. Values k turbulent kinetic energy dissipation rate and ε are obtained from the transport system of equations:

$$\rho \frac{Dk}{dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\Pr_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \quad (1)$$

and

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\varpi + \frac{\mu_t}{\Pr_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k + G_{3\eta}C_b\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (2)$$

where: ρ - density of the air; μ - viscosity air; $x_{i,\,j,\,k}$ - considered as a remote position; t - time; G_k - term generation turbulent kinetic energy; G_b- the term that takes into account the effect of buoyancy; Y_M - the term that takes into account the effect of compressibility. $\Pr_k$ and $\Pr_\varepsilon$ - turbulent Prandtl numbers for k and ε respectively.

The kinetic energy per unit mass is given:

$$k = \frac{1}{2}\overline{u'_i u'_j} \quad (3)$$

The term generation turbulent kinetic energy is:

$$G_k = -\rho\overline{u'_i u'_j}\frac{\partial \overline{u_j}}{\partial x_i} \quad (4)$$

where: $u'_{i,\,j}$ - the fluctuant air velocity on direction i, j and average component respectively.

The term buoyancy in this case is neglected because it is considered that the density varies with temperature or otherwise and gravity forces also appear neglecting. The effect of compressibility on turbulence occurs at higher flow velocity of sound, resulting in the neglect to the present model. The calculation is done with the relationship for turbulent viscosity:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

Equations (1, 2) of the obtained system will vary depending on certain terms and imposed assumptions.

The mathematical model for heat transfer is given by the energy equation based on the first principle of thermodynamics of energy conservation. The abbreviated form of this equation is:

$$\rho \frac{DU}{dt} = \frac{\partial Q}{\partial t} + k\nabla^2 T + \Phi \quad (6)$$

where: U is the internal energy, t time, Q term heat source, k coefficient of thermal conductivity, T temperature, Φ the term dissipation.

Depending on the nature of the physics governing air movement, one or more terms may be neglected. In the step of processing, the mathematical models are used to define the purpose of obtaining the flow field of the vertical dryer and the trajectory of the hot air, from the set of equations and equations describing physical properties of substances. The FLUENT simulation create an algorithm that is based on a mathematical model, which in addition is added to the contour conditions defined in the pre-processing has shown in Table 2.

Table 2. Boundary conditions for the CFD simulation

Boundary sections	Status	Boundary conditions
		Fluid
Inlet hot air	normal	u = constant
Inlet fresh air	open	p = 0
Outlet hot air used	open	p =0
Wall dryer (cones, nozzle, etc.)	close	$\frac{\partial u}{\partial n} = 0$ (n – normal to the surface)

The air velocity on the hot air inlet section is considered to be constant with values ranging from 0.1 to 6.9 m·s^{-1}. The boundary condition of the hot air used was imposed as (outflow type) a free discharge into the environment, atmospheric pressure (101325 Pa = 1 atm). Overpressure was considered null (p = 0). The air flow through the deflector walls and air duct was considered null. The conditions for solving the equation systems for simulating the vertical dryer are shown in Table 3.

Table 3. Terms of solving differential equations

Terms of solving differential equations		Algorithm/Scheme	Order
Velocity-pressure coupling		Simple	-
Mesh equations	Pressure	upwinding (meshing scheme)	1
	Moment		1
	Turbulent kinetic energy		1
	Turbulent dissipation rate		1

When connecting velocity-pressure parameters between equations of continuity and time was performed using SIMPLE algorithm (Patankar and Spalding, 1972; Vandoormaal and Raithby, 1984). The meshing pressure and other conservation equations were used for meshing upwind scheme (velocity value *u* is ”transported” to the edge of the volume relative to local velocity purposes) first order (Fluent 2010). It was used in the simulation scheme linear (first order kinetics) for solving the equation of pressure in order to maintain the stability of the final solution. All the simulations carried out were steady. Flow regime for the simulation is tested in order to obtain a steady state of convergent evolution residues. Density and viscosity of air were considered constant for a given temperature (25°C) with the conditions of boundary. For the stability of the calculation, air flow parameters were under-relaxation following: pressure - 0.3; moment - 0.7; density - 1; turbulent kinetic energy - 0.8; turbulent dissipation rate - 0.8; turbulent viscosity - 1. The convergence of the solution through the stationary server was performed using the coefficients of the sub-relaxation time of 0.35 to 0.5 for the equations of turbulence. The convergence criterion used for all variables was imposed solutions to the value of 0.001. The number of iterations required for convergence equations system solutions in the processing was 863. Processing subjected model simulation was performed with TYAN Workstation (Intel Xeon 2xCPU-3.33 GHz; RAM – 16GB DDR3 2600). The numerical solution tends to converge when analytic solution and the mesh step tend to zero. A numerical solution converges if the values of variables in the field of computing nodes tend to approach the exact solution. Also, the process of solving numerical errors is considered stable if not growing significantly discreet solution otherwise the result is not real.

RESULTS AND DISCUSSION

The solver produces a map of the distribution of all the variables throughout the domain. This result must be processed so that it can be easily reported, visualized and analyzed. This is the main purpose of the post-processing task, which is essential for comprehensive evaluation of the simulation. Usual outcomes of post-processing for visualization are temperature and velocity maps, pathlines, etc. The post-processor can also give information about the instantaneous value of all variables at certain positions in the domain, and can perform balances and numerical calculations. Simulation describes the temperature distribution in the innovative vertical dryer model with heat recovery for agricultural seed. Temperature transducers can be placed at different points in this vertical dryer, but can not be so numerous that to draw a precise temperature profile in both horizontal and vertical section of the dryer. CFD simulation allows description of the temperature field at any point of the vertical dryer.

The temperature gradient distribution on the drier vertical section has shown in Fig. 4.

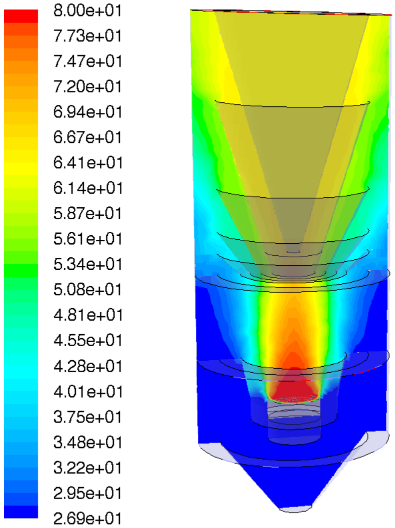

Figure 4. Temperature field on the vertical section of the dryer (°C)

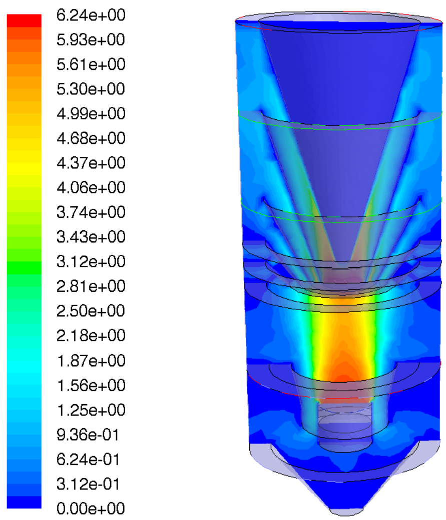

Figure 5. Velocity field on the vertical section of the dryer ($m \cdot s^{-1}$)

The two regions can be distinguished vertically from the dryer: the upper drying region where the average temperature is 53°C, decreasing from top to bottom, and the cooling region at the bottom where the temperature is 27°C. The temperature in the hot air inlet area for drying is 80°C. Experimentally, a temperature transducer was introduced into the three drying regions, and after 25 minutes of operation, the temperature obtained in the drying region was 48.6°C, and in the cereal seed cooling region was 23.3°C. Thus the differences obtained with the simulation are reduced and can be explained by the thermal inertia due to the mass transfer (humidity) to the environment which leads to the temperature decrease by a few degrees. The introduction of the nozzle at the bottom of the dryer in the immediate vicinity of the hot air supply duct makes it possible to obtain two vertically regions with different temperatures for the drying and cooling of the grain seeds.

By the introducing of the five cones inside the dryer, the air velocity distribution in the three drying zones becomes uniform, and the velocity vector is oriented from the inside of the dryer to the outside, Fig. 5. In the two cooling regions at the bottom of the dryer, the nozzle insertion makes it possible to orient the velocity vector from the outside to the interior, by absorbing cold air from the atmosphere to cool the grain layer.

The air velocity at the inlet of the dryer is 6 $m \cdot s^{-1}$, and in the grain layer it is between 1 and 2 $m \cdot s^{-1}$.

The distribution of the pathlines inside the vertical drier has shown in Fig. 6. This shows the role of the deflector cones and the nozzle inside the drier. By introducing the nozzle at the bottom, the section between the hot air duct and the lower nozzle wall decreases, causing a drop in the pressure. This pressure drop leads to the absorption of air in the atmosphere through the two lower regions of the dryer, which leads to the cooling of the cereals. With the cooling of the seeds, some of the heat accumulated by them through the drying process is recovered and reintroduced into the dryer's overall circuit, by mixing it with the hot air from the heater battery. The hot air mix pathlines from the bottom of the dryer are distributed evenly over the entire height of the three drying zones by means of the five cones. The highest temperature is distributed at the top of the dryer.

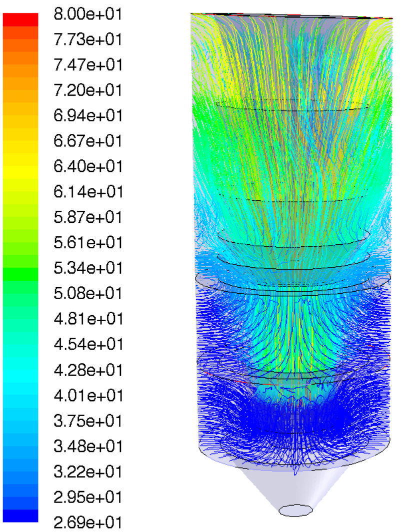

Figure 6. Temperature pathlines in the vertical dryer (°C)

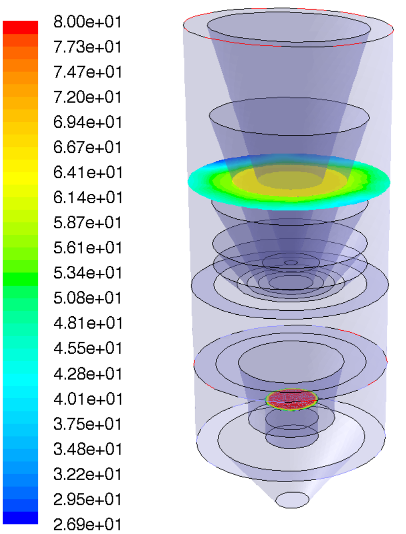

Figure 7. Temperature field on the cross section in the drying region of the dryer (°C)

By cross-sectioning the dryer at the various height elevations shown in (Fig. 7), the temperature distribution in the hot air inlet region of the air heater battery has shown. In the drying region the distribution of the average temperature of 53°C in the grain seed layer was observed.

The ability to segment both the longitudinal and transversal vertical dryer by CFD simulation makes it possible to analyze the temperature and velocity fields and the pathlines and gives a 3D image of the distribution of cooling and heating/drying streams in the dryer. This makes possible to optimize the interior design of the dryer by varying the number of cones, their position and angle of inclination as well as the bottom section of the nozzle. The FLUENT software enables a functional optimization by introducing a large number of variants for input parameters (hot air velocity and temperature).

The results of the heat transfer inside the dryer are comparable to those in the literature and Fluent guide specifications.

Vertical grain dryers, currently available on the market, have an internal construction without additional devices to guide airflows to the grain layer and research in this field is at the beginning.

CONCLUSIONS

The paper presents the CFD simulation of an innovative vertical dryer for drying grain seeds, where the temperature and velocity field is presented.Temperature obtained by the CFD simulation of the vertical dryer have an error of ± 5% against the experimental determinations, which is an accepted level in the heat transfer field. The temperature profile in seed layer resulting from the CFD simulation are presented with a high degree of accuracy. Both experimental and simulation were unsteady preformed on a 3D geometry vertical dryer. The CFD simulation for drying allows large variations of temperature and velocity for hot air inlet.

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