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RESEARCHES OF MASS AND HEAT TRANSFER OF AN INNOVATIVE VERTICAL DRYER

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SUMMARY

Drying of agricultural seeds is important during storage for a longer time period. Convective drying is accomplished with heat input from the drying agent passing through a porous layer of agricultural seed, taking up a certain amount of moisture. An uneven distribution of the seed layer temperature during drying results in overheating in some regions and underheating in other regions, leading to uneven seed drying.

The paper aims to determine the optimum thickness of the seed layer from a new vertical drier so that the temperature gradient in the layer is as uniform as possible. Determining the temperature profile in the seed layer can optimize hot air flow and energy consumption.

Over time, several mathematical models have been developed for the heat and mass transfer that takes place during the drying process, treating the seed layer as a solid body. By applying a heat and mass transfer model in a porous seed layer, the temperature field was simulated in three consecutive layers of thickness with 100 mm each.

Validation of the proposed mathematical model for the porous seed medium was achieved by measuring the seed temperature at several positions in the dryer.

The results obtained by simulation and experiment gave an optimum seed layer of 100 mm thick with an uniform gradient temperature.

Key words: numerical simulation, heat transfer, drying process, corn seeds.

INTRODUCTION

By the drying process the corn seeds lose a quantity of moisture until they reach the constant moisture to which they can be stored without suffering any loss of quality.

Typically, this drying process takes place convectively by means of a heat transfer hot air which penetrates the porous corn layer by taking up an amount of moisture which is eliminated in the atmosphere. If the heat required for drying is not recovered from the used hot air, the energy consumption increases. In order to reduce energy consumption and reduce drying time, it is necessary that the temperature distribution be as uniform as possible in the seed layer need to be dried.

Knowing the temperature distribution in the corn layers indicate overheating or unheating areas and can layer a uniform temperature. By knowing the temperature profile in the layer of corn can be optimized the air flow and temperature in the layers.

Many mathematical models have been developed to simulate the heat and the moisture transfer in the aerated bulk stored grains. The 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, 1994) and (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, but, 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). Based on model and simulation of CFD (Thorpe, 2008; Zhang et al., 2016) developed and validated by experimental measurements of temperature transducers introduction the theoretical model at different points in a grain silo. The models proposed by the authors were introduced and air product temperature of less than 30°C, and two-dimensional simulations were performed.

The aim of this paper is to propose the mathematical modeling of mass and heat transfer in a cylindrical dryer with three layers of grain seeds. CFD simulation for the proposed dryer model was made with FLUENT software.

MATERIALS AND METHODS

In the drying process corn seeds from the hybrid DKC 4717 were used.

Experimentally, a three-layer concentric seed dryer was designed and developed to study temperature and moisture content distribution in order to improve the qualitative indices of corn seeds subject to preservation, Fig. 1 a. The internal deflectors of the dryer have the role of uniformity the hot air, on the height of the layer.

The experimental dryer is provided with a series of sensors for monitoring the temperature, humidity and velocity parameters of the hot air.

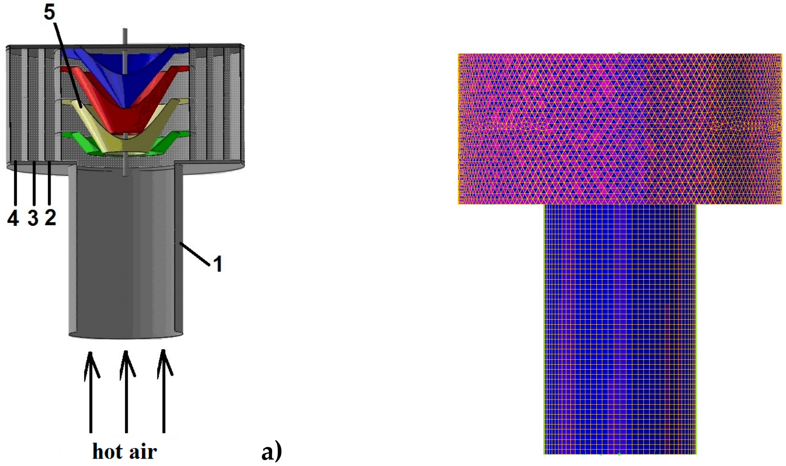

Figure 1. Geometry of the three-layer dryer and deflectors: a) section view; b) hybrid mesh (1 heat duct; 2 first seed layer; 3 second layer, 4 third layer, 5 deflectors).

The sensors used in the laboratory drier were subsequently used in the innovative vertical dryer model with heat recovery with an optimal thickness of the seed layer, Fig. 2 a, b.

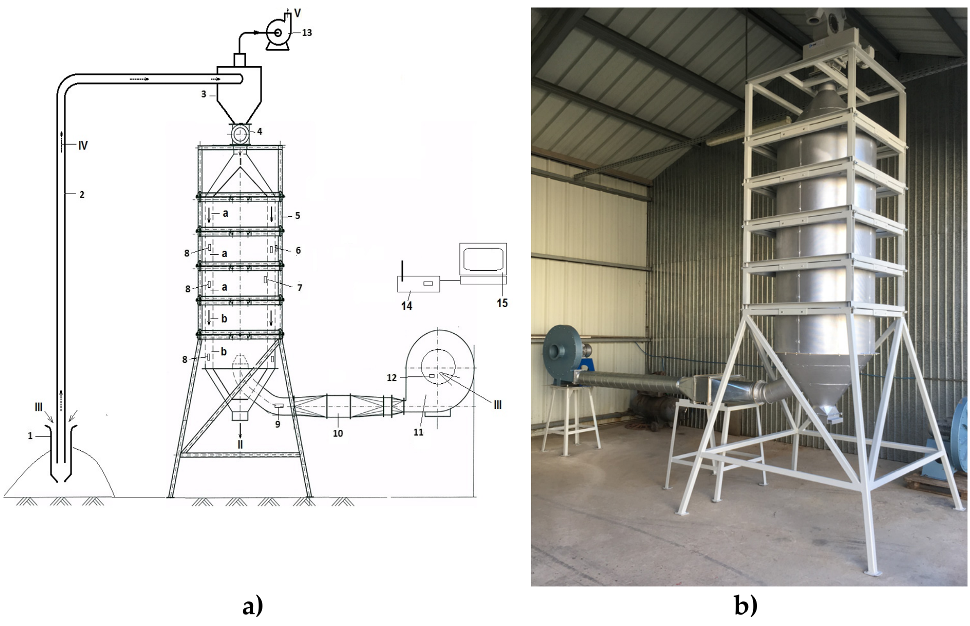

Figure 2. Innovation vertical dryer with heat recovery: a) dryer scheme; b) dryer construction (1 seed feed device; 2 pipe; 3 seed-air separator, 4 air lock, 5 vertical drier, 6 wireless sensor hot air used; 7 wireless sensor hot air; 8 temperature sensor inside the dryer; 9 velocity sensor; 10 air heater 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 temperature and humidity of the product were determined by K- type sensors (measuring range -40°C to +400°C, accuracy +/-0.3°C) located in each of the three layers. Additionally, the moisture and temperature of the hot air prior to penetration into the corn seed layer and after, were monitored by means of some DLPTH1 moisture and temperature sensors (measuring range 0°C to +100°C, accuracy +/-0.1°C; 0 to 100% RH, accuracy +/-0.1% RH). Corn seed moisture content was recorded at constant time intervals using a Grain Moisture Meter Tester MD-7822 (measuring range -10°C to +60°C, accuracy +/-2°C; 2 to 30% RH, accuracy +/-1%RH).

Determination of porosity in the seed layers was performed with the 3D SKYSCAN 1172 micro CT scanner and related software. The hot air velocity at the inlet and outlet of the dryer was monitored using the TROTEC TA 300 hot wire anemometer (measuring range 0.1 ms^{-1} to 30 ms^{-1}, accuracy ± 0.1 ms^{-1}). Information obtained by the sensors is numerically transferred and graphically represented on a computer by means of a graphics card. The research method has been developed by mathematical modeling of mass and heat transfer phenomena in corn seed layers based on a series of data obtained by experiment on the laboratory model and verified on the innovative vertical dryer model with heat recovery. The physical drying phenomenon that occurs in the corn layers obeys the law of conservation. However, to solve such a diversity of problems the equations that govern heat and mass transfer are expressed in very general terms and they do not model heat and mass transfer in the corn bulks during corn self drying. As a result, they have to be tailored to suit corn drying applications. To date, making the modifications to the standard CFD (Computational Fluid Dynamics) software appears to have been a stumbling block for most corn-dry technologists. This physical phenomenon is described mathematically by a partial differential equation of general form:

$$\frac{\partial(\rho_a \phi)}{\partial t} + \nabla(\rho_a v \phi) = \nabla(\Gamma \nabla \phi) + S\phi, \qquad (1)$$

where: Φ is the quantity of interest which in this case is the energy or moisture content of the intergranular air, ρ_a is the density of air, v is the superficial or Darcian velocity of the air as opposed to the average velocity of the air flowing between the corn kernels, Γ is the effective diffusion coefficient of Φ through a bed of corn, t is time, ∇ is the del operator, S_Φ is a source term.

Eq. (1) refers to a differentially small region of corn and this implies that the properties have been averaged over some finite volume, otherwise they would be discontinuous at the boundaries of the corn kernels and intergranular air.

The variable, Φ, in the generalised transport Eq. (1) can also represent energy. In the case of porous media, such as a bulk of corn, the enthalpies of the fluid (air) and solid (corn kernels) phases must be considered. The computer software used in this work solves an enthalpy balance by Eq. (2)

$$\begin{aligned}\left((\rho_a \varepsilon c_a + \rho_s (1-\varepsilon)\left(c_s + c_w W + \frac{\partial H_W}{\partial T}\right)\right)\frac{\partial T}{\partial t} + c_a \nabla(\rho_a v T) = \\ = k_{\text{eff}} \nabla^2 T + S_{\text{en}},\end{aligned} \qquad (2)$$

where: c_a, c_s and c_w are the specific air heats, corn and liquid water, respectively, ρ_s is the density of corn kernels on a dry basis, ε – void fraction of the layer of corn (we assume that value 0,15) , W – corn moisture content , H_W - is the integral heat of corn wetting, T – temperature, k_{eff} is the effective thermal bulk conductivity of corn (0.167 W/m^2K), S_{en} is the thermal source term that results from heat being liberated or extracted from the corn when they adsorb or desorb moisture.

It has been demonstrated that $\partial H_w/\partial T$ is negligibly small for corns compared with the specific heat of moist corn and it can be ignored (Thorpe, 2007). A feature of FLUENT software is that the specific heat of the porous zone must be entered as a constant, but in this application the term equivalent to specific heat, i.e. $c_g+c_wW+(\partial H_w/\partial T)$, varies with moisture content. For the simulation presented here we assume that the start value of the corn moisture content, W, is 0.157, which corresponds to a moisture content of 25% wet basis and the corn has a temperature of 21 ºC. The source term, S_{en}, takes the form

$$S_{\text{en}} = -h_s(1-\varepsilon)\rho_s \frac{\partial W}{\partial t}, \tag{3}$$

where: h_s is the sorption heat of water on the corn.

It has been obtained (Hunter, 1989) that the ratio of the heat of sorption to the latent heat of vaporisation, h_v, of free water is given by

$$\frac{h_s}{h_v} = 1 + \frac{p_{\text{sat}}}{r}\frac{\mathrm{d}T}{\mathrm{d}p_{\text{sat}}}\frac{\mathrm{d}r}{\mathrm{d}T}. \tag{4}$$

Hunter provides the following empirical relationship between the saturation vapour pressure of water and temperature (Hunter, 1987)

$$p_{\text{sat}} = \frac{6\cdot 10^{25}}{\left(T+273.15\right)^5}\exp\left(-\frac{6800}{T+273.15}\right). \tag{5}$$

The relative humidity, r, of the intergranular air is defined as in Eq. (6), where p_{sat} is the saturation vapour pressure of free water.

$$r = \frac{p}{p_{\text{sat}}}. \tag{6}$$

where: p vapour pressure of water vapour may be expressed in terms of the humidity, w, of the intergranular air by

$$p = \frac{w p_{\text{atm}}}{0.622 + w}. \tag{7}$$

where: p_{atm} is atmospheric pressure. Differentiation and inversion of Eq. (5) results in

$$\frac{\mathrm{d}T}{\mathrm{d}p_{\text{sat}}} = \left(\frac{T+273.15}{p_{\text{sat}}}\right)\Bigg/\left(\frac{6800}{T+273.15}-5\right). \tag{8}$$

and

$$\frac{\mathrm{d}r}{\mathrm{d}T} = \frac{Ar}{\left(T+C\right)^2}\exp(-BW_e). \tag{9}$$

where: A, B and C are empirical constants widely used to sorption isoterm proposed by Chung and Pfost (1967) and for this case assume the values of (921.69, 18.077 and 112.35).

The corn layers constitutes a porous medium and FLUENT software accounts for the resistance to air flow by adding a source term, S_i, to the standard momentum transport equation. S_i as the pressure gradient along a bed of corn uniformly aerated in the *i-th* direction with air with a velocity v_i. It takes the form

$$S_i = -\left(\sum_{j=1}^{3} D_{ij} \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{\rho_a}{2} |v| v_j \right), \text{ i = 1, 2, 3} \tag{10}$$

where: μ is the intergranular air viscosity, v_j represent the components of the velocity in all three dimensions, ρ_a is the air density, v is the superficial or Darcian velocity of the air as opposed to the average velocity of the air flowing between the corn kernels, D_{ij} is tensor component what represent the Darcian or viscous resistance, C_{ij} is tensor component what represent inertial resistence. The empirical coefficients D_{ij}, C_{ij} can be related to those in the FLUENT software Eq. (11).

$$D_{ij} = \begin{cases} R_h/\mu; \; i = j = 1,2, \\ R_v/\mu; \; i = j = 3, \\ 0; i \neq j, \; i = 1,2,3, \; j = 1,2,3. \end{cases} \qquad C_{ij} = \begin{cases} 2 \cdot S_{h0}/\rho_a; \; i = j = 1,2, \\ 2 \cdot S_v/\rho_a; \; i = j = 3, \\ 0; i \neq j, \; i = 1,2,3, \; j = 1,2,3. \end{cases} \tag{11}$$

The components of the resistance in these two directions and resistance terms in the horizontal direction can be designated as R_h and S_{ho}, and those in the vertical direction R_v and S_v. Two orthogonal horizontal directions are designated by the indices 1 and 2, and the vertical direction has the index 3.

This is implemented in FLUENT by introducing temperature of 30 °C the air viscosity and density, respectively $18.37 \cdot 10^6$ Pas and 1.191 kgm^{-3}. Using these values, we find that D_{11}=D_{22}=$1.833 \cdot 10^8$, D_{33}=$2.037 \cdot 10^8$ and C_{11}=C_{22}=18371, C_{33}=26767.

The aim of this paper is to illustrate how a standard CFD package may be modified so it can be used to simulate heat and moisture processes that occur during corn drying process. The features that apply specifically to bulk dry corn are accommodated by User-Defined Functions (UDF-s) written in a high-level computer language such as C and introduce in the FLUENT software.

Pre-processing as a first step in CFD simulation is achieved by creating the drying zone geometry and meshes it with the GAMBIT software. The geometry is discretization with hybrid mesh and 938,000 elements, Fig. 1 b.

For both the drying and CFD simulation experiment the corn seeds with an initial moisture content of 25% were used in the three layers and the porosity index determined experimentally by CT scan of a volume of 68.7 cm^3 with a number of 78 seeds of corn was 34.5%. The drying velocity used in both experiment and simulation was 2 ms^{-2} and the temperature was 40°C and 70°C, respectively. The process of calculating the drying of the corn seeds for both used temperature used temperatures was about 4 hours.

The initial conditions imposed for corn seeds in the two CFD experimental and simulation variants have shown in Table 1.

Table 1. Initial conditions imposed for corn seed processing

Layers	X (kg vap. H_2O/kg dry prod.)	Density ρ (kg·m^{-3})	Specific heat c_p (J·kg^{-1}· K^{-1})	Conductivity k (W·m^{-1}·K^{-1})	Porosity index ε (-)
I, II, III	0.156	615	1679	0,158	0.34…0.38

For processing in the FLUENT software, in addition to boundary conditions defined in pre-processing, the conditions in Table 2 was added.

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).

Table 2. Boundary conditions for the CFD simulation

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

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
	H_2O		1
	Air		1
	Energy		1

For the stability of the calculation flow of air applications was under-relaxation following factors: pressure - 0.3; moment - 0.7; density - 1; turbulent kinetic energy - 0.8; turbulent dissipation rate - 0.8; turbulent viscosity - 1.

CFD simulation was performed with the Ansys FLUENT software using the TYAN workstation (2XCPU-Intel Xeon 3.33GHz; RAM- 16GB DDR3 2600).

RESULTS AND DISCUSSION

CFD simulation post-processing follows the presentation of the main parameters of interest in the color scheme of the corn seed drying process. Parameters are presented, for each computation node, in the form of temperature 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 corn seed layers following the temperature and moisture content distribution in the seed layers. The temperatures for the two simulated drying variants were 313 K (40°C) and 343 K (70°C).

In the first variant, with a hot air input, the temperature of 313 K (40°C) on the longitudinal section of the three-layer corn seed dryer, the average temperature of the heat air decreases progressively from the layer I, which first contacts the hot air with 311 K (38°C) at the second layer with 305 K (32°C), reaching the third layer at an average temperature of 301 K (28°C) until the end of the drying process. The temperature gradient distribution on the three layers has shown in Fig. 3a.

The distribution of the absolute moisture content of the corn seeds in the three seed layers of the dryer shows a lower mean value in the first layer of 0.001 (kg of water vapor/kg of dry product) (11.6%), a higher value in the second layer 0.005 (kg water vapor/kg dry product) (12%) and the highest value in the third layer of 0.11 (kg of water vapor/kg of dry product) (22%).

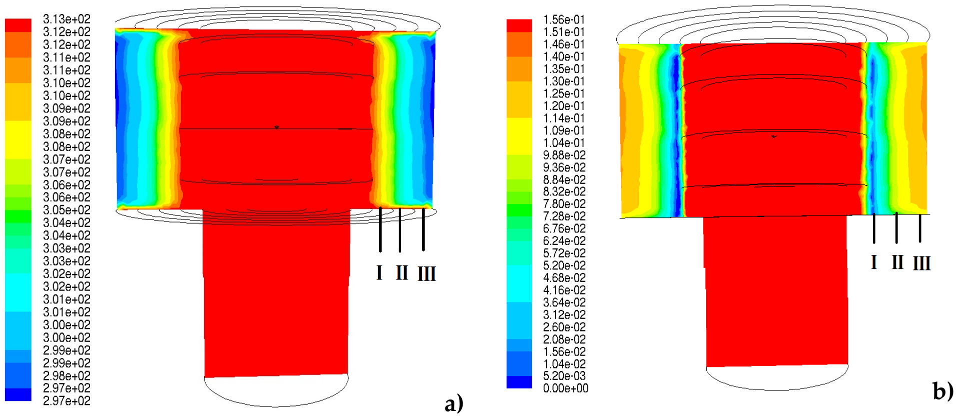

Figure 3. Vertical dryer: a) the temperature field *K*; b) the absolute moisture field kg water vapors/kg dry product. I first layer; II second layer, III third layer. ($v=2\ m \cdot s^{-1}$;$T=313$ K)

The gradient of absolute moisture content distribution in the three layers of corn seeds has shown in Fig. 3b. Inside the dryer, the red color is the starting quantity of 0.156 (kg of water vapor/kg of dry product) corn seed moisture, which in this case has no physical significance because hot air circulates inside. CFD simulation was done unsteady and the results presented are at the end of drying, after 65 minutes.

By experiment, at the end of the drying process, both the moisture content and temperature in the three layers of corn seeds decrease unevenly in the radial direction as follows: the first layer 11.5% and 35°C , the second layer 11.7% and 30°C, the third layer 14% and 29,3°C.

In the second version of the CFD hot air simulation, entering the temperature of 343K (70°C) on the longitudinal section of the dryer, the average temperature decreases progressively from the first layer by 338K (65°C), to second layer by 318K (45°C), reaching the third layer at an average temperature of 308K (35°C) until the end of the drying process. The temperature gradient distribution on the three layers has shown in Fig. 4a.

The distribution of the absolute moisture content of the corn seeds in the three seed layers of the dryer shows a lower mean value (the equilibrium moisture) in the first layer of 11.5%, a higher value in the second layer of 0.0058 (kg water vapor/kg dry product) (17%) and the highest value in the third layer of 0.104 (kg of water vapor/kg of dry product) (21%).

The gradient of absolute moisture distribution in the three layers of corn seeds has shown in Fig. 4b. Inside the dryer, the red color is the starting quantity of 0.156 (kg of water vapor/kg of dry product) corn seed moisture, which in this case has no physical significance because hot air circulates inside. CFD simulation was done unsteady and the results presented are at the end of drying after 27 minutes.

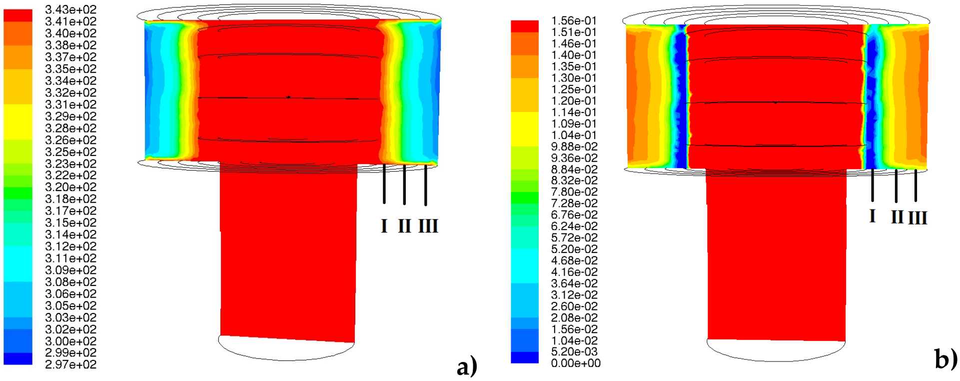

Figure 4. Vertical dryer: a) the temperature field *K*; b) the absolute moisture field kg water vapors/kg dry product. I first layer; II second layer, III third layer. (v =2 m·s^{-1}; T =343 K)

According to the experiment, at the end of the drying process, the moisture content and temperature in the three layers of corn seeds decreases unevenly in the radial direction as follows: the first layer 9.8% and 68.2°C, the second layer 18.4% and 4.1°C, the third layer 19.9% and 38.3°C.

The innovative vertical dryer model has a single layer with a thickness of 0.1 m. The experimentally measured parameters for this dryer at 40°C were temperature and moisture. In the seed layer, at the end of drying, an average moisture content of 11.9% and an average temperature of 32°C were obtained. The temperature and moisture of the first layer of the cylindrical dryer with three layers differ with 0.4% for moisture and 3°C for the temperature, compared to the temperature and moisture in the layer of the innovative vertical dryer. The difference between laboratory ambient temperature (22°C) and the one outside (15°C) where the two tests were made, could be the explanation for the temperature difference that occur in seed layer.

CONCLUSIONS

The corn seeds are irregular dried in the three layers of the dryer, leading to an over-drying of the first layer and keeping a high percentage of moisture in the outer layer of the dryer.

The moisture and temperature differences between the first and the last layer seeds are 10.4% and 10°C respectivelly, when the hot air temperature is 40°C, while for hot air temperature of 70 °C, the recorded differences are 9.5% and 30°C.

In the three-layers vertical dryer, the average temperature and moisture differences recorded between CFD simulation and experiment differ by 1°C and 4.05% for a hot air temperature of 40 °C, and 3.25 °C and 2.9% for a hot air temperature of 70°C.

By mathematical modeling of mass and heat transfer and using experimental data, CFD simulation results in an optimal layer thickness of corn in the dryer of 0.1 m.

Compared with the temperature and humidity in the innovative vertical dryer layer, the differences in temperature and moisture in the first layer of the three-layers cylindrical dryer were of 0.4% for moisture and 3 °C respectivelly for temperature.

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