OBJECT-ORIENTED MODEL OF FIXED-BED DRYING OF COFFEE BERRIES

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ABSTRACT

The aims of this work were to validate a new model of a fixed-bed drying process with experimental data, compare this model with a traditional one (MSU Model), and analyze the sensitivity of each model parameter. A low level model of a thin-layer was developed, based on mass and heat balance between the drying air and the product. It also considered the product physical properties variation during drying. Thus a high level model was created by connecting four thin-layer models, in order to represent a thick layer. The proposed model was validated by the analysis of model performance index between the experimental data and simulated results. Finally, the efficiency indexes of the proposed model and the MSU model were compared. The models and the simulation were done using OpenModelica® 1.6.0, based on the Modelica language. The proposed model had shown good performance indexes compared with the MSU model.

Keywords: Modelica, physical properties, MSU Model, model performance.

1. INTRODUCTION

After harvest, coffee is very perishable due to the high moisture and sugar content. Thus, coffee passes through a drying operation, to enable safe storage and minimize quality degradation prior to subsequent processing. Drying is defined as an operation of moisture removal through to simultaneous heat and mass transfer (Henderson et al. 1997). It is also one of the preservation methods of agricultural products which are most often used and is the most energy-intensive process in industry (Dincer 1998). Moreover, drying is a difficult food processing operation mainly because of undesirable changes in the quality of the dried product. Such changes can occur because of substantial changes in the product's chemical and physical properties during the drying process.

In a drying system, two fundamental tasks must be performed. First, energy must be provided to the product to be dried so that moisture contained in the product is vaporized. Second, the vaporized moisture must be removed by the drying system (Henderson et al. 1997). Thus, air used to dry the product, after passing through a thin-layer of product, experiences a decrease in temperature and an increase in its humidity ratio. Consequently, thick-layer drying is a complex dynamic system, considering that the drying kinetics will change due to the changes in air and product properties through time and space.

In order to reduce costs and robustly control drying systems, simulation of the process is important, as a mean to understand the system dynamics and then optimize the system. Many models have been developed to simulate fixed-bed drying. A commonly used model is the MSU model (Michigan State University). This model consists of a system of four differential equations resulting from mass and energy balances of a control volume (Dalpasquale et al. 2008). The MSU model is easy to apply to different agricultural products because it assumes that some product properties is equal to water properties, e.g, specific heat. However, this model tends to overestimate the drying rate (Brooker et al. 1992), due to the model assumptions.

Currently, with the rapid improvement of computer and software technology and the widespread availability of computational resources, high fidelity models can be implemented with simulation that more closely represent reality. Some recent examples of new drying models include the work of Izadifar and Mowla (2003), who considered the theory of simultaneous mass and heat convection and internal mass diffusion in their model; Guiné et al. (2007) who based their model on the liquid diffusion theory, considering the product shrinkage and physical properties variation during drying; and Lecorvaiser et al. (2010), who considered the dynamic phenomena of air turbulence.

In addition, the dynamics of the drying system are coupled with those of various components that are necessary for the operation of the entire system including motors, fans, conveyors, heaters and control devices. Each component performs a specific operation that effect the entire system and the system affects the operation of each component. The simulation of this type of system is usually performed by simulating each component individually. This approach is taken due to the difficulty of developing an overall system model that represents many physical domains including the electrical, mechanical, thermodynamic, hydraulic, chemical, and control domains.

Recently though, modeling technologies have been advanced to ease the development of complex, multi-domain, physical models. For example, *Modelica* is an object-oriented equation-based programming language which enables multi-domain modeling, meaning that model components corresponding to physical objects from several different domains that can be described and connected (Fritzson, 2003). Therefore, the Modelica language is promising for drying system modeling, since this language can enable modeling of all the physical domains and mechanisms in this type of system.

The aims of this work were to: (1) model the drying process of a fixed-bed coffee dryer considering the variation of the product physical properties and drying air flow; (2) validate the model by comparing the simulate results with experimental data; (3) compare this model with the MSU Model; and (4) analyze parameter sensitivity in order to understand and simplify the proposed model.

2. METHODOLOGY

The present work was conducted in the Laboratory of Evaluation of Physical Properties and Quality of Agricultural Products in the Brazilian Grain Storage Training Center – CENTREINAR, Federal University of Viçosa, Viçosa, MG, Brazil.

2.1. Modeling

The proposed model to describe the fixed-bed coffee dryer was built *Modelica* language. Real physical objects are represented on *Modelica* language as *object* block. Each object is an instance of a specific *class*, also called *model*. Furthermore, *models* contain both the state of the object, represented by *variables*, and the behavior of the object, represented by *equations*.

Object-oriented language enables a process known as *inheritance*. *Base-class* states (variables) and behaviors (equations) can be extended to a *sub-class*. Thus, the model hierarchy is organized by levels, where models are classified as a higher level than the inherited model. Figure 1 shows the schema of the proposed fixed-bed-dryer model and the model hierarchy.

The coffee fixed-bed was considered to be a thick layer composed of a finite number of thin layers. Each thin layer is a control volume that has a fixed transversal area *A* and a variable thickness *L*. The drying kinetics in each control volume were described using thin layer drying theory and were modeled as a Modelica model class.

Modelica model classes are connected with connector class which represents the conservation relations between model classes. In this case, the connector variables were air properties. The connector`s flow variable is the velocity (*V*) which is proportional to mass flow rate. The connector`s potential (non-flow) variables are the temperature (*T*), pressure (*p*) and relative humidity (*rh*) of the air. The sub-index *a* denotes an input variable and the sub-index *b* denotes an output variable. Figure 2 shows a scheme of the thin layer model (*DryLayer*) with the inlet and outlet connector.

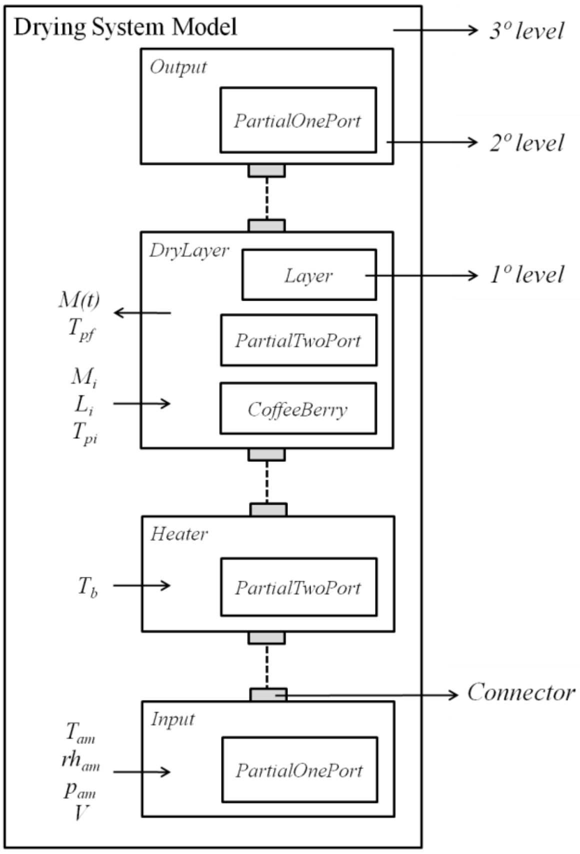

Figure 1: Hierarchy schema of the thick layer drying

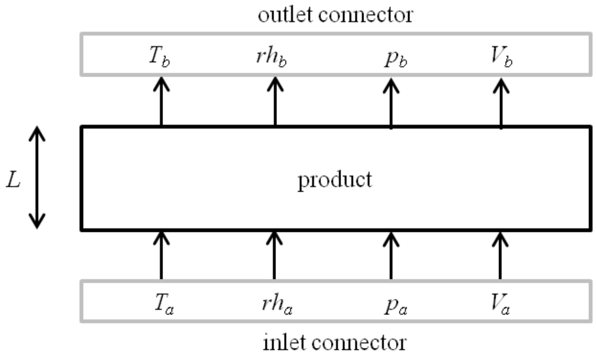

Figure 2: Control volume and air connectors of the *DryLayer* model.

The first-level-models were created containing the air psychometrics equations and properties. The second-level-model to represent the air inlet and outlet are named *Input* and *Output*, respectively. These models need only a single connector, inlet or outlet. Thus, a first-level-model, named *PartialOnePort*, was created containing the psychometrics equations and a connector. The others second-level-models need a pair of connectors (inlet-outlet). Thus, a first level model was created, named *PartialTwoPort*.

The saturation vapor pressure was described as function of temperature by an empirical equation proposed by Keenan and Keyes (Henderson et al. 1997).

$$\ln\left(\frac{p_{vsat}}{R'}\right)=\frac{A+BT+CT^2+DT^3+ET^4}{FT-GT^2} \tag{1}$$

where: p_{vsat} is the air saturation vapor pressure, Pa; T is the air temperature, K; R', A, B, C, D , F and G are the adjusted empirical coefficients.

The air vapor pressure, humidity ratio, enthalpy and density were calculated using basic psychometrics equations. These equations were formulated based on Dalton`s law, mass and energy conservation principles.

$$H=\frac{p_v}{1.605\,(p-p_v)} \tag{2}$$

$$\rho_{ar}=\frac{(1+H)\,(p-p_v)\,MM_{H_2O}}{R\,T} \tag{3}$$

$$p_v=rh\;p_{vsat} \tag{4}$$

$$h=c_{ar}(T-T_0)+H\,[h_{g,0}+c_v(T-T_0)] \tag{5}$$

where: H is the air humidity ratio, kg of vapor per kg of dry air; p is the air absolute pressure, Pa; p_v is the air vapor pressure, Pa; ρ_{ar} is the humid air density, kg m^{-3}; MM_{H_2O} is the water molar mass, 18.02 kg kmol^{-1}; R is the universal gas constant, 8314 J mol^{-1} K^{-1}; rh is the air relative humidity, dimensionless; h is the humid air enthalpy, kJ kg^{-1}; $h_{g,0}$ is the water latent heat at the reference temperature, 2502.5352 kJ kg^{-1}; T_0 is the reference temperature, 273.15 K; c_{ar} is the dry air specific heat, 1.0069 kJ kg^{-1} K^{-1}; and c_v is the vapor specific heat, 1.8757 kJ kg^{-1} K^{-1}.

The air and vapor mass flows are calculated in the first level models. These variables are used in the mass and energy balance equations.

$$m''=\rho_{ar}\,V \tag{6}$$

$$m''_v=\left(\frac{H}{H+1}\right)m'' \tag{7}$$

where: m'' is the air mass flow, kg m^{-2} s^{-1}; m_v'' is the vapor mass flow, kg m^{-2} s^{-1}; e V is the air velocity, m s^{-1}.

The first-level-model named *CoffeeBerry* was created containing the mathematical equation that describes the product physical properties as functions of its moisture content. This model is stored in a Package named *Product*, which can be used to storage many types of product models.

The coffee volume, density, porosity and specific heat were described using the equations 8 to 11, which were developed by Junior (2001). Assuming the coffee berry to be a perfect sphere, the product average diameter can be calculated using equation 12.

$$v=10^{-9}\,(621.46+152{,}78\,M+12.417\,M^2) \tag{8}$$

$$\rho_p=420.8490+198.8201\,M-53.8475\,M^2 \tag{9}$$

$$\varepsilon=10^{-3}(432.324+114.307\,M-32.317\,M^2) \tag{10}$$

$$c_p=0.9447+3.6197\,M-1.9920\,M^2 \tag{11}$$

$$v=\frac{\pi\,d_p{}^3}{6} \tag{12}$$

where: M is the product moisture content, kg of water per kg dry mass (d.b.); v is the product volume, m^3; ρ_p is the product density, kg m^{-3}; ε is the product porosity, dimensionless; d_p is the product average diameter, m; and c_p is the product specific heat, kJ kg^{-1} K^{-1}.

The drying constant was calculated using the equation 13, proposed by Young and Dickens (Henderson et al. 1997). This equation relates a general drying constant to a referential one, obtained experimentally. The empirical equation of Junior (2001) was used as the referential drying constant. The saturation vapor pressure ratio in equation 13 was assumed to be equal to 1 due to the equation 14 already considering the variation of relative humidity. The referential velocity is equal to 0.2166 m s^{-1}, the value used in Junior's experiment.

$$k=\frac{1}{3600}\,k_r\left(\frac{p_{sat}}{p_{satr}}\right)^{0.46}\left(\frac{V}{V_r}\right)^{0.7} \tag{13}$$

$$\begin{aligned}k_r={}&-0.1196+1.4180\,10^{-3}\,T_c+6.9938\,10^{-5}\,T_c^2\\&+0.6545\,rh-0.5369\,rh^2-7.5170\,10^{-3}\,T_c\,rh\end{aligned} \tag{14}$$

where: k is the drying constant, s^{-1}; k_r is the referential drying constant, h^{-1}; p_{satr} is the referential saturation vapor pressure, Pa; V_r is the referential air velocity, m s^{-1}; T_c air temperature in Celsius degree , °C.

The product water latent heat was described using equation 15, adjusted by Junior (2001). The Modified Henderson equation (16), adjusted by Correa et al. (2010), was used to describe the hygroscopic equilibrium between the product and the air.

$$\begin{aligned}h_{fg}={}&(2502.49-2.43\,T_c)\\&(1+7.7866\,10^6\,\exp(-19.6621\,M^{0.0499}))\end{aligned} \tag{15}$$

$$1 - rh_e = \exp(-0.0001\,(46.8549 + T_c)\, M_e^{1.8299}) \qquad (16)$$

where: h_{fg} is the water latent heat inside the product, kJ kg^{-1}; M_e is the product equilibrium moisture content, d.b.; and rh_e is the equilibrium relative humidity, dimensionless.

A first-level-model named *Layer* was created to define initial values of the variables: the initial layer thickness (L_i), initial moisture content (M_i) and initial product temperature (T_{pi}). The initial layer thickness of the control volume has to be as small as possible, in order for the thin layer drying theory to be applicable.

The *Input* model extended the *PartialOnePort* model and has the structure to receive the boundary variables of the air. The *Output* model only needs to extend the *PartialOnePort* model.

The *Heater* model was created to represent the air heater. This model extended the *PartialTwoPort* model and has the structure to receive the variable T_b, which represent the temperature that the air is heated (drying temperature). As result, all outlet air variables are calculated by the *Heater* model.

The *DryLayer* model was created to represent the control volume of product. This model extended the *PartialTwoPort*, *CoffeeBerry* and *Layer* models and has the mass and energy balance of the drying process.

The exponential equation, proposed by Sherwood (Henderson et al. 1997), was used to describe the thin layer drying of the product. This equation assumes that the drying rate is proportional to the difference between the moisture content and the equilibrium moisture content, proportionality given by the product drying constant.

$$\frac{dM}{dt} = -k(M - M_e) \qquad (17)$$

where: dM/dt is the drying rate, s^{-1}.

The heat balance equation considering on *DryLayer* model neglects the heat transfer due to conduction between the particles and radiation between the particles and the dryer's walls. Moreover, it was assumed that all heat transferred by the air is used to the product water evaporation and to heat the product. Thus the changes in air properties can be related to the variation on product moisture content, using the mass (18) and heat (19) balance equations. The convective heat transfer coefficient was calculated using the Barker`s empiric equation (21), presented by Brooker et al. (1992).

$$m''_{vb} - m''_{va} = -\frac{dM}{dt}\,\frac{\rho_p\, L}{1+M} \qquad (18)$$

$$m''_b\, h_b - m''_a\, h_a = \frac{dM}{dt}\,\frac{\rho_p\, L}{1+M}\, h_{fg} - \rho_p\, L\, c_p\, \frac{dT_p}{dt} \qquad (19)$$

$$m''_b\, h_b - m''_a\, h_a = -\,h'\,(T_a - T_p) \qquad (20)$$

$$h' = 0,9918\, c_{ar}\, m''_a \left(\frac{3600\, d_p\, m''_a}{0,06175 + 16,5\, 10^{-5}\, T_c} \right)^{-0,34} \qquad (21)$$

where: dT_p/dt is the product temperature rate, K s^{-1}; T_p is the product temperature, K; and h' is the heat transfer coefficient W m^{-2} K^{-1}.

The pressure variation through the product layer was calculated using the equation 22, which assumes that the total pressure variation is equal to the vapor pressure variation plus the friction loss. The friction loss was calculated using the Darcy equation (23) and the friction factor was calculated using the Ergun equation (24) (Henderson et al. 1997).

$$p_b - p_a = \left(p_{vb} - p_{va}\right) - p_f \qquad (22)$$

$$p_f = f\, \rho_{ar,a}\, \frac{L}{d_p}\, \frac{V_a^2}{2} \qquad (23)$$

$$f = \left(\frac{1-\varepsilon}{\varepsilon^3}\right)\left(3.5 + \frac{300\,(1-\varepsilon)}{Re}\right) \qquad (24)$$

$$Re = \frac{\rho_{ar,a}\, V_a\, d_p}{\mu_{ar,a}} \qquad (25)$$

where: p_f is the friction loss, Pa; f is the friction factor, dimensionless; Re is the modified Reynolds number, dimensionless; μ_{ar} is the air dynamic viscosity, Pa s.

The layer thickness variation was calculated using the equation 26. This equation considers the dry mass conservation and that the volume shrinkage only happens on the thickness direction, due to the fixed transversal area of the dryer. The sub-index *i* denotes initial.

$$\frac{\rho_v\, L}{1+M} = \frac{\rho_{v,i}\, L_i}{1+M_i} \qquad (26)$$

Many *DryLayer* model can be connect to form a third-level-model that represents a thick fixed layer. The model was implemented in *Modelica* language and simulated using the *OpenModelica*$^{®}$ 1.6.0 package.

2.2. Experimental Data

The experiment was conducted in a prototype dryer consisted by three chambers with equal dimension of 0.57 x 0.35 x 0.64 m. It was used coffee berries (*Coffea arábica L.*) variety *Mundo Novo*, manually harvested and pre-dried with ambient air.

The coffee was dried with dryer air (initial inlet air) with temperature at three levels: 40, 50, 60 °C. Three replicates were done for each temperature, resulting in nine experimental tests. Each test had a specific condition of ambient air and different initial moisture content of the product, presented on Table 1.

The coffee samples were withdrawn at predetermined periods at the heights of 0.10, 0.25, 0.40 and 0.55 m, in order to determine the product moisture content in different layers. For the simulation, it was assumed that each sample was withdrawn at the center of the layer, so the first and third layers have 0.20 m of thickness and the second and forth layers have 0.10 m of thickness.

Table 1: Drying and ambient conditions for each experimental tests.

Test	T_s **°C**	T_{am} **°C**	rh_{am} **%**	p_{am} **kPa**	V **m/min**	M_i **d.b.%**
40.1	40	23.5	55.9	93.843	8.60	17.91
40.2	40	25.4	52.7	93.683	8.81	20.41
40.3	40	20.2	67.7	94.216	8.27	20.25
50.1	50	22.9	48.0	94.376	9.20	38.56
50.2	50	23.2	62.2	93.750	8.82	18.56
50.3	50	19.8	69.6	94.136	8.72	18.10
60.1	60	22.9	57.7	93.790	7.10	17.45
60.3	60	16.7	45.7	94.083	8.27	32.32
60.3	60	24.3	43.9	93.817	8.81	19.70

where: T_s is the drying air temperature; T_{am} is the ambient temperature; rh_{am} is the ambient air relative humidity; p_{am} is the ambient air absolute pressure; V is the inlet air velocity; M_i is the product average initial moisture content.

2.3. Model Validation

The model statistical performance was evaluated by analysis of the relative standard deviation (*RSD*) and the performance index (27). This index evaluates the model performance by multiplying one dimensionless number that corresponds to the model precision, given by correlation coefficient (*r*), and another that corresponds to the model accuracy, given by agreement index (28) (Willmoot et al. 1985).

$$i = r\,d \tag{27}$$

$$d = 1 - \left[\frac{\sum_{j=1}^{n} \left(Y_j - \hat{Y}_j \right)^2}{\sum_{j=1}^{n} \left(\left| Y_j - \bar{Y} \right| + \left| \hat{Y}_j - \bar{Y} \right| \right)^2} \right] \tag{28}$$

where: i is the performance index; r is the correlation coefficient; d is the agreement index; Y is the observed data; $\hat{Y}$ is the model-predicted data; $\ddot{Y}$ is the average value of observed data; e n is the number of observed data.

2.4. Model comparison

The proposed model performance was compared with the MSU model, in order to investigate the validity of the new model. The performance comparison between the models was done by analyzing the performance index of each model.

The MSU model is completely described by Brooker et al. (1992), and was implemented in *Modelica* language and simulated with the same conditions of the proposed model using the *OpenModelica*® 1.6.0 package.

If compared with the proposed model, the MSU model have the following particularities: constant physical properties; assumption of water latent heat being equal to the free water; neglecting of pressure variation due to the increasing of vapor pressure through the drying; and neglecting of the layer volume shrinkage.

2.5. Sensitivity Analysis

Model sensitivity to parameter variation was evaluated using the differential sensitivity analysis method. In this method, all model parameters were classified by means of the sensitivity coefficient (29). The sensitivity coefficient represents the ratio between the output variable variation (response) and the analyzed parameter variation (perturbation), while all other parameters remain constant (Hamby 1994). The model result while all parameters are held constant is defined as the “base case”. The sensitivity coefficient was calculated to response of M, T_p, rh and T of all layers, and a global value S_t was calculated as an average value of all calculated sensitivity coefficients. The analysis was done considering a variation of ± 20% of each model`s parameter.

$$S_{X,\beta} = \frac{\left| X - X_i \right|}{\left| \beta - \beta_i \right|} \frac{\beta}{X} \tag{29}$$

where: $S_{X,\beta,}$ is the sensitivity coefficient response of X to the β variation; X is the output variable value to the base case; X_i is the output variable value to the β variation; β is the value of the analyzed parameter to the base case; β_i is the varied value of the analyzed parameter.

3. RESULTS

3.1. Simulation Results

Figure 3 shows the experimental observed values and predicted simulate results of moisture content for test 40.3, 50.3 and 60.3.

It can be observed in Figure 3 that the drying capacity increases when the temperature increases. This behavior occurs due to the increase of the product internal water diffusion and the increase of vapor pressure gradient between the water layer surface and the drying air.

Vossen (1979) indicated that a moisture content lower than 14 % (d.b.) is essential to ensuring safe storage of coffee. Furthermore, a low moisture content of coffee berries is important in the husking process. For the experimental conditions of the 40.3° C test, the 12 hour drying time was not enough to ensure a moisture content of 14 % (d.b.) in all layers. It is recommended for the industrial coffee drying process that the process end when the last product layer reaches the 14 % (d.b.) moisture content.

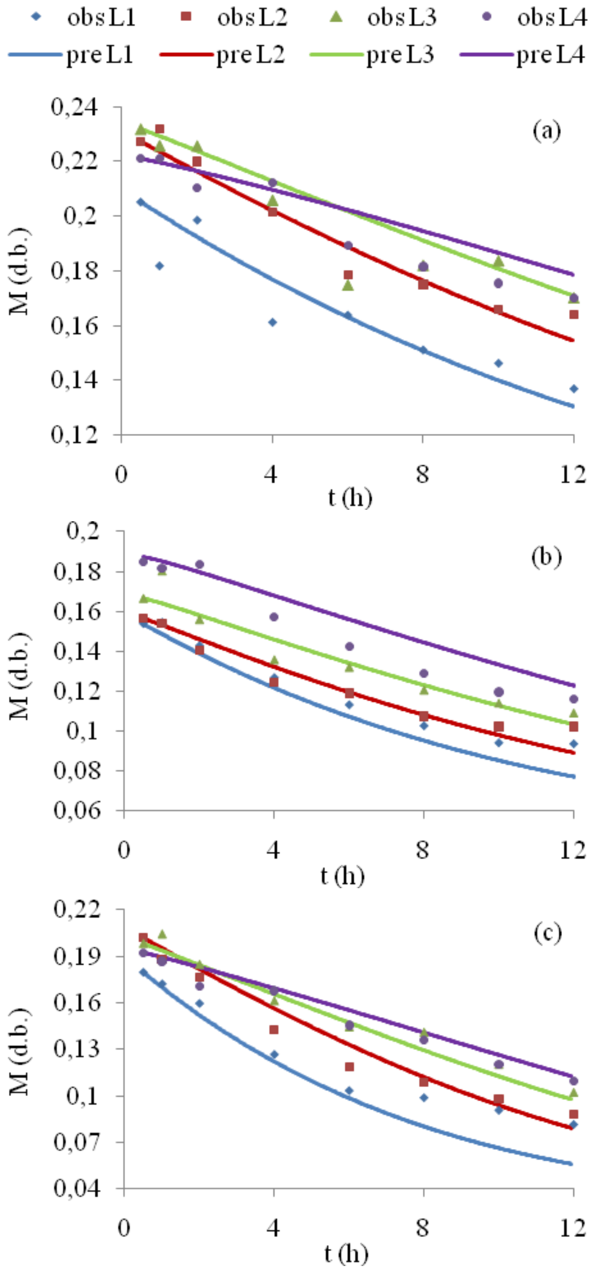

Figure 3: Observed (obs) and predicted (pre) values of moisture content of test 40.3 (a), 50.3 (b) and 60.3 (c).

Another important parameter to evaluate for process quality is the product temperature (T_p). Clarke and Macrae (1987) stated that if the coffee berry reaches a temperature of 40°C, the product suffers physical and chemical changes that will decrease the quality of the coffee beverage. Thus, it is recommended that the maximum drying temperature for static dryers be 40°C (Sfredo et al. 2005). Figure 4 shows the simulate results of product temperature for the test 40.3, 50.3 and 60.3.

It can be observed in Figure 4 that T_p reached a value higher than 40 °C for layer 1, 2 and 4 in the 60.3° C test. Based only on the simulation results, the use of a temperature higher than 60 °C for drying will generate a low quality product. In the 50.3° C test, only T_p of layer 2 reaches a value higher than 40 °C. Probably the use a temperature of 50 °C can be used to drying coffee depending on the drying conditions and system control.

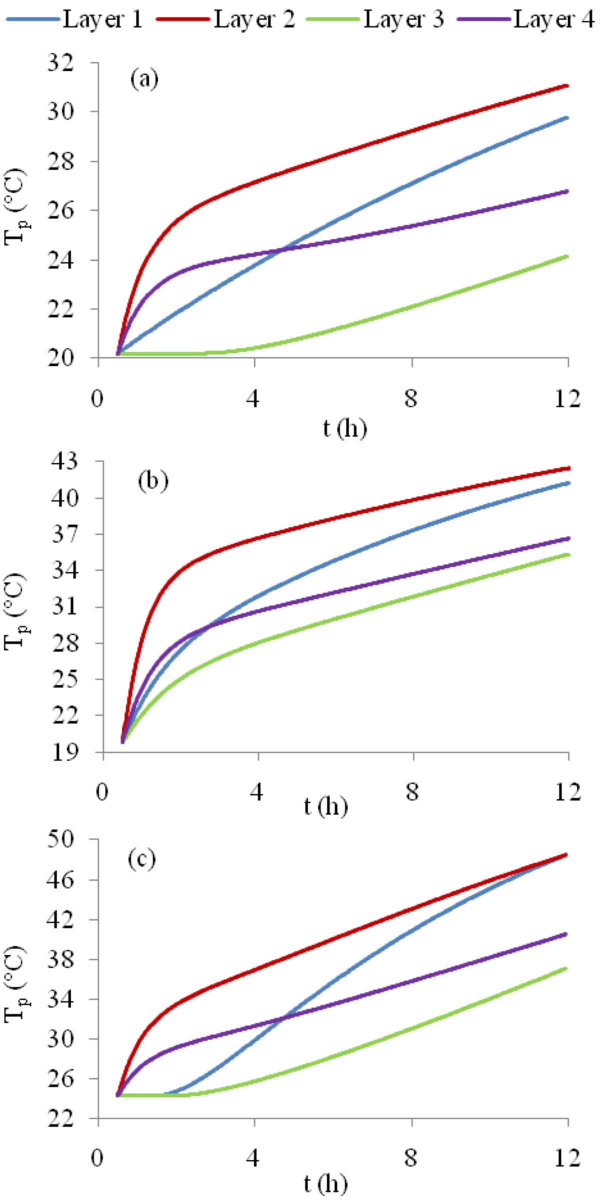

Figure 4: Predicted values of T_p for each analyzed layer of test 40.3 (a), 50.3 (b) and 60.3 (c).

The temperature of small particles is hard to measure incisively due to the size of the measurement equipment. Usually the product surface temperature or the transfer fluid temperature is used as a quality process parameter. In this contest the simulation results of product temperature can be used as a process control.

3.2. Validation

Table 2 shows the agreement index, correlation coefficient, performance index and the relative standard deviation of all simulated tests.

Table 2: Statistical validation parameters of each simulated test.

Test	***d***	***r***	***i***	***RSD* (%)**
40.1	94.55	92.07	87.05	3.41
40.2	93.62	94.75	88.71	4.53
40.3	96.48	95.12	91.77	3.36
50.1	97.01	95.35	92.49	5.79
50.2	97.44	95.93	93.48	4.16
50.3	97.38	96.33	93.81	4.18
60.1	97.62	96.63	94.33	5.24
60.2	97.53	97.92	95.51	6.66
60.3	98.37	97.77	96.18	5.21

All simulated tests of the proposed model presented values of relative standard deviation lower than 10 %, indicating satisfactory representation of the studied phenomena (Chen and Morey, 1989; Madamba et al., 1996; Mohapatra and Rao, 2005).

Moreover, all simulated tests presented values of performance index were higher than 85 %, indicating accuracy and precision of the proposed model to describe the system (Camargo and Sentelhas 1997).

Based on the analyzed statistical parameters the proposed model can safely describe the fixed-bed system to drying coffee berries, for the range of analyzed conditions.

3.3. Model comparison

Figure 5 shows the experimental observed values and MSU predicted results of moisture content for tests 40.3, 50.3 and 60.3.

The results showed in Figure 5 corroborate with the affirmation of Brooker et al. (1992) that the MSU model tends to overestimate the drying results, due to the considerations inherent to the model.

Table 3 shows the agreement index, correlation coefficient, performance index and the relative standard deviation of all simulated tests using MSU model.

Almost all condition simulated using the MSU model presented values of relative standard deviation higher than 10 % and/or a performance index lower than 85 %, indicating that this model not satisfactory describes the studied phenomena.

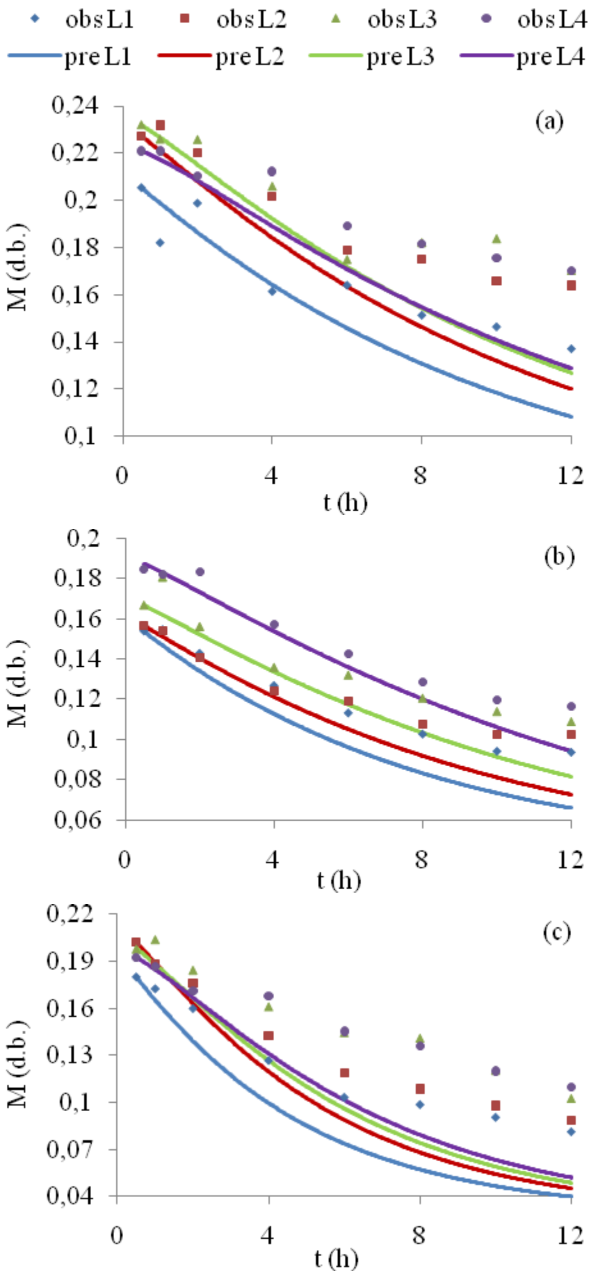

Figure 5: Observed and MSU predicted values of moisture content of test 40.3 (a), 50.3 (b) and 60.3 (c).

Table 3: Statistical validation parameters of each MSU simulated test.

Test	***d***	***r***	***i***	***RSD* (%)**
40.1	86.72	92.96	80.62	7.96
40.2	92.8	94.23	87.45	5.99
40.3	84.85	93.67	79.48	8.41
50.1	79.04	94.66	74.82	20.91
50.2	87.75	95.14	83.48	12.86
50.3	92.78	98.33	91.23	7.95
60.1	84.04	96.85	81.39	21.58
60.2	85.55	94.92	81.21	19.78
60.3	81.35	88.14	71.7	26.83

It can be observed by comparing Table 2 and Table 3 that all values *i* and *RSD* of the proposed model are better than the MSU model, indicating that the proposed model has a better performance.

3.4. Sensitivity Analysis

Table 4 shows all sensitivity coefficients calculated for each analyzed parameter, organized in increasing order of the S_t value.

Table 4: Sensitivity coefficients of each analyzed parameter of the proposed model.

S_i	S_M (%)	S_{rh} (%)	S_{Tp} (%)	S_T (%)	S_t (%)
T_s	119.11	170.24	75.93	85.03	115.16
M_i	91.26	46.80	27.65	50.43	46.30
T_{am}	29.91	95.58	41.98	34.82	45.30
V	53.37	44.12	22.94	31.69	34.71
rh_{am}	31.04	82.17	7.17	13.76	31.19
ρ_{ar}	30.67	46.81	22.61	28.56	29.87
L_i	27.58	42.77	27.17	30.97	28.85
p_{am}	23.34	33.78	20.66	24.01	24.32
c_{ar}	19.90	29.98	24.15	25.74	22.85
k	34.30	14.83	6.56	9.51	15.38
M_e	32.19	11.38	5.69	8.04	13.51
h_{lv}	14.15	18.98	6.50	9.83	12.73
h_{fg}	5.29	9.98	17.26	15.21	9.56
k_h	6.69	7.22	11.98	12.80	7.58
d_p	0.74	0.80	1.37	1.46	0.85
c_p	0.35	0.68	1.15	1.02	0.64
c_v	0.23	0.32	0.11	0.17	0.21
ε	0.05	0.08	0.01	0.03	0.04
ρ_p	0.01	0.02	0.01	0.01	0.01

It is observed in Table 3 that all input and initial parameters presented high sensitivity coefficients, higher than 24 %. The drying temperature (T_s) presented the greatest sensitivity coefficient (higher than 100 %), probably due to the high interference on the mass and heat transfer parameters and air properties.

The mass and heat transfer parameters and air properties presented substantial sensitivity coefficients, higher than 7.5 %. The air properties are only dependent of the thermodynamic conditions. They are well known and described on literature and can't be changed in the model structure. The transfer parameters are dependent of the fluid and particle properties, since the fluid is the air, the product transfer kinetics, represented by specific empiric equations, are the unique reason on changes of the model results.

All product physical properties presented low value sensitivity coefficients, less than 1 %. The variation of these parameters can be neglected, so an average or initial value can be used in order to simplify the model.

The unique product property that presented a considerable sensitivity was the water latent heat inside the product (h_{fg}). Probably, the consideration of this parameter on the model is one reason for a better performance than MSU model.

Furthermore, other reasons that can explain the improved performance are the consideration of pressure variation and layer volume shrinkage. As can be seen in Table 4, the model is very sensitive to the variation of L_i and p_{am}, presented a S_M value of 27.58 % and 23.34 %, respectively.

On the other hand, physical properties variation does not contribute to performance improvement of the proposed model, since the model is not very sensitive to these parameters.

4. CONCLUSIONS

From this research, it can be concluded that the proposed model can accurately describe the fixed-bed drying system to dry coffee berries. Furthermore, this model had better performance than the MSU model. Probably this result was due to the consideration of water latent heat inside the product, pressure variation and layer volume shrinkage. However, future studies must be completed to investigate the use of the proposed model to describe other drying systems for other products.

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