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Numerical Simulation of the moisture content in rough rice drying process in a fixed bed

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Abstract. *This article presents a numerical study of the rough rice drying process in a fixed bed. The study considered the following parameters: air temperature, volume flow and grains initial moisture content. The mathematical model used in literature was verified based on the influence of the air temperature and humidity partial differentials related to time, as those terms are neglected in simplified mathematical models used by other researches. The air temperature and air absolute humidity partial differentials, grains temperature and moisture content partial differentials were numerically solved using the finite elements method, through COMSOL Multiphysics software. The data acquired using the simulation were compared to experimental data obtained in literature, referring to moisture content of the rough rice bed. As a result, the complete model- using the air temperature and humidity partial differentials - presents a closer alignment with experimental data for bed depth near to the warm air input. The numbers on the improvement are measured using relative error and mean relative deviation, resulting on a improvement up to 23.51 % for the relative error and up to 12.12 % for the mean relative deviation.*

Keywords: *Grains dryin. Numerical Simulation. Numerical Studies. Partial differential equation. Numeric Methods.*

1. INTRODUCTION

According to Naghavi *et al.* (2010), the drying grains process consumes more than 65 % of the total energy consumed on the grains production. Valente (2012) attributes the high cost of grain drying process to the heating of the air, needed in order to increase the shelf life and prevent losses. The economical benefits of the grain drying are evident on the planting, harvesting, storage and distribution. According to Ferrari Filho (2011), the phases of planting and harvesting, for example, there is a possibility of anticipating the harvest, reducing field losses. On the storage and distribution phases, it's possible to increase the storage time, preserving the same, reducing costs due to weight and volume reduction, form market regulation storage and, at last, offer quality products.

Facing the economical importance of the drying grains process, its control, as its parameters control, is very important. According to Zare *et al.* (2006), the computer simulation is fastest and cheapest method for controlling the drying process dynamics. To Lopes *et al.* (2014), the simulation is an important optimization tool for the agricultural processes, which brings cost reductions. Therefore, many models have been presented and modified to simulate grains drying.

The literature highlights the importance of computational modeling on the grains drying process. Valente (2012), for example, states that using mathematical models is needed to predict the final moisture content and the output temperature of the final product. Thus, it is justified the execution of a study on mass and heat transfer, having as result an empirical equation to each studied situation. Valente (2012) reinforces that the obtained results present a nice precision, if compared to literature experimental data, but they are specific for each process.

MJ *et al.* (2016) affirms that modeling contributes to a better understanding of heat and mass transfer and it is very useful for improving drying project and drying process control. Malekjani and Jafari (2018) also reinforces that computational modeling advances and simulation techniques can aid on developing new dryers, changes on the current systems, energy saving and process optimization.

The main goal of the current article is to numerically study the rough rice drying process in a fixed bed, using the finite elements method, in order to identify the importance of the moisture content on the drying process of this grain. Moreover, it attempts to validate the studied mathematical models, through confrontation with literature experimental data and compare the influence of time term to the equations related to air temperature and humidity.

2. DEVELOPMENT

2.1 Physical Problem

The hypotheses used by Zare *et al.* (2006) to the development of the present model on this article are:

1. The volumetric contraction of the grain bed is neglected during the drying process;

2. The temperature gradient on the individual seed interior is neglected;

3. The mass and heat transfer by conduction between the grains core are neglected.

4. The time temperature variations and air humidity were considered neglected related to their variations along the grain layer thickness;

5. The walls of the dryer are adiabatic, with neglected heat capacity;

6. During some small timing gap, the air and grain humidity heat capacity are constant.

The present study compares the models in which the time temperature variations and air humidity are neglected (simplified) and the model in which terms are considered (complete).

The present study treats the unidimentional flow in which the border effects are considered negligible. The grain is considered in thermal and hygroscopic balance with the environment, on the beginning of the drying process.

2.2 Mathematical model development

To obtain the set of equations that form the model, the balance of mass and energy for the drying air and for the grain bed must be considered.

The mass balance of the system provides:

$$G\frac{\partial W}{\partial x} = -\rho_p\frac{\partial M}{\partial t} - \epsilon\frac{\partial W}{\partial t} \tag{1}$$

In which:
W = Absolute humidity of air;
x = depth in bed from air inlet;
G = specific mass flow rate of air;
ρ_p = particle density;
M = moisture content of grain;
t = time;
ϵ = void ratio.
The balance of energy for the air, in turn, supplies the relation expressed for:

$$G(c_a + c_v W)\frac{\partial T}{\partial x} = \rho_p c_v(T - \theta)\frac{\partial M}{\partial t} - h_a(T - \theta) - \rho_a\epsilon(c_a + c_v W)\frac{\partial T}{\partial t} \tag{2}$$

In which:
c_a = specific heat capacity of air;
c_v = specific heat capacity of water vapor;
T = air temperature;
θ = grain temperature;
h_p = grain bed volumetric heat transfer coefficient;
ρ_a = air density.
Finally, the energy balance for the grain results in

$$\frac{\partial \theta}{\partial t} = \frac{1}{\rho_p(c_p + c_w M)}\left[h_p(T - \theta) + h_{fg}\rho_p\frac{\partial M}{\partial t}\right] \tag{3}$$

In which:
c_p = specific heat capacity of moist rough rice;
c_w = specific heat capacity of water;
h_{fg} = latent heat of vaporization.

After a series of algebric manipulations, Zare *et al.* (2006) obtains the equation of the bed moisture content as:

$$\frac{\partial M}{\partial t} = [M(t) - M_e](-XYt^{Y-1}) \tag{4}$$

In which:
M_e = equilibrium moisture content.
In order to determine the dimensionless X, it will be used the equation described by Brooker *et al.* (1992):

$$X = 0.01579 + 0.0001746T - 0.01413UR \tag{5}$$

in which:
UR = relative humidity
The dimensionless Y is described by:

$$Y = 0.6545 + 0.002425T + 0.078867RH \tag{6}$$

The humidity on the equilibrium is:

$$Me = 0.001\left(\frac{A}{B}\right)^C \tag{7}$$

The dimensionless are indicated by:

$$A = -ln(1 - UR)T_{abs} \tag{8}$$

$$B = 2.667E - 7\left(1 - \frac{T_{abs}}{641.7}\right)^{-23.438} \tag{9}$$

$$C = \frac{1}{4.0E5T_{abs}^{-2.1166}} \tag{10}$$

The grain properties were obtained from Zare *et al.* (2006) are shown in table 1:

Table 1. Grain and air properties

Properties	Equations	Unity
Grain	$\rho_p = 4.44M + 504.7$	kg/m^3
	$h_p = 0.2755c_aG\left(\frac{2r_0G}{\mu_a}\right)^{-0.34}a_s$	J/m^3Ks
	$c_p = 1109 + 4186M$	J/kgK
	$h_{fg} = 2.503*10^6 - 2.386*10^3(T_{abs} - 273.16)$	J/kg
Air	$T_{abs} = T + 273.15$	K
	$c_a = 1009.26 - 0.0040403T + 6.1759*10^{-4}T^2 - 4.097*10^{-7}T^3$	J/kgK
	$c_v = 1.883*10^3 - 1.6737*10^{-1}T + 8.4386*10^{-4}T^2 - 2.6966*10^{-7}T^3$	J/kgK
	$\mu_a = 1.691*10^{-5} + 4.984*10^{-8}T - 3.187*10^{-1}T^2 + 1.319*10^{-14}T^3$	kg/ms
	$\rho_a = \left(\frac{101.325}{0.287T_{abs}}\right)$	kg/m^3
	$UR = \left(\frac{101.3W}{0.62189P_{sat} + WP_{sat}}\right)$	$decimal$
	$P_{sat} = 0.1exp\left[27.0214 - \frac{6887}{T_{abs}} - 5.31ln\left(\frac{T_{abs}}{273.16}\right)\right]$	Pa

The constant parameters are shown in table 2:

Table 2. Models parameters.

Parameter	Unity	Value
G	W/m^2	0.22
c_w	$J/kg/K$	4186
r_0	m	0.00457
a_s	m^2	2381

The value for the bed porosity (ϵ) is obtained by Sadeghi *et al.* (2010).To this end, the Sazandegi quality must be chosen and therefore obtain the 48.85 % value.

The equations are related to the air moisture content and temperature are obtained as $\frac{\partial T}{\partial t}$ and $\frac{\partial W}{\partial t}$ are ignored. This way, the equations used in each simulation, to the complete and simplified cases, are shown on Table 3:

It is still valid to emphasize that the boundary and initial conditions remain the same for the cases studied with the simplified model.

Table 3. Complete and simplified models equations

Parameter	Equation	Model
W	$G\frac{\partial W}{\partial x} = -\rho_p\frac{\partial M}{\partial t} - \epsilon\frac{\partial W}{\partial t}$	Complete
	$G\frac{\partial W}{\partial x} = -\rho_p\frac{\partial M}{\partial t}$	Simplified
T	$G(c_a + c_v W)\frac{\partial T}{\partial x} = \rho_p c_v (T - \theta)\frac{\partial M}{\partial t} - h_p(T - \theta)$ $-\rho_a\epsilon(c_a + c_v W)\frac{\partial T}{\partial t}$	Complete
	$G(c_a + c_v W)\frac{\partial T}{\partial x} = \rho_p c_v (T - \theta)\frac{\partial M}{\partial t} - h_p(T - \theta)$	Simplified
θ	$\frac{\partial \theta}{\partial t} = \frac{1}{\rho_p(c_p + c_w M)}\left[h_p(T - \theta) + h_{fg}\rho_p\frac{\partial M}{\partial t}\right]$	Both
M	$\frac{\partial M}{\partial t} = [M - M_e](-XYt^{Y-1})$	Both

3. RESULTS

The simulations were conducted on the COMSOL software environment, applying FEM (Finite Element Methods) technique for each Zare *et al.* (2006) suggested cases. The applied mesh was defined by the software as a normal sized, with a maximum element size of 0.0168 meters, and the growth rate 1.3 . This mesh, specifically, presents the greater refinement for the important regions, as shown on Figure 1:
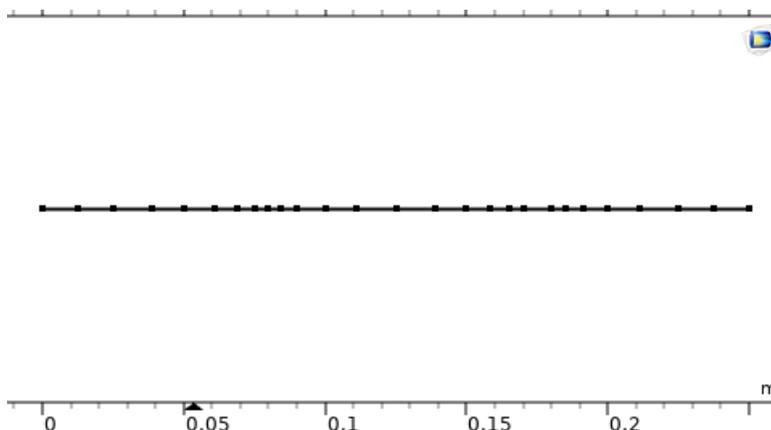

Figure 1. Mesh applied on the simulations

According to Zare *et al.* (2006), the initial and boundary conditions must be defined. The initial conditions (I.C.) and Boundary Conditions (B.C) are shown in the table 4.

Table 4. C.C. e C.I. by Zare *et al.* (2006)

C.I.	$\theta(x,0)$	$25°C$
	$M(x,0)$	$24,6\%$
	$T(0,t)$	$50°C$
	$W(0,t)$	1%
C.C.	$T(0,t)$	$50°C$
	$W(0,t)$	1%

In order to validate the proposed model, the experimental data present on the Zare *et al.* (2006) study must be used. These authors studied and analyzed the median bed humidity on the gaps of 8 to 9 cm and 17 to 18 cm, for each four tests suggested by Zare *et al.* (2006), as displayed on Table 5:

Table 5. Cases suggested by Zare *et al.* (2006)

Case	Temperature ($°C$)	Specific flow ($kg/m^2 s$)	Bed humidity (kg/kg)
1	50	0.22	0.2469
2	45	0.22	0.2587
3	50	0.16	0.2475
4	45	0.16	0.2512

The obtained results are compared to experimental data, as shown in Figure 2.

(a) Case 1 - range from 8 to 9 cm

(b) Case 1 - range from 17 to 18 cm

(c) Case 2 - range from 8 to 9 cm

(d) Case 2 - range from 17 to 18 cm

(e) Case 3 - range from 8 to 9 cm

(f) Case 3 - range from 17 to 18 cm

(g) Case 4 - range from 8 to 9 cm
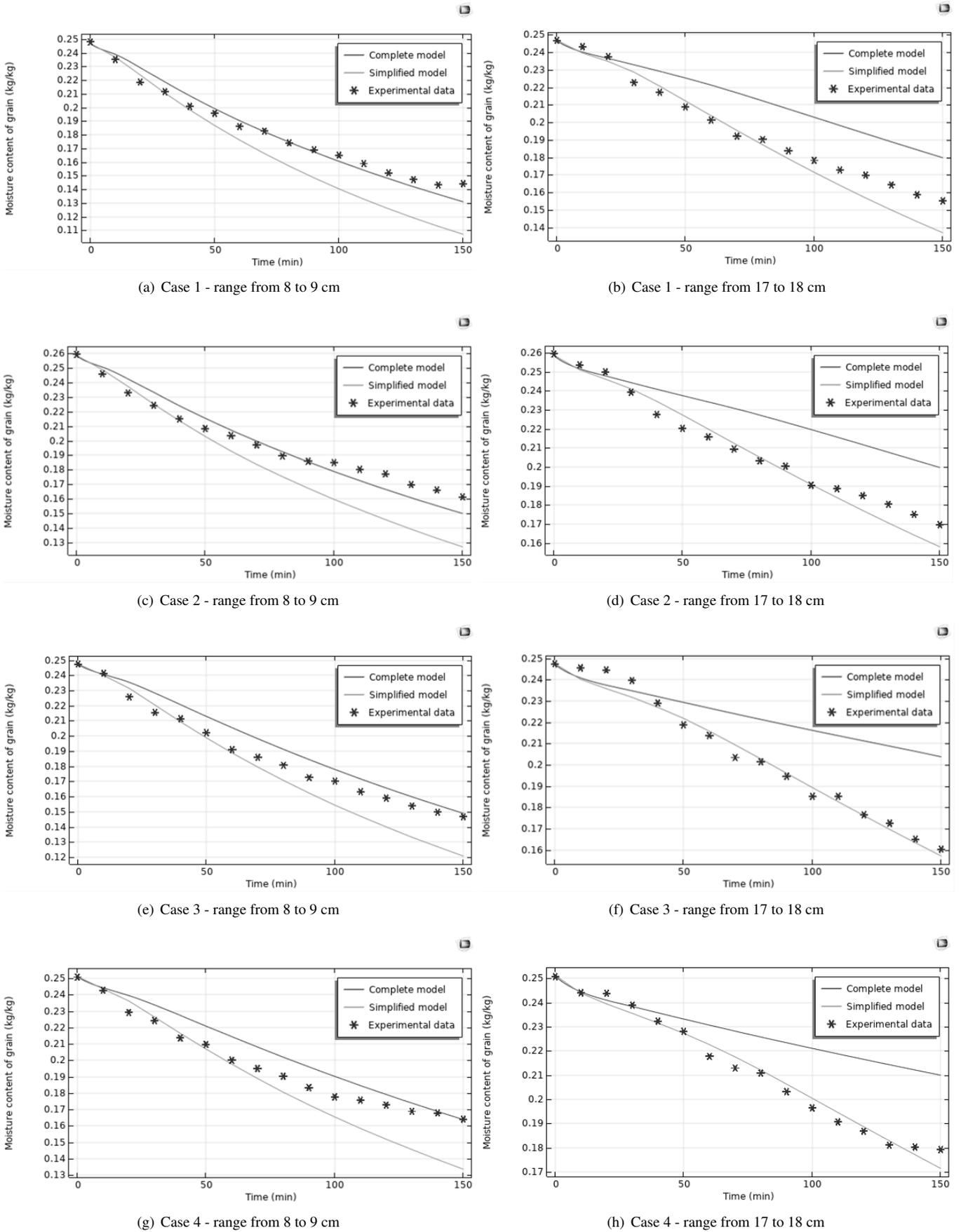
(h) Case 4 - range from 17 to 18 cm

Figure 2. Comparison between complete and simplified models

In order to compare the obtained results, the relative errors were computed for each case, according to the formulation proposed by Zare *et al.* (2006).

$$E = \frac{|M_j - \hat{M}_j|}{M_j} \times 100 \tag{11}$$

In which:
E = Relative error;
M_j = Experimental bed humidity;
$\hat{M}_j$ = Numerical bed humidity.
Another distinct way to measure the precision of each model is the medium relative deviation. This measurement is conducted by Zare *et al.* (2006):

$$\left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{M_j - \hat{M}_j}{\hat{M}_j}\right)^2\right]^{0.5} \times 100 \tag{12}$$

In which:
MRD = Medium Relative Deviation
n = Number of measurements in each experiment.
Maximum relative errors and mean relative deviation have been calculated, to each presented case, as it is shown in table 6.

Table 6. Maximum relative errors and mean relative deviation for each case - Complete and simplified models

Case	Model	Maximum error (%)	MRD (%)
Case 1 - range from 8 to 9 cm	Complete	9.18	3.59
	Simplified	25.69	12.85
Case 1 - range from 17 to 18 cm	Complete	16.16	11.24
	Simplified	11.75	5.212
Case 2 - range from 8 to 9 cm	Complete	19.02	6.23
	Simplified	21.35	11.51
Case 2 - range from 17 to 18 cm	Complete	17.71	11.21
	Simplified	6.83	3.26
Case 3 - range from 8 to 9 cm	Complete	7.62	4.85
	Simplified	17.69	8.47
Case 3 - range from 17 to 18 cm	Complete	27.09	13.99
	Simplified	3.58	1.87
Case 4 - range from 8 to 9 cm	Complete	7.23	4.93
	Simplified	18.57	8.64
Case 4 - range from 17 to 18 cm	Complete	18.39	10.66
	Simplified	4.35	1.78

How it can be seen as for the maximum relative error, like the medium relative deviation, the complete model, in this case is more appropriate for the analyses located on the bed depths near to the warm air input, while the simplified model is more appropriate to the analyses located on farther depths from the warm air input.

The only possible interpretation for this behavior resides on the fact that for the regions nearest to the hot air input, the air temperature derivative by time ($\frac{\partial T}{\partial t}$) is larger compared to further regions, altering reasonably the results obtained for absolute bed humidity.

In order to compare the absolute bed humidity obtained data for the complete and simplified models contrasting to data obtained on the Zare *et al.* (2006), maximum error (%) and MRD (%) as shown in Table 7:

As it was inferred on the MRD calculation, the complete and simplified models obtained better performance to the absolute bed humidity, compared to the results on the Zare *et al.* (2006) simulations.

This difference is probably given due to the distinct numerical methods used to solve the PDEs from the mathematical model presented: Zare *et al.* (2006) applied the finite difference method (FDM), and the present study applied the Finite Elements Method (FEM).

Table 7. Maximum relative errors and mean relative deviation for each case - Zare *et al.* (2006) and this studies data comparison

Case	Model	Maximum Error (%)	MRD (%)
Case 1 - range from 8 to 9 cm	Zare *et al.* (2006)	15.05	8.47
	Complete	9.18	3.59
Case 1 - range from 17 to 18 cm	Zare *et al.* (2006)	14.48	8.55
	Simplified	11.75	5.22
Case 2 - range from 8 to 9 cm	Zare *et al.* (2006)	13.45	8.65
	Complete	7.06	6.23
Case 2 - range from 17 to 18 cm	Zare *et al.* (2006)	17.62	8.54
	Simplified	6.83	3.26
Case 3 - range from 8 to 9 cm	Zare *et al.* (2006)	14.59	8.36
	Complete	7.62	4.85
Case 3 - range from 17 to 18 cm	Zare *et al.* (2006)	13.23	7.70
	Simplified	3.58	1.87
Case 4 - range from 8 to 9 cm	Zare *et al.* (2006)	14.20	7.45
	Complete	7.05	4.93
Case 4 - range from 17 to 18 cm	Zare *et al.* (2006)	14.06	8.50
	Simplified	4.35	1.78

4. Conclusion

The present study purpose is to study moisture content in rough rice drying process in a fixed bed, using COMSOL software, by finite element method.

The selected model on this study was the one used by Zare *et al.* (2006). The presented model was disposed in two distincts versions: complete and simplified models, and the difference between them was the inclusion of $\frac{\partial W}{\partial t}$ and $\frac{\partial T}{\partial t}$. The results obtained in each model were confronted in two different bed ranges: from 8 to 9 cm and from 17 to 18 cm, for each 4 distinct cases. Consequently, the complete model is better for the bed lanes nearest to the air inlet, since on this regions the air/time differential temperature has extensive influence. Further to the inlet lanes delivered better results on the simplified model.

The present study selected the complete model for the range from 8 to 9 cm from the inlet, and the simplified model for the range from 17 to 18 cm. Hence, the results of the simulations were confronted to the numeric results obtained by Zare *et al.* (2006).As a conclusion, the models proposed on this study had better performance, with reduction on the medium relative deviation up to 6.72 %.

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