COMPUTATIONAL SIMULATION OF FLUID-THERMAL BEHAVIOR OF A DRYER

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Abstract. *In convective drying process, one important aspect to be considered, is the solid - drying gas interface conditions, such as relative velocity, temperature and pressure distribution. Usually the available information about industrial dryers are global relations of drying gas flow, usually air, mean temperature, energy consumption and efficiency. These global informations may give the impression that everything inside the equipment is uniform: the temperature, velocity and pressure distributions; and these are not the real conditions, especially if there is not agitation or material movement inside, just like tray dryer models. The non uniform conditions inside these dryers models can be proved by the fact we have constantly change trays positions during drying process, otherwise some part of material will be dry and other not. Computational fluid dynamics tool was used to identify the critical regions and to show that none of variables analyzed has uniform distribution inside a static tray dryer used in Curcuma Longa L drying process, and this is the major problem present in this kind of dryer. Four different boundary conditions in mass gas flow were used to numerical computations and compared to experimental measurements of temperature.*

Keywords: *drying, dehydratation, Curcuma Longa L, computational simulation, CFD.*

1. INTRODUCTION

Computational or experimental study of industrial equipments and processes have been an important tool in design development, because it give us information that can be used to approximate a system behavior, and then the path to optimization will be clear even more.

The use of computational tools in food industry is recent if compared to other areas such as mechanical and structural engineering. Works of Scott and Richardson (1997), Xia and Sun (2002), presents a historical review of some computational tools applications in food industry equipment and process like sterilization, drying, pasteurization, refrigeration and blending. These kinds of tools offers interesting attractive like no construction need of an experimental model that sometimes is out of budget.

Drying is one of the oldest processes to food conservation because the water activity is reduced to levels that are not adequate to microbiological grown. Three stages are very distinct during the process and they are shown in Fig. 1.

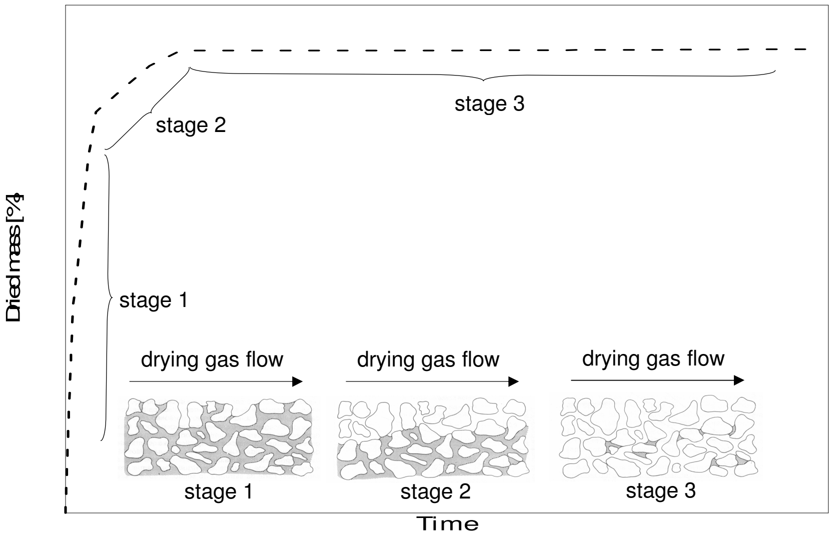


Figure 1. Drying process stages

Stage 1) is characterized by very short period of high and transient rate of drying, after that a high and constant rate of drying. After steady state has been reach, solid temperature is the humid bulb temperature of drying gas and its remains stable until the end of stage, that is when solid reaches the critic humidity.

Stage 2) is characterized by decreased rate of drying, solid temperature raises and mass dried is low.

Stage 3) is characterized by lowest rate of drying, near to zero, and solid humidity is the equilibrium humidity that is the lowest that can be achieved in those drying conditions.

This process changes some organoleptic food properties like texture, taste, color and new products like raisins, powder and flakes stuffs are obtained. Solid food drying can be obtained by heat and mass transfer fundamentals, and the use of solar radiation heat transfer is the cheaper source of energy to drying process. Commonly used in agricultural dryers, these systems have two important particularities. The first is the very long time necessary to dry, if considering industry scale production, and the second is if the dryer is not very well constructed the water dried during the day can get back, at least a portion, overnight. Some dryers models are presented in Rossi (1980) and Brace Research Institute (1975) and these facts can be clearly observed.

Is important to remember that even the cases that radiation heat is the source of energy to drying process, is convective heat and mass transfer the responsible in drying, because the drying gas is the vehicle to extract humidity from inside the food to outside.

If there is convection phenomena, then Reynolds number is an important parameter to be observed. Is well known that higher the Reynolds number, higher will be temperature, pressure, velocity and concentration gradients evolved, and this is the motivation to artificial methods of drying gas moving, using blowers to forced convection cases, and reducing the drying time.

New drying techniques have been experimented and a promising one is the use of microwave as heat source. Valenti *et al* (1998) used this technique in corn seed drying process, Foggiato and Ribani (1999) used the same technique in bean seed and Cabrita *et al* (1999) used in tea leaf drying. The major advantage observed by authors was the drying time significantly reduced.

Convective based static trays are one of the most used commercial dryers models and a common problem to all of them is the non uniform drying medium. This means that at determined time some part of food has been dried and some part of food has not been dried. In some cases such as vegetables, the fermentation process may occurs because the temperature, not high enough to dry, and humidity, still high, is a perfect medium to microbiological grown, and if this happens some of production can be lost. To avoid this kind of problem today, the user must manually change places of the trays at stipulated times.

The present paper shows how computational fluid dynamics applied to industrial equipment can be a useful tool to help design engineering to prevent and optimize undesired conditions in industrial equipments, since bad regions of low velocities and temperatures can be identified.

2. MATERIALS AND METHODS

The saffron (*Curcuma longa L.*), also known as curcuma, golden ginger, is a native specie from asian southwestern region, that belongs to *Zingiberaceae* family, small plants with 1 meter high, and it has been used for a long time in medicine and as food sauce and natural coloring. Some physical-chemical properties of saffron are listed in Tab. 1.

Table 1. Physical-chemical properties of saffron (centesimal composition).

	Pruthi (1980)	Gonvidarajan (1980)	Filho and Villas-Boas (1996)	Leonel and Cereda (2002) (humid base)
Humidity	--	--	74,70	81,23
Protein	--	6 – 11	11,68	2,02
Starch	24,40	30 – 50	35,30	8,83
Fiber	--	--	5,50	1,78
Ash	9,00	2 – 6	6,44	2,01
pH	--	--	--	6,54

The considered dryer was a typical static trays model which general technical data provided by manufacturer are listed in Tab. 2., and it was used to *Curcuma longa L.* drying.

Table 2. Dryer technical data

	Model PD25
Voltage	220 Volts
Power	1/4 hp
Weight	60 kg
Drying area	2,0 m2
Dimensions	560x930x900 mm
Liquefied Petroleum Gas consumption	0,195 kg/h

A scheme describing the equipment, trays, blower and heat system positions is presented in Fig. 2.

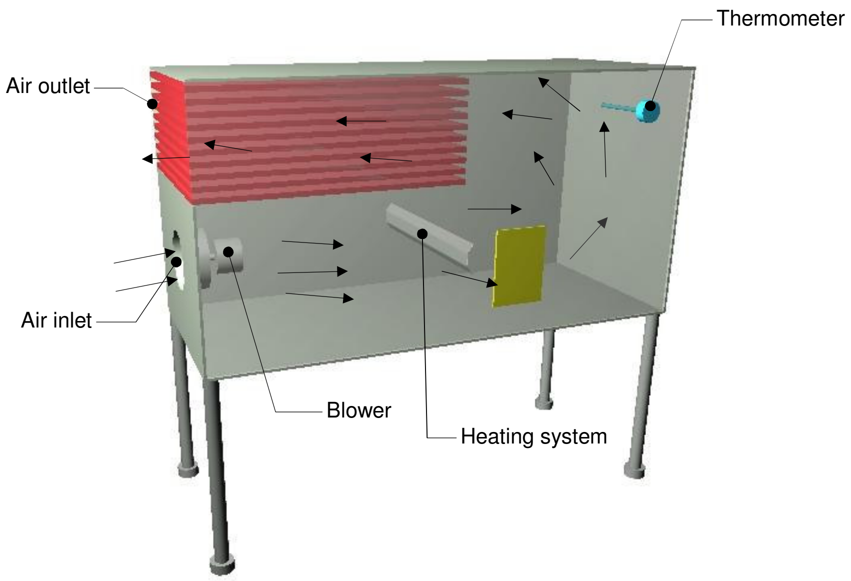


Figure 2. Equipment scheme

To secure uniform conditions over time, this dryer was located in a temperature and humidity controlled room. *Curcuma longa L* was prepared considering two different shapes which geometric relations are presented in Tab. 3. and disposed in trays according the scheme shown in Fig. 3.

Table 3. Geometric relations of *Curcuma longa L* shapes

Cube side=**L**	Disc/Cylinder high=**h,** diameter=**d**	
L=5mm	**h**=5mm	**d**=10mm
L=10mm	**h**=10mm	**d**=15mm
L=20mm	**h**=15mm	**d**=20mm
	h=20m	

As defined in Perry (2000), mean diameter and high, and dried mass percentage are calculated as following, according to Fig. 3:

$$d_m = \frac{(d_1 + d_2)}{2} \tag{1}$$

$$h_m = \frac{(h_1 + h_2)}{2} \tag{2}$$

$$m\% = \left(\frac{m_{initial} - m_{actual}}{m_{initial}} \right) \times 100 \tag{3}$$

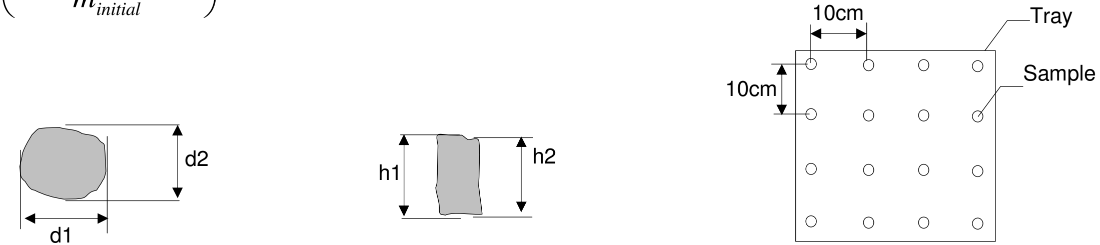


Figure 3. *Curcuma longa L* slices and positions in trays

3. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

In this problem, the main objective was to determine by numerical means, the temperature, velocity and pressure distributions inside the dryer, more specific over the sample disposed in trays. The numerical mass transfer problem, drying problem, would not be study here, but the effects of different drying conditions were presented and discussed. Some approaches were considered to simplify the general equations of continuity, momentum and heat transfer.

The problem was solved considering the general conditions:

- Two dimensional approach
  The equipment has a symmetry plane and then symmetrical boundary conditions.

- Steady state condition
- Rectangular coordinates
- Constant fluid properties
- Laminar flow
- By the fact that there were very small portions of *Curcuma* samples, the humidity transfer to drying air was not considered in the formulation, it was considered as uncoupled problem.

The governing equations reduce to:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{4}$$

Steady state two dimensional Navier-Stokes equations in rectangular coordinate form

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\rho g_x \tag{5a}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g_y \tag{5b}$$

Two dimensional energy equation without internal heat generation

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\Phi \tag{6}$$

where

$$\Phi=2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]+\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2 \tag{7}$$

In original Ansys© formulation, all terms in Continuity, Navier-Stokes and Energy equations are modeled in finite element formulation, and the viscous term, equation (7), was preserved. All equations, (4), (5), (6) and (7), were solved using coupled formulation, and the solution were considered converged if all R^2 errors go down 10^{-8}.

Boundary conditions considered in this problem is presented in Fig 4.

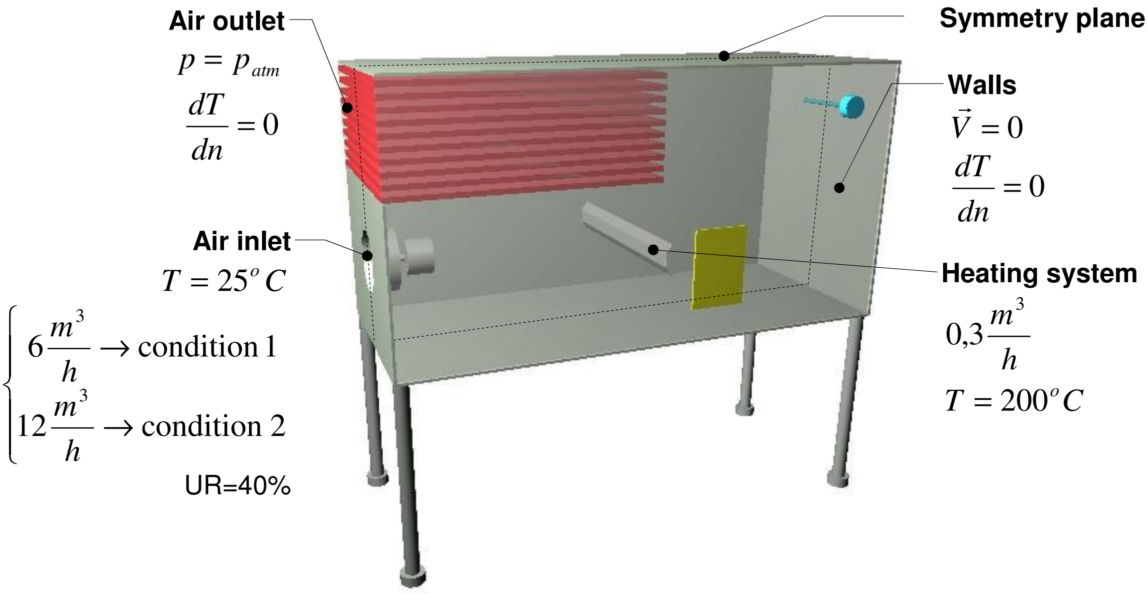
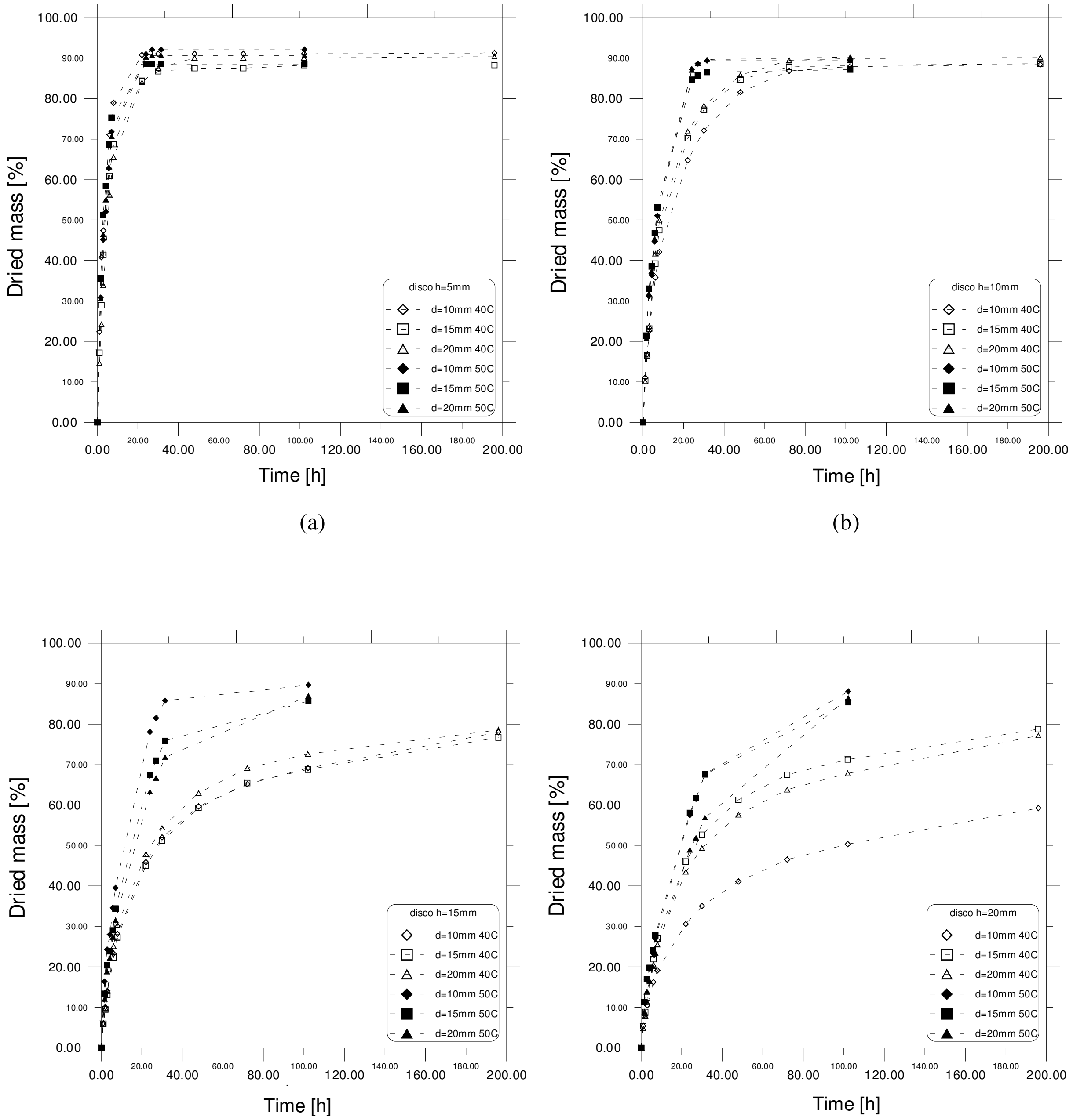


Figure 4. Boundary conditions

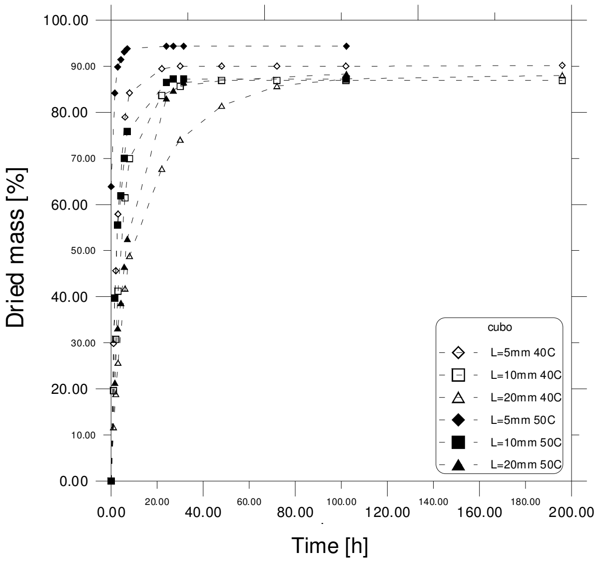
5. RESULTS AND DISCUSSION

However numerical simulation were performed in steady state conditions, it was used to approximate velocity and temperature distributions inside the equipment, the drying process, that was considered as a uncoupled phenomena, was a time dependent process, and as experimental procedure, drying curves were obtained where the typical three stages in drying can be clearly observed in Fig. 5. These experiments were performed considering the third and fourth inlet velocity boundary conditions, U_{in}=0.05 m/s and U_{in}=0.1 m/s, corresponding to measured temperatures T≈50 ^{o}C and T≈40 ^{o}C respectively.



(a) (b)

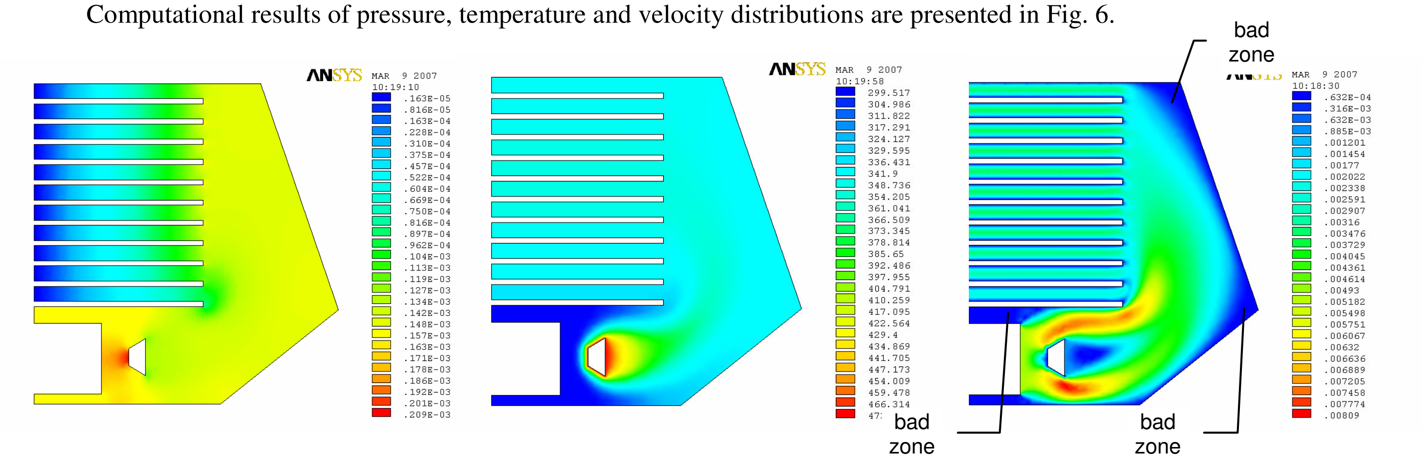
(c) (d)



(e)

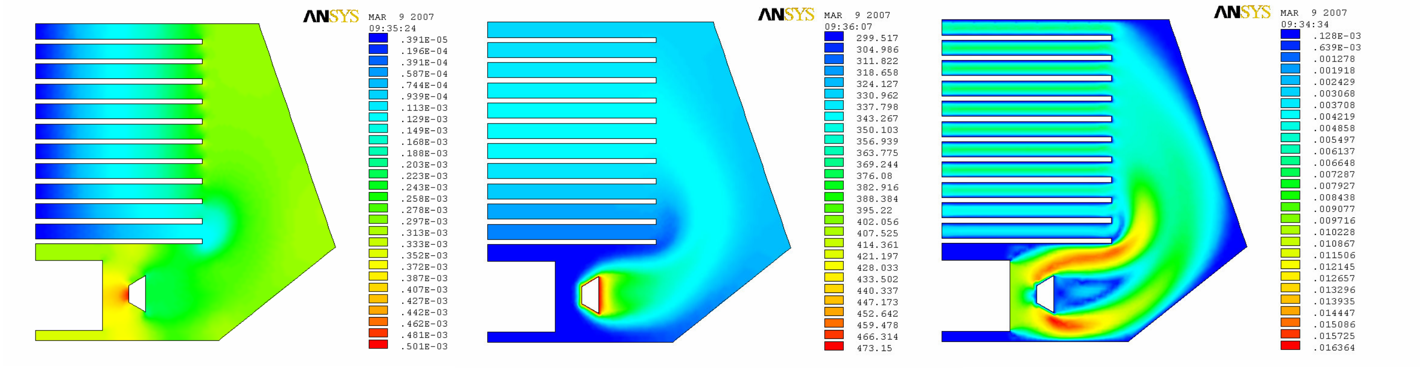
Figure 5. *Curcuma longa L* drying curves. (a) disc h=5mm, (b) disc h=10mm, (c) disc h=15mm (d) disc h=20mm, (e) cube

Computational results of pressure, temperature and velocity distributions are presented in Fig. 6.



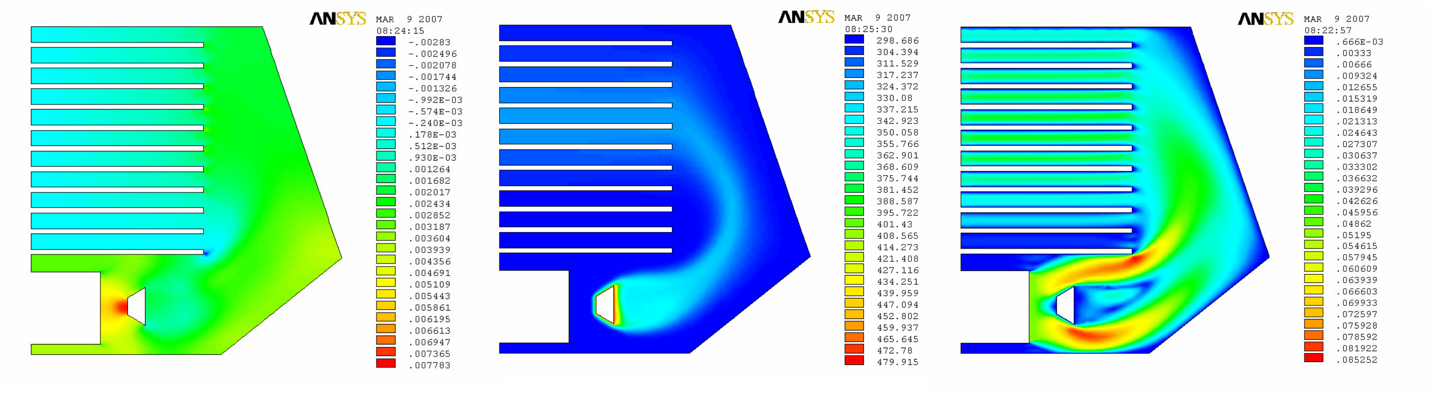
(a) (b) (c)

Pressure (a) , Temperature (b), Velocity (c)
U_{in}=0.005 m/s



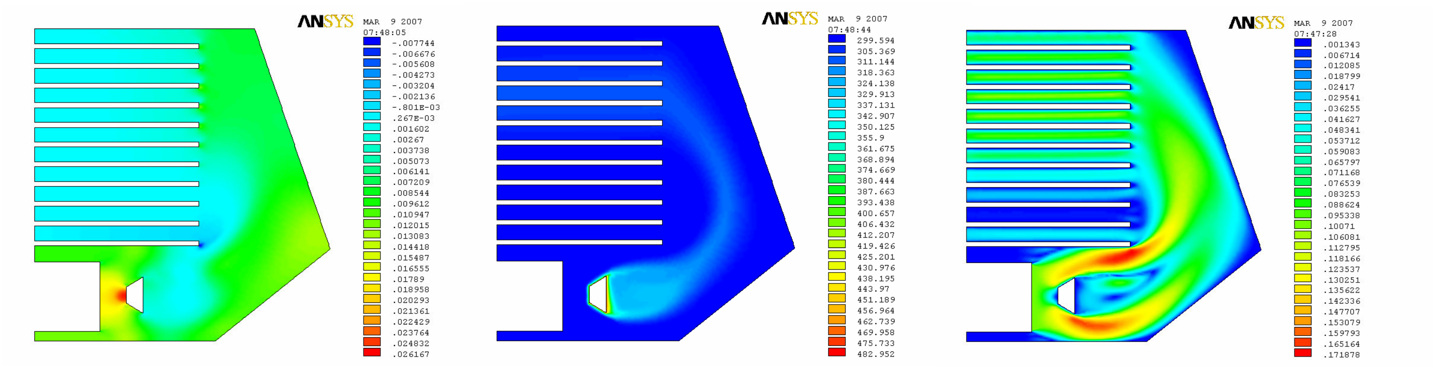
(d) (e) (f)

Pressure (d) , Temperature (e), Velocity (f)
U_{in}=0.01 m/s



(g) (h) (i)

Pressure (g) , Temperature (h), Velocity (i)
U_{in}=0.05 m/s



(j) (k) (l)

Pressure (j) , Temperature (k), Velocity (l)
U_{in}=0.1 m/s

Figure 6. Pressure, temperature and velocity distribution

Numerical study of an equipment, can reveal some aspects that sometimes is not noticed in traditional way. Regions of low velocities or recirculation can be observed in cases just like Figure 6 (c) just behind the blower and near the deflection wall, assigned by pointer and considered as a bad zone. It is clearly noticed that higher the inlet velocity, keeping constant the heating system, the outlet temperature will be lower and non uniform. So, is preferred to operate the equipment with lower velocity, to obtain better distribution of velocity and temperature inside the dryer.

An initial analysis was performed to identify the best region to drying process in equipment, which is characterized with higher temperatures and velocities, and results pointed to tray number six. A thermometer was located in this tray to read temperature information and later comparison to numerical results.

Numerical results presented in Tab. 4. and Tab. 5. shows the mean temperature and velocity distribution in each tray.

Table 4. Mean temperature and velocity distribution in trays. U_{in}=0.005 m/s and U_{in}=0.01 m/s

	U_{in}=0.005 m/s		U_{in}=0.01 m/s	
Tray	**T_{num}[K]**	**V_{mean} [m/s]**	**T_{num} [K]**	**V_{mean} [m/s]**
01	349.37	0.347E-02	329.52	0.679E-02
02	350.12	0.331E-02	331.49	0.653E-02
03	351.39	0.331E-02	334.40	0.656E-02
04	352.90	0.331E-02	337.75	0.653E-02
05	354.25	0.331E-02	340.40	0.649E-02
06	354.85	0.330E-02	340.76	0.648E-02
07	353.92	0.306E-02	338.35	0.643E-02
08	351.29	0.322E-02	332.57	0.626E-02
09	346.32	0.274E-02	326.34	0.596E-02
10	340.11	0.286E-02	319.84	0.499E-02
11	332.71	0.270E-02	315.52	0.391E-02

Table 5. Mean temperature and velocity distribution in trays. U_{in}=0.05 m/s and U_{in}=0.1 m/s

	U_{in}=0.05 m/s			U_{in}=0.1 m/s		
Tray	**T_{exp} [K]**	**T_{num} [K]**	**V_{mean} [m/s]**	**T_{exp} [K]**	**T_{num}[K]**	**V_{mean} [m/s]**
01	-	301.48	0.276E-01	-	300.06	0.672E-01
02	-	304.97	0.314E-01	-	303.58	0.807E-01
03	-	310.06	0.329E-01	-	307.72	0.837E-01
04	-	315.36	0.347E-01	-	310.44	0.871E-01
05	-	318.49	0.360E-01	-	308.49	0.855E-01
06	313 (≈50°C)	316.40	0.374E-01	308 (≈40°C)	303.59	0.807E-01
07	-	309.20	0.350E-01	-	300.00	0.650E-01
08	-	303.10	0.317E-01	-	298.47	0.442E-01
09	-	299.61	0.244E-01	-	298.25	0.238E-01
10	-	298.51	0.156E-01	-	298.25	0.375E-02
11	-	298.34	0.901E-02	-	298.25	0.363E-01

After analyzing temperature, pressure and velocity distribution inside the dryer, is notorious that the drying medium is not homogeneous, and then the process will not be too. The real conditions in food interfaces, that is important to drying process, are very different of those mentioned by equipment manufacturer, which provides only general information like global temperature, energy consumption and some expected drying time for some products.

In some cases, differences about 25 K in temperatures and 0.15 m/s in mean velocities, are non desirable situations in drying process, and because of that, trays must be interchangeable at time. Numerical results shows in detail what is happening inside the dryer, and with this information is possible to suggest equipment adaptations to prevent non homogeneous medium. Figure 7. and Fig. 8. shows that in cases of lower inlet velocities, the temperature and velocity distribution in trays presents more uniform, and this is something that we are looking for, where the whole equipment will work in same manner every point, but even with this situation supposed ideal, lower velocities are not interesting because the lower rate of drying, and it could be cooking but not drying. In cases of higher inlet velocities, temperature and velocity distribution is not very uniform like in lower cases, but drying process will be faster. In these cases, some areas problems appears. Those areas were identified by trays numbers 8 to 11, where temperature and velocity are very low and fermentation process may occurs.

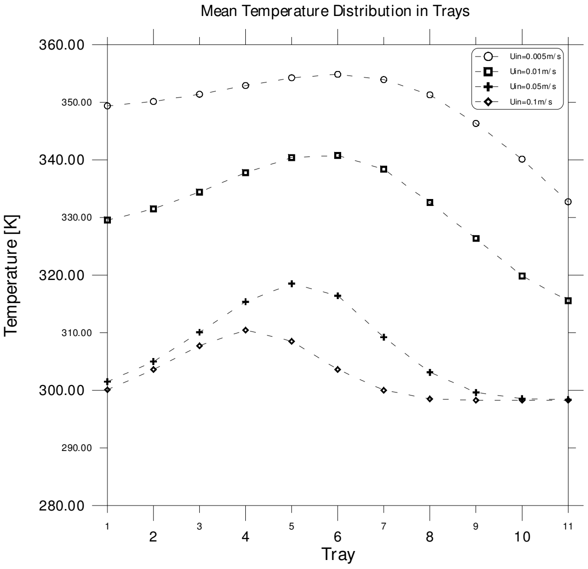


Figure 7. Temperature distribution in trays

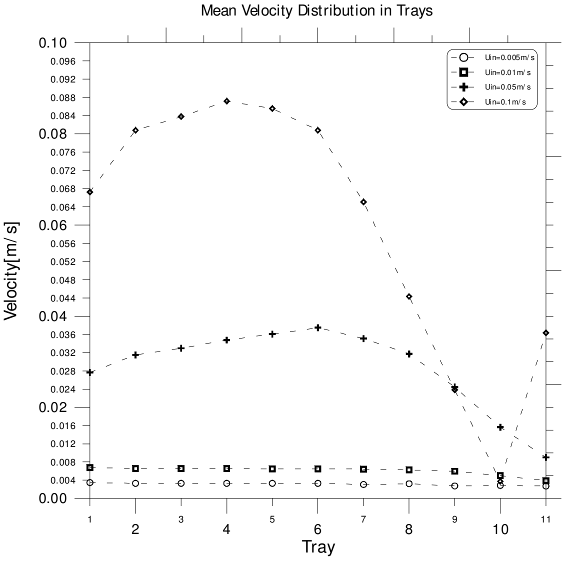


Figure 8. Velocity distribution in trays

6. CONCLUSION

Computational fluid mechanics is a powerful tool in engineering, and in the presented case it shows to be an important way to detail dryer behavior as function of velocities, and some undesirable areas could be detected pointing us how to prevent problems like that. In this kind of equipment, is desirable to have uniform distribution of temperature and velocity, or serious problems in drying will happen. Extreme cases can be observed in practice where some samples located in high temperature and velocities can be extremely dried, almost burnt, while in some samples located in bad zones, characterized by low temperature and velocity can be fermentated.

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