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NUMERICAL SIMULATION OF GREENHOUSE SOLAR DRYER IN NATURAL CONVECTION

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ABSTRACT

Traditionally, vegetables and fruits are dried outdoors in the sun without any protection against external pollutants or in direct dryers, causing very significant (nutritional and quantitative) losses. The objective of this work is to conduct a numerical simulation of a solar dryer in natural convection. For simulation, we use COMSOL software. The numerical resolution generated the heat flows in the system, the temperature field, the air velocity field and the pressure variation in the system. The variation of the temperature of 60°C in the dryer obtained by vacuum simulation is in line with the tolerated temperatures for the drying of fruits and vegetables.

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INTRODUCTION

The energy density of the solar radiation at the surface of the earth is relatively low and the use of a solar collector concentration would promote a good collection of solar energy. Thus, depending on the technology and the amount of energy desired, the use of concentration sensors is necessary for the storage of solar thermal energy. The performances of the systems, using these sensors, are closely related to the thermal efficiencies, the sizing of the system and the quality of the product to obtain. Today, the availability of food products is a major problem in some countries. Preserving food products by drying could be a solution. In this work, we propose a prototype of indirect solar dryer, greenhouse by natural convection. We will conduct a numerical simulation of this device on the COMSOL software.

MATERIALS AND METHODS

The scientific and technological development allowed the development of drying methodologies and the provision of several ranges of dryers (direct, indirect) by Dilip (2007), El Mokretar and Mahfoudia (2001), Singh *et al*. (2004), Ramana Murthy (2008). Youcef-Ali *et al*. (2008) used the results of research on the kinetics of rice drying in natural convection. They have succeeded in showing that indirect solar dryers have the best performance and reduce the risk of rice destruction for high thermal intensities in tropical countries. Several researchers, among whom Pangavhane (2002) and Amar *et al*. (2010) were interested in the drying of food products.

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Description of the system

Figures 1 and 2 show respectively a picture and a diagram of this solar dryer.

Our prototype is a greenhouse solar dryer with the following four parts:

a) The cylindrical concrete slab of surface S1 = 6.28 m^2 and of thickness e_o = 10 cm to absorb the heat during the day and to restore it at the fall of the night.
b) The enclosure formed by the ten flat panes of surface Sv = 0.37056 m^2 and of thickness e_v = 0.5 cm each,

constitute a total surface of capture of 3.7056 m^2 and about a volume V_0 = 0,628 m^3.

c) The enclosure formed by the metal cylinder and having the three trays from which will be placed the dried products of a volume V_2 = 2,355 m^3 of height h = 1.20 m. Each rack has a surface S_2 = 1.57 m^2. The wall consists of a metal sheet 1.5 mm thick.
d) The cone forming the upper enclosure from which the exhaust air escapes, of a volume of about V_3 = 0.2125 m^3.

Principle of operating

The system transforms solar radiation into thermal energy. It is designed for drying fruits and vegetables. It is an indirect dryer whose coolant is air. This device is designed to adapt to different wet seasons. The strongly inclined glazing 45°, maximizes the capture during the winter season during which we can harvest a huge amount of fruits and vegetables. The floor, made of reinforced concrete, is a reservoir of energy to continue the drying process even after sunset. A tarpaulin is provided to cover the glazing during the night period in order to prevent heat loss. Products to be dried are not exposed directly to solar radiation. They are arranged on racks inside the oven. The drying air is admitted into the oven after passing through the greenhouse constituted by the ten flat glazed sensors.

Parameters that define the thermal performance of the system include:

- The amount of product to be dried;
- Drying time;
- The amount of energy produced by the greenhouse;
- The amount of energy required for drying per kilogram of fruit or vegetables;
- The ratio of the amount of energy supplied by the greenhouse to the total amount of energy required for drying.

Numerical simulation of dryer

The numerical simulation in fluid mechanics is based on a strategy of approximate resolution of the Navier-Stokes equations. The Navier-Stokes equations generalize the Euler equations: the former are reduced to the seconds by canceling the viscosity term, linked to friction. By its movement, the fluid carries a momentum characterized by convective transport.

The equation of the momentum is given by:

$$\frac{d(\overrightarrow{\rho v})}{dt} + \vec{\nabla}.(\rho\vec{v} \otimes \vec{v}) = -\vec{\nabla}\mathrm{P} + \vec{\nabla}.\mathrm{T} + \rho\vec{f} \quad (1)$$

Diffusion of the fluid momentum at any point in the system is analogous to heat transfer.

The equation of heat transfer is given by:

$$\frac{\partial\vec{v}}{\partial t} + (\overrightarrow{v}.\vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}\mathrm{P} + \nu\,\nabla^2\vec{v} + \vec{f} \quad (2)$$

- t represents the time (s) ;
- ρ is density of the fluid (kg.m^{-3}) ;
- $\vec{v}$, velocity of fluid (m.s^{-1}) ;
- P, la pressure (Pa) ;
- T , the tensor of viscous contraints (Pa) ;
- ν = μ/ρ is kinetic viscosity ;
- $\vec{f}$ is the resultant of massic forces which are practising on the fluid (N.kg^{-1}).

The conservation of the mass is also verified by the Navier-Stokes equations, and is expressed by the same equation as for the Euler equations ($\nabla.\nu$ = 0). $(\overrightarrow{v.\nabla})\vec{v}$ is the convective term and characterizes the non-linearity of Navier Stokes equations. The Navier-Stokes equations are supposed to describe the flows of fluids. They model a fluid as a continuous medium, that is, characterized by physical quantities defined at any point in space and at any time. The Navier-Stokes equations are supposed to describe the flows of fluids. They model a fluid as a continuous medium, that is, characterized by physical quantities defined at any point in space and at any time. To date, the mathematical consistency of these equations has not been proven. The phenomenon of turbulence is one of the main obstacles to such a demonstration. Euler's equations reveal a difficulty they share with Navier-Stokes equations: they are non-linear. The property of non-linearity, which can be easily read on an equation, means that the sum of two possible solutions of the equation is not, in general, another possible solution. This implies significant differences from the linear equations.

Theorical approach by COMSOL Multiphysics

COMSOL Multiphysics is a powerful interactive environment for modeling and solving scientific and engineering problems based on partial differential equations (PDEs). This opportunity does not require a thorough knowledge of mathematics or numerical analysis. With built-in calculation modes, it is possible to build models by defining physical characteristics, such as material properties, loads, constraints, sources, and flows, rather than defining underlying equations. We can always apply to these variables, expressions or numbers directly to solid domains, boundaries, edges and points regardless of the mesh of calculation. COMSOL Multiphysics then internally compiles a set of partial differential equations that represent the entire model. We access the power of COMSOL Multiphysics as a standalone product through a flexible user interface, or MATLAB programming scripting. When solving models, COMSOL Multiphysics uses the Finite Element Method (MEF). The software performs finite element analysis with adaptive mesh and error control using a variety of numerical solvers. The COMSOL Multiphysics user interface contains a set of geometric modeling tools in 1D, 2D and 3D. The package can also import geometry using the DXF, STL, VRML, and COMSOL file formats. COMSOL Multiphysics can directly import 3D meshes in NASTRAN format. In combination with programming tools, we can even use images and magnetic resonance imaging (MRI) data to create geometry. COMSOL Multiphysics uses a Cartesian or cylindrical coordinate system. We can select the geometry dimension and coordinate system when building the model. By default, the names of the variables for the spatial coordinates are x, y and z in Cartesian coordinates and r, and z in cylindrical coordinates. These variable coordinates are independent variables in the COMSOL Multiphysics models. In our approach, after drawing the model in 2D, the resolution is done taking into account some initial parameters.

Several researchers have proposed mathematical models to describe heat and mass transfer in dryers. Among these models we distinguish those of Raymond (2004), Path (2010), Bali and Benkhelfellah (2002), Sverák (2007).

Physical parameters

Table 1 shows the physical parameters used for numerical simulation.

Table 1. Physical parameters for numerical simulation

Name	Expression	Value	Description
Gravity intensity	g	9.81	kg/N
Kinetic viscosity	ν	1.85E−5	m^2/s
Thermal coefficient of expansion	β	0.0033	K^{-1}
Density of air at ambient temperature	ρ_0	1.29	Kg/m^3
Ambient temperature	T_0	300	K
Concrete temperature	T_b	363	K
Pressure of air at the entrance	P_o	1E5	p_a
Thermal flow	q_o	50	W/m^2
Glass temperature	T_v	323	K

Energy and mass balances of the dryer

The equations resulting from the simulation of the vacuum dryer are as follows:

- Force volume

$$\rho\,(\mathbf{u}.\nabla)\,\mathbf{u} = \nabla.(-\,\mathbf{pI} + \mu(\nabla\mathbf{u} + (\nabla\ u\ )^{\top}) + F \quad (3)$$

$$\rho\ \nabla.(\ \mathbf{u}) = 0 \quad (4)$$

Taking into account the correlation between the fundamental relationship of the dynamics and equation (3), we find that the characteristic expression of laminar flow is totally neglected in favor of that related to turbulent flow. We can verify this with the value of the Reynolds number Re. The interest of the Reynolds number is that it makes it possible to classify the different flows. For low Reynolds numbers (typically small in front of the unit), viscosity plays a predominant role. The flows will be very stable and well defined (we speak of creeping flows). This type of flow is associated with highly viscous fluids (high v) at low speeds for small systems. Note also that at these low numbers the convective term of the N-S equation is negligible. It is the "disappearance" of this non-linear term which then gives these flows their great stability. For high Reynolds numbers, convection plays a preponderant role and flows become unstable and turbulent: this type of flow is encountered for low-viscosity fluids, at high speeds, for large systems. This turbulence exists when the speed is greater than a limit beyond which the viscosity is no longer sufficient to regulate the movements. Again the preponderance of the nonlinear convection term is at the origin of the phenomena of turbulence. However, for these high numbers, it is possible to meet geometric configurations maintaining stable flows whose configuration remains the same as for a low number: this will obviously be the case for laminar flows for which, structurally, the convective term of the NS equation is zero. For a laminar flow, the calculation of the Reynolds number seems a priori useless since the convective term does not intervene. In fact this calculation becomes relevant to discuss the possibility of a laminar structure of the flow, or more precisely of its stability. Increasing velocity for example in a laminar flow may create instabilities changing the flow to a turbulent regime. Studies of a purely experimental nature then make it possible to define a numerical limit value of the Reynolds number separating the two types of regime. This value obviously depends on each flow, but we can retain a usual value of the order of 2000.

Heat transfer in fluids

$$L_{entr}\nabla_{t.}\,(-\,\mathbf{pI} + \mu\,(\nabla_t\mathbf{u} + (\nabla_t\ u\ )^{\top}) = -\,\rho_{entr}\,\boldsymbol{n} \quad (5)$$

The heat transfer is essentially related to the variation of the velocity of the fluid elements that is to say the kinetic energy and the mass transfer. This transfer is at the origin of the variation of the density which allows the upward movement of the coolant.

Heat flux

$$\boldsymbol{q} = -\,d_z\,k\,\nabla_{T} \quad \text{With} \ -n.q = d_z.q_o \quad (6)$$

Figure 1. Photo of greenhouse solar dryer in natural convection

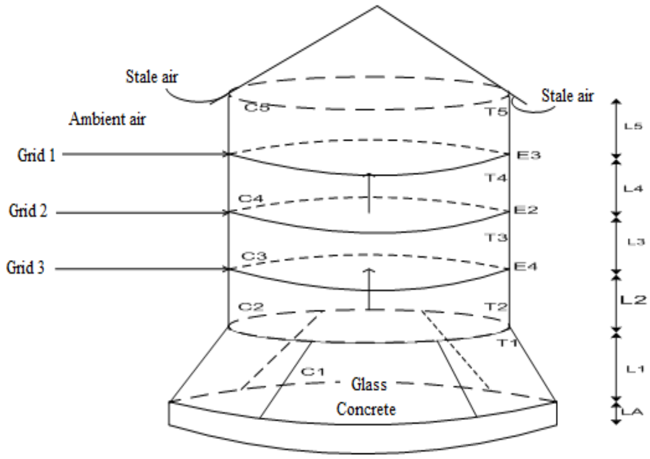

Figure 2. Diagram of greenhouse solar dryer

The heat flow is due to the variation of the temperature along the axis of the ribs z. Figures (3; 4; 5; 6) describe the propagation of heat and the air velocity field as well as the variation of the pressure in the system. These figures highlight the phenomena of convection and diffusion. The appearance of the random variation of temperature (Figure 3) and velocity (Figures 4 and 5) characterizes a turbulent flow (Figure 4).

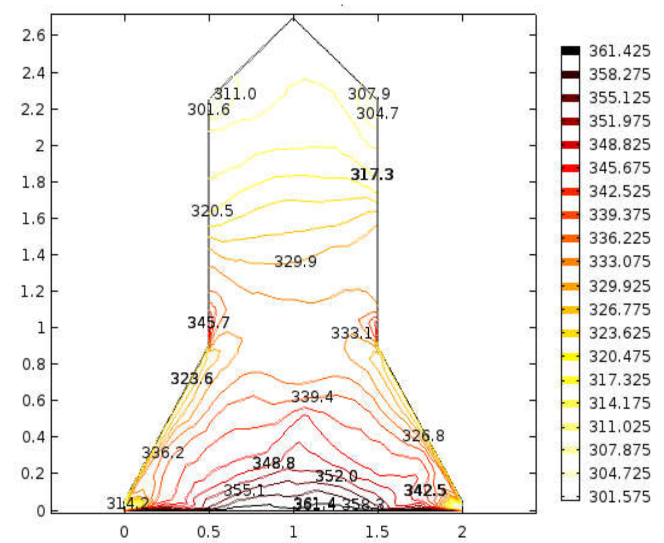

Figure 3. Variation of temperature in the dryer

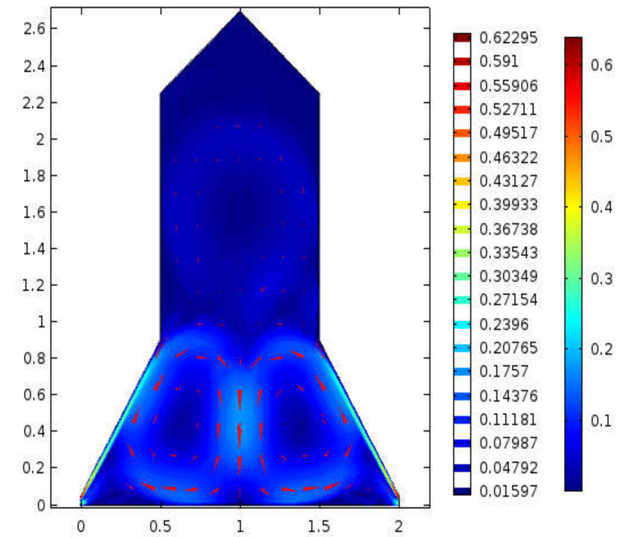

Figure 4. Velocity field

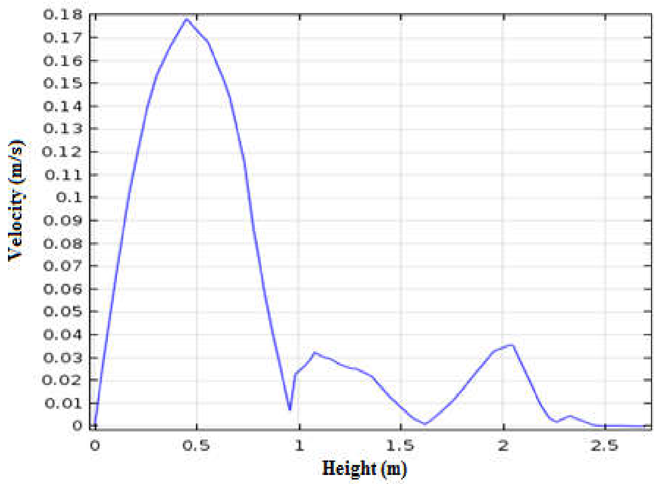

Figure 5. Variation of velocity of air in function of height of dryer

We can also consider the hypothesis of stationary flow by the use of the average values of these characteristic quantities. This arrangement is at the base of the tenfold increase of the NAVIER STOKES equation and that of the conservation of thermal energy. In this case, the problem of convection is solved in two stages:

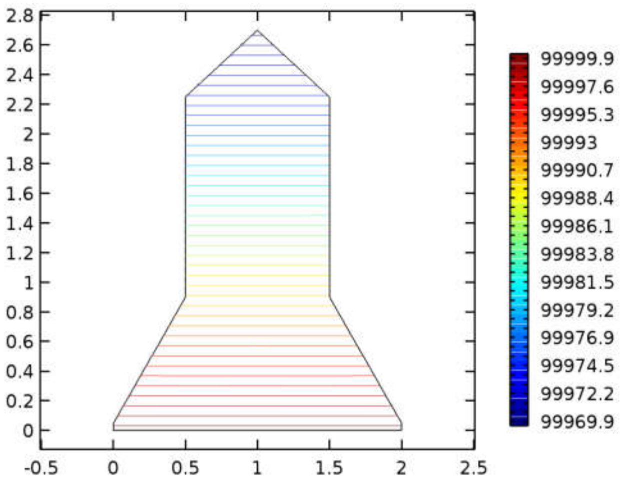

Figure 6. Variation of pressure in function of height of dryer

Speed field determination by solving the Navier-Stokes equation;

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}p + \upsilon\nabla^2\vec{v} + \vec{f} \qquad (7)$$

Avec $\quad v = \sqrt{(g\beta\delta TH)}$

The use of this identified velocity field in the conduction equation.

In natural convection, stationarity is conserved but ρ is a function of temperature T.

$$\rho = \rho_0\,(1 - \beta\,(T - T_b)) \qquad (8)$$

The movement of fluid is caused exclusively by Archimède thrust df resultant of thermal variations of ρ.

$$df = \rho_0\, g\, \beta\, (T - T_b)\, d\tau \qquad (9)$$

The convergence of the program made it possible to obtain the above results which will be useful for the validation of the calculation code by exploiting the experimental results. The upward movement of hot air extracts moisture from the products exposed on the trays. Moisture-laden air escapes through the chimney. The decrease in air velocity from bottom to top shows that the kinetics of drying are normal. The variation of the temperature of 60 ° C in the dryer obtained by simulation is in adequacy with the experimental results of the studies carried out on the transfers during the drying, like those of Bennamoun *et al.* (2007), Jos van Schijndel (2008), Merhzad (2014).

Conclusion

Solar thermal energy is promised for significant future development because it is a clean source and available in many parts of the world. The simulation carried out on the solar indirect greenhouse in natural convection consisted in using the COMSOL software which exploits the NAVIER - STOKES equation to describe the flow of air which is the heat transfer fluid in the system. After drawing the model in 2D, the resolution was possible thanks to the parameters initially defined. Iterations used by the COMSOL software from the proposed model have generated equations of heat transfer in fluids, heat fluxes and figures that describe the propagation of heat, the field of air velocities as well as than the variation of the pressure in the system. The convergence of the program made it possible to obtain these results which are useful for the validation of the calculation code. The variation of the temperature of 60°C in the dryer obtained by vacuum simulation is in line with the temperatures tolerated for the drying of fruits and vegetables which recommend a variation between 30 and 80°C.

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