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Chapter

Dynamic Modelling by Bond Graph Approach of Convective Drying Phenomena

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Abstract

Drying operations play an important role in food industries. They are often the last operation of the process of manufacturing a product, with a strong influence on the final quality. The processes are numerous and depend on the type and amount of product to be dried and water to be evaporated, the desired final quality, or the desired functionality for the dried product. In this chapter, we present a modeling study of heat transfer during drying a moist agricultural product placed in a hot air flow in a tunnel dryer with partial solar heating. The bond graph approach has been used for system modeling, and it is an object-oriented graphical approach based on an energetic description between subsystems. Some drying tests have been carried out on tomatoes and the experimental results are compared with the theoretical results for the validation of the developed model.

Keywords: tunnel dryer, bond graph modelling, simulation, thermal transfer, temperature, moisture content

1. Introduction

Dehydration and drying involves the partial or complete elimination of the water contained in the food. Due to low water activity (a_w), microorganisms cannot proliferate, and most chemical or enzymatic deterioration reactions are slowed down. Solar drying, which is most commonly practiced in developing countries, can significantly improve the quality of the dried product compared to traditional drying methods such as sun and shade drying [1–3] while minimizing losses during the harvest period.

The shape or physical state of the product to be dried can help the industrialist to choose the right way or technique to practice drying. This requires a high heat input to cause the water to be easily removed from the wet product.

The drying device is a partial solar heating tunnel dryer (**Figures 1** and **2**); it uses solar energy as a source of renewable energy that represents an available market, furthermore to be practically free. Heat and mass transfers were investigated with the development of a mathematical model of the thin layer solar drying of food products, in a convective tunnel dryer.

Multiple numerical and experimental studies on convective drying were realized [4, 5]. On the one hand, they focus on understanding the phenomena that govern the internal migration of moisture, heat and mass transfer at the level of the
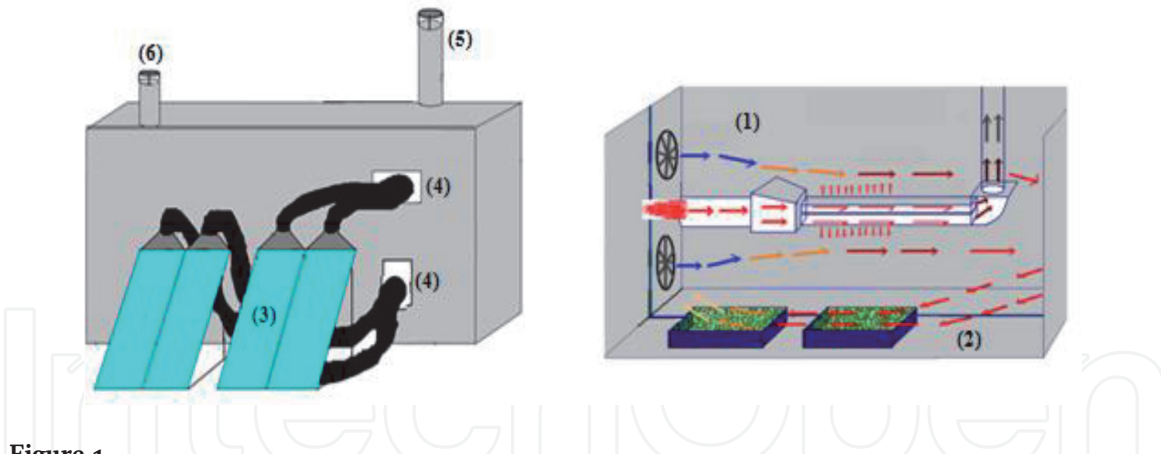
Figure 1.
Schematic view of drying device. (a) External view and (b) outside view. (1) Auxiliary heating system (two fans, burner, heat exchanger, air heating room), (2) drying chamber containing the trays, (3) solar module (four solar air collectors), (4) solar airflow vanes, (5) first chimney (smoke out), (6) second chimney (out moist air).

Figure 2.
Photo of the convective drying process.

air-product contact [6, 7]. On the other hand, they studied the physical analysis of the dryers and the optimization of their behaviour [8–10].

We recall that the drying is a complex phenomenon, and it includes many other phenomena that emerge from fluid mechanics, thermodynamics and heat and mass transfer [6, 11]. These phenomena are in turn playing a leading role in the drying process. The modelling tool used in this work is the bond graph approach [12]. It can model multi-disciplinary systems [13] whose their comportment is nonlinear. This is explained by the diversity of physical phenomena (thermal, mechanical, electrical, thermodynamic, chemical, etc.). The bond graph approach is a modelling tool that provides both the behaviour and the necessary analysis of models. It is a causal and modular energy modelling approach allowing the generation of ordinary differential equations. The bond graph approach can be used as a solution for the design and understanding of physical phenomena in complex industrial systems.

In process engineering, the use of the pseudo-bond graph approach is often widespread for reasons that have been widely justified [13–15], but for this approach, the product of effort and flow has not the dimension of power.

The first part of this work focuses on the development of a graphical model and the deduction of mathematical equations that describes the phenomena of heat and mass transfer for convective drying process. In the second part, we show an analysis of the results with the influence of different aerothermal parameters.

2. Drying kinetics

The theory of drying is described by Lewis [16], especially during thin film drying.

The most important parameter used in process drying is the drying rate equation [17]:

$$-\frac{dX}{dt} = k(X - Xe) \tag{1}$$

$$k = 0.00719 \exp\left(-\frac{130.64}{T_{ma}}\right) \tag{2}$$

T_{ch}, X and Xe are respectively the moist air temperature, the instantaneous moisture content and the equilibrium moisture content of the vegetable or the wet agricultural product. According to GAB model [18, 19] Xe is expressed by:

$$Xe = \frac{W_m C K a_w}{(1 - Ka_w)[1 + (C - 1)Ka_w]} \tag{3}$$

W_m, C and K are parameters related with air temperature by the following expressions:

$$W_m = 0.0014254 \exp\left(\frac{1193.2}{T_k}\right) \tag{4}$$

$$C = 0.5923841 \exp\left(\frac{1072.5}{T_k}\right) \tag{5}$$

$$K = 1.00779919 \exp\left(-\frac{43.146}{T_k}\right) \tag{6}$$

T_k and a_w are the air absolute temperature and the water activity.

3. Experimental device

The device studied is an indirect convective solar dryer composed of a tunnel and four solar collectors. The tunnel is of dimensions: 4 m × 2 m × 1.8 m, consisting of a drying chamber and an auxiliary heating system. The width of the drying chamber is 0.9 m with a chimney on the roof used for the evacuation of humid air. The chamber is made of galvanized sheet metal, the side walls of which are insulated with a layer of polyurethane 0.15 m thick (**Figures 1** and **2**).

The drying chamber contains perforated iron trays. The solar module is formed by four air collectors placed with an inclination between 36.7° and 45° for optimal operation. The ambient air was sucked in by the fans and warmed up then mixed by the solar air forming the drying air. The latter comes into contact with dry agricultural products placed in the trays (**Figures 1** and **2**).

The auxiliary heating system consists of a gas burner and an exchanger that transfers the heat produced by the burner into the incoming air. The tunnel dryer has two fans in the centre that blow hot air into the drying chamber.

The agricultural products placed on a tray are brought into contact with a flow of hot air; the moist air accumulates in the drying chamber and then escapes through the chimney due to the difference in vapour pressure between the room and the exterior for a type of non-forced flow.

For the study of this drying process, we take into consideration the following hypotheses:

- Dry air is often a mixture of solar air and auxiliary air for a hybrid drying operation (**Figure 3**).

- The contact surfaces between air and product remain constant during drying.

- The agricultural product to be dried is estimated as a thin layer of water.

- The phenomenon of heat transfer by conduction between the grains of products is neglected.

- The phenomena of condensation and radiation transfer are neglected inside and outside the drying chamber.

- The products to be dried are characterized by their surface temperature.

The phenomena that will be studied:

- Convective heat transfer and evaporation between air and product.

- Heat transfer by convection between the air and the inner walls of the chamber.

- Heat exchange by conduction between the internal air and the external environment.

- Evacuation of humid air to the outside through the chimney.

4. Modelling technique

The dynamic behaviour of the thermal processes is generally described by the nonlinear differential equations. Their formulation and resolution by the classic numerical methods are limited [20]. These equations are really associated with the physical phenomena such as storage and energy dissipation. The bond graph approach allows by their graphical description to show these energy exchanges in the system.

The bond graph modelling approach is a unified and causal approach applied to all types of dynamical systems; it allows the modellers to obtain the mathematical model in the form of a state equation easier than the classical modelling methods.
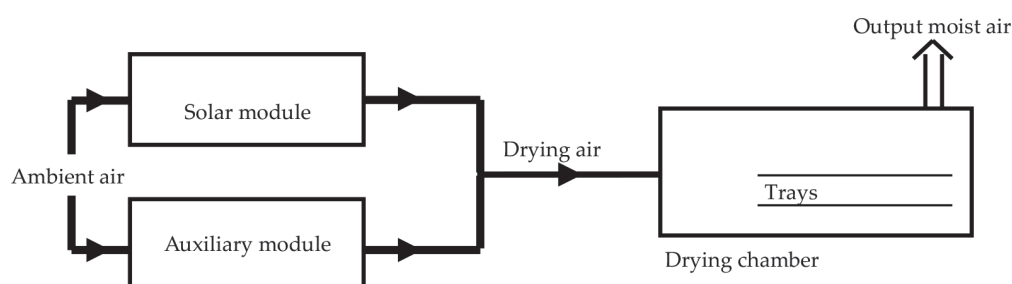

Figure 3.
Flow diagram of drying process in a tunnel dryer.

Moreover, to provide information on the structural properties of the studied system.

The first modelling step is to divide the global system into subsystems that exchange power with each other; this is the word-pseudo bond graph (**Figure 4**). The effort and flow variables are marked at the input and output of each subsystem. Depending on the physical phenomena that occur during drying and using the properties of the bond graph approach, the words are replaced by their corresponding elements, which lead to the complete models shown in **Figure 5**.

The pseudo-bond graph model of the studied tunnel dryer was developed based on the equations derived from the energy balances of the system.

The variables of effort and flux are respectively temperature (T) and heat flux ($\dot{Q}$), moreover, the pseudo bond graph model of **Figure 4** is constructed by five elements which are **Se, R, C, 0** and **1**.
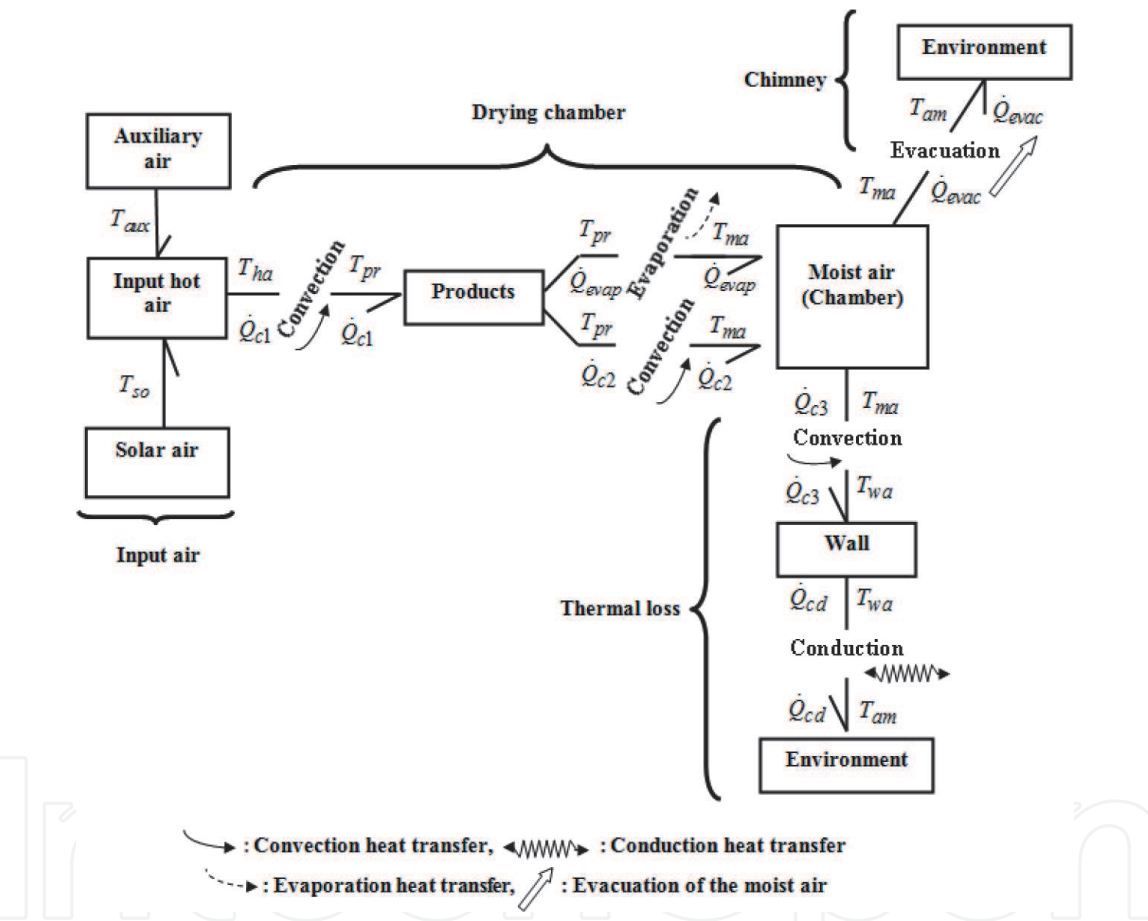
Figure 4.
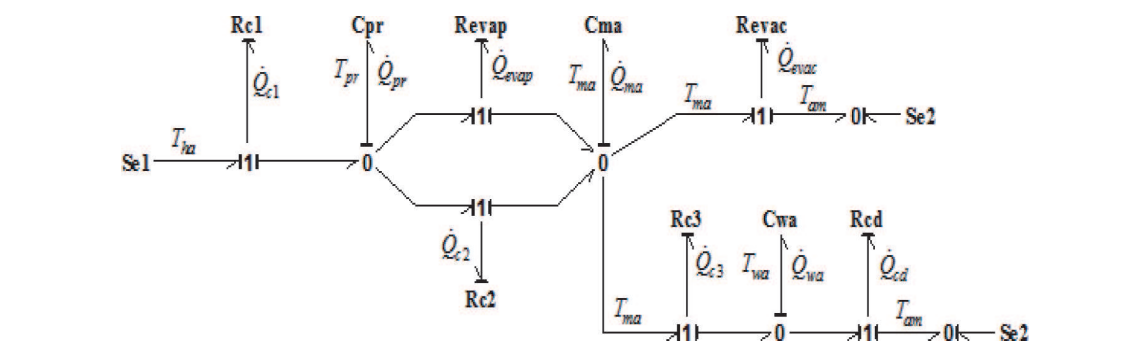*Word pseudo bond graph model of the tunnel dryer.*

Figure 5.
Pseudo bond graph model of the tunnel dryer.

4.1 Effort sources

The two sources of effort used in this pseudo-bond graph model are **Se1** and **Se2** which respectively model the average temperature of the air drying T_{ha} and the ambient air temperature T_{am}.

$$T_{ha} = \frac{T_{aux} + T_{so}}{2} \tag{7}$$

4.2 C-fields

The energy storage phenomena are modelled by the **C** elements, the effort or flux variable is determined according to the attributed causality using the following relation:

$$e = \varphi_c^{-1} \int f dt \tag{8}$$

On the surface of the product modelled by the element **Cpr**, the corresponding temperature is expressed by:

$$T_{pr} = \frac{1}{C_{pr}} \int \dot{Q}_{pr} dt \tag{9}$$

$\dot{Q}_{pr}$ is the thermal heat flow accumulated on the surface of the product and C_{pr} is thermal capacity of products.

$$C_{pr} = m_{pr} C_{p,pr} \tag{10}$$

with m_{pr} being the mass and $C_{p,pr}$ being the specific heat of the product.

Cma represents the accumulation of energy inside the drying chamber, the moist air temperature in the chamber is given by:

$$T_{ma} = \frac{1}{C_{ma}} \int \dot{Q}_{ma} dt \tag{11}$$

$\dot{Q}_{ma}$ is the thermal heat flow accumulated in the chamber and C_{ma} is the thermal capacity of the moist air.

$$C_{ma} = \rho_{ma} V_{ma} C_{p,ma} \tag{12}$$

ρ_{ma}, V_{ma} and $C_{p,ma}$ are respectively the density of the moist air, the volume of the chamber and the specific heat of the moist air.

The accumulation of energy on the inner wall of the chamber is modelled by the **Cwa** element; the temperature of the inner wall is expressed by:

$$T_{wa} = \frac{1}{C_{wa}} \int \dot{Q}_{wa} dt \tag{13}$$

$\dot{Q}_{wa}$ and C_{wa} are the thermal heat flow and the thermal capacity of the inner wall.

$$C_{wa} = \rho_{wa} V_{wa} C_{p,wa} \tag{14}$$

ρ_{wa}, V_{wa} and $C_{p,wa}$ are respectively the density, the volume and the specific heat of inner walls.

4.3 R-fields

The heat transfer phenomena in the thermal processes are modelled by the **R** elements and according to the causality attributed we determine the variable effort (e) and flux (f) by using the following relation:

$$f = \varphi_R^{-1}(e) \tag{15}$$

Note: the thermal resistance R is equal to the inverse of the heat transfer coefficient h ($R = 1/h$).

Convective heat transfer phenomena between hot air and agricultural product are modelled by $\mathbf{R_{c1}}$, where the convective heat flux is expressed by:

$$\dot{Q}_{c1} = \frac{1}{R_{c1}}(T_{ha} - T_{pr})A_{pr} = h_{c1}(T_{ha} - T_{pr})A_{pr} \tag{16}$$

A_{pr} and h_{c1} are respectively the area of product and the convective heat transfer coefficient.

$$h_{c1} = h_c = Nu\frac{\lambda_a}{D} \tag{17}$$

Nu is the Nusselt number determined by the Reynolds number (Re), which provides information on the flow regime.

λ_a and D are respectively the thermal conductivity of the air and the characteristic diameter of the layer of the product.

The Reynolds number is given by this relation:

$$\mathrm{Re} = \frac{U_a l}{v} \tag{18}$$

The airflow will certainly be turbulent in the dryer, to calculate the number of Nusselt we use the following correlation [21]:

$$Nu = 0,023.\,\mathrm{Re}^{0,8}.\mathrm{Pr}^{0,4}, \mathrm{Pr} = 0.7 \text{ (Prandtl number)}. \tag{19}$$

$\mathbf{R_{c2}}$ models the convection heat transfer phenomena between the agricultural product and the moist air in the chamber, the convective heat flow is given by:

$$\dot{Q}_{c2} = \frac{1}{R_{c2}}(T_{pr} - T_{ma})A_{pr} = h_{c2}(T_{pr} - T_{ma})A_{pr} \tag{20}$$

$h_{c2} = h_c$ is the convective heat-transfer coefficient.

The phenomena of heat transfer by convection between the humid air and the internal wall of the chamber are modelled by the element $\mathbf{R_{c3}}$ in which the convective heat flux is expressed by:

$$\dot{Q}_{c3} = \frac{1}{R_{c3}}(T_{ma} - T_{wa})A_{wa} = h_{c3}(T_{ma} - T_{wa})A_{wa} \tag{21}$$

where A_{wa} is the area of the wall and $h_{c3} = h_c$ is the convective heat transfer coefficient between the moist air and the inner wall, taking as Nusselt number [22]:

$$Nu = 0,036.\,\mathrm{Re}^{4/5}.\mathrm{Pr}^{1/3} \tag{22}$$

$\mathbf{R_{cd}}$ models the conduction heat transfer phenomena the chamber walls and the external environment through the insulation, the conduction heat flow is given by:

$$\dot{Q}_{cd} = \frac{1}{R_{cd}}(T_{wa} - T_{ma})A_{wa} = h_{cd}(T_{wa} - T_{ma})A_{wa} \quad (23)$$

h_{cd} is the conductive heat-transfer coefficient across the insulation and estimated by:

$$h_{cd} = \frac{\lambda_i}{d_i} \quad (24)$$

λ_i is the thermal conductivity of the insulation and d_i is the average mean thickness of the insulation.

$\mathbf{R_{evap}}$ models the evaporation heat transfer phenomena from the agricultural product and the moist air in the drying chamber, the evaporation heat flow is given by:

$$\dot{Q}_{evap} = \frac{1}{R_{evap}}(T_{pr} - T_{ma})A_{pr} = h_{evap}(T_{pr} - T_{ma})A_{pr} \quad (25)$$

$$h_{evap} = 0.016h_c\frac{[P(T_{pr}) - \gamma_{ma}P(T_{ma})]}{(T_{pr} - T_{ma})} \quad (26)$$

h_{evap} is the evaporative heat transfer coefficient [23] and γ is the relative decimal humidity and $P(T)$ the saturated vapour pressure given by Jain and Tiwari [22]:

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273.15}\right] \quad (27)$$

$\mathbf{R_{evac}}$ models the phenomenon of discharge of humid air to the outside through the chimney for a natural type of flow [24], the corresponding heat flow is given by:

$$\dot{Q}_{evac} = c_dA_e\sqrt{2g\Delta H}\Delta P \quad (28)$$

ΔP and ΔH are the difference in partial pressure and the difference in pressure head (m), respectively.

$$\Delta P = [P(T_{ma}) - \gamma_{am}P(T_{am})] \quad (29)$$

$$\Delta H = \frac{\Delta P}{\rho_a g} \quad (30)$$

4.4 (0.1)-junctions

Using the mathematical properties for the junctions (0.1):
$(\sum_i e_i = 0)$ for **1**-junctions.
$(\sum_i f_i = 0)$ for **0**-junctions.
The energy flow balances equations are:

- energy balance equation of the product

$$\dot{Q}_{pr} = \dot{Q}_{c1} - \dot{Q}_{c2} - \dot{Q}_{evap} \quad (31)$$

- energy balance equation of the moist air in the drying chamber

$$\dot{Q}_{ma} = \dot{Q}_{c2} + \dot{Q}_{evap} - \dot{Q}_{c3} - \dot{Q}_{evac} \quad (32)$$

- energy balance equation of the wall of the drying chamber

$$\dot{Q}_{wa} = \dot{Q}_{c3} - \dot{Q}_{cd} \tag{33}$$

The above equations determined by bond graph elements can be used to develop the detailed equations for the energy flow balance:

- energy balance equation of the product

$$C_{pr} \frac{dT_{pr}}{dt} = h_{c1}(T_{ha} - T_{pr})A_{pr} - (h_{c2} + h_{evap})(T_{pr} - T_{ma})A_{pr} \tag{34}$$

- energy balance equation of the moist air in the drying chamber

$$C_{ma} \frac{dT_{ma}}{dt} = (h_{c2} + h_{evap})(T_{pr} - T_{ma})A_{pr}$$
$$-h_{c3}(T_{ma} - T_{wa})A_{wa} - c_d A_e \sqrt{2g\Delta H}\Delta P \tag{35}$$

- energy balance equation of the wall of the drying chamber

$$C_{wa} \frac{dT_{wa}}{dt} = h_{c3}(T_{ma} - T_{wa})A_{wa} - h_d(T_{wa} - T_{am})A_{wa} \tag{36}$$

5. Results and discussion

For the numerical evaluation of the thermal performance of the model developed for the tunnel dryer, the calculations were performed using the system parameters (**Table 1**). The [20-sim] software has been used for all simulations and is dedicated to bond graph simulation. Its use is quite simple and straightforward.

The measurements made were recorded in different operating variables following a series of experiments carried out in order to determine the performance of the studied tunnel dryer. This section presents the experimental results for several tomato drying operations and also a comparison with the theoretical results.

Parameters	Values	Parameters	Values
A_{pr}	2 (m^2)	γ_{ma}	0.65 (*dec*)
A_{wa}	3 (m^2)	γ_{am}	0.45 (*dec*)
A_e	0.00785 (m^2)	l	1 (*m*)
a_w	0.2	m_{pr}	10 (*kg*)
$C_{p,pr}$	4180 (*J/kg°C*)	X_{in}	16.1 kg kg^{-1} (*dry basis*)
$C_{p,ma}$	1006 (*J/kg°C*)	ρ_{ch}	1.16 (kg/m^3)
$C_{p,wa}$	860 (*J/kg°C*)	ρ_{wa}	2700 (kg/m^3)
c_d	0.6	λ_a	0.0262 (*W/m°C*)
D	0.15 (*m*)	λ_i	0.022 (*W/m°C*)
d_i	0.10 (*m*)	υ	2.10^{-5} (m^2/s)
g	9.8 (m/s^2)		

Table 1.
Values of parameters used in numerical simulation.

The interpretation of the results depends on the influence of the aerothermal parameters (velocity and temperature of drying air).

5.1 Influence of the hot air temperature

In a first step, we consider that the speed of drying air is constant and we only vary its temperature.

Figures 6 and 7 show the evolution of the product temperature and the temperature of the humid air, they reach after a certain time the temperature of the drying air. With the same conditions, we also represent the evolution of the moisture content of the product (**Figure 8**). Increasing the drying air temperature from 55 to 75°C is accompanied by a reduction in drying time. This is due to a potential increase to water evaporation.

Experimentally, for a temperature of 75°C, an air velocity of 2 m/s is sufficient 125 minutes to dry tomatoes. A decrease in temperature of 10° results in an increase
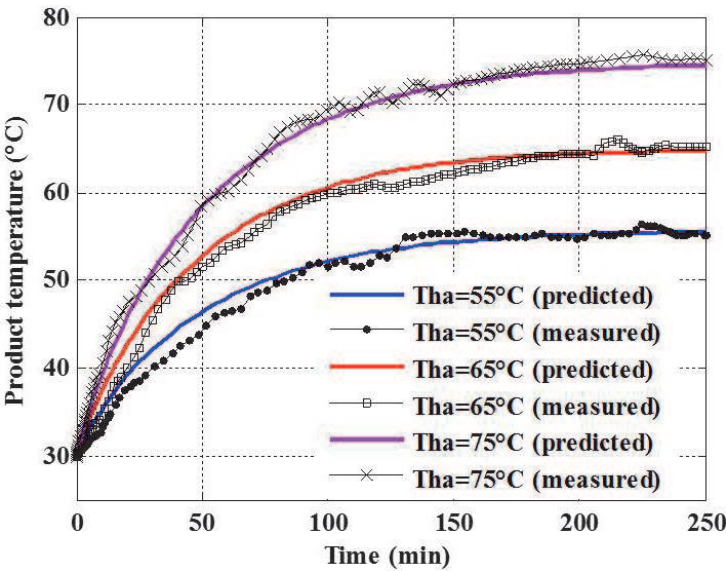

Figure 6.
Effect of the hot air temperature on the variation of the product temperature for U_a = 2 m/s and T_{am} = 30°C.

Figure 7.
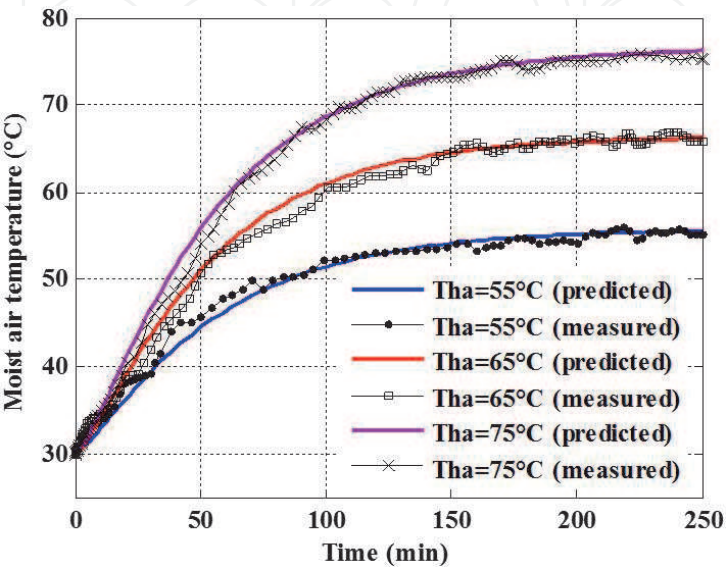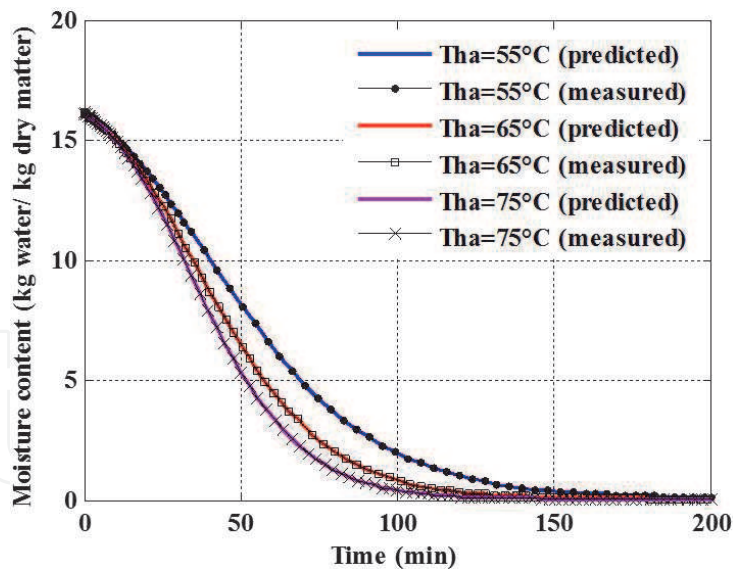*Effect of the hot air temperature on the variation of the moist air temperature for U_a = 2 m/s and T_{am} = 30°C.*

Figure 8.
Effect of the hot air temperature on the variation of the moisture content for U_a = 2 m/s and T_{am} = 30°C.

in drying time of 150 minutes to reach this content. Still with a lower temperature of 55°C, the drying time increases up to 180 minutes.

These results clearly show the influence of drying air temperature on the drying of agro-food products and are in good agreement with previous work [25, 26].

5.2 Influence of hot air velocity

For a constant drying air temperature 55°C and an increase in air velocity beyond 2 m/s does not show a good influence on the variation of the product temperatures and the humid air temperature in terms of reducing the drying time, this is clear in **Figures 9** and **10**.

The evolution of the moisture content is shown in **Figure 11** we see that the influence of the drying air velocity is less important than the drying air temperature because an increase in the air velocity has brought a small decrease in drying time [27, 28].
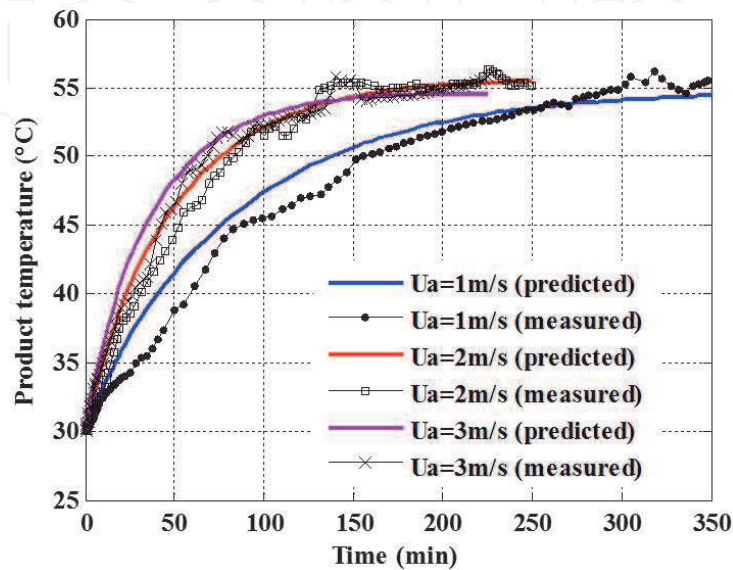

Figure 9.
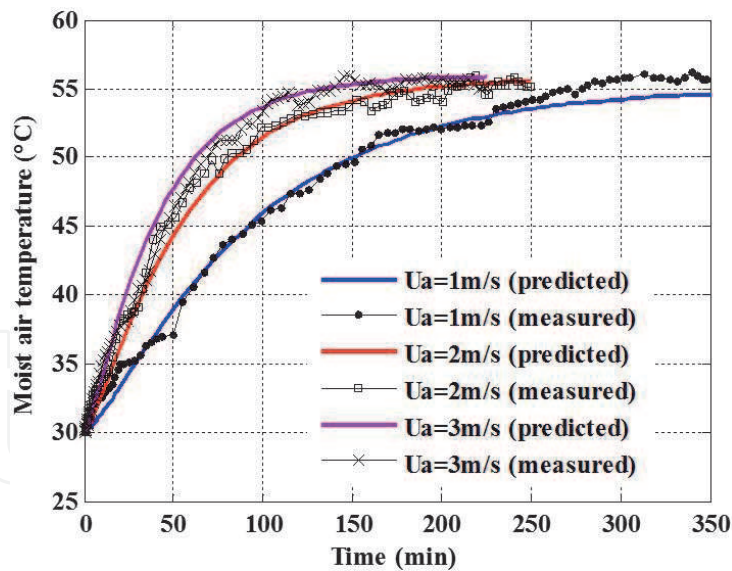*Effect of the hot air velocity on the variation of the product temperature for T_{ha} = 55°C and T_{am} = 30°C.*

Figure 10.
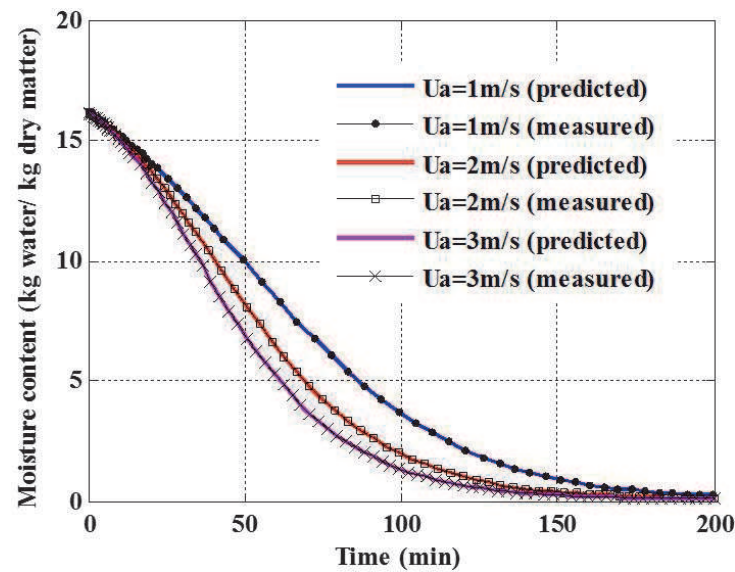*Effect of the hot air velocity on the variation of the moist air temperature for T_{ha} = 55°C and T_{am} = 30°C.*

Figure 11.
Effect of hot air velocity on the variation of the moisture content for T_{ha} = 55°C and T_{am} = 30°C.

The predicted values of the different variables are in good agreement with the experimental values. The quality of the fit was determined using the Root Mean Square Errors (RMSE).

Variables	Influence of drying air temperature (Ua = 2 m/s)			Influence of drying air velocity (Tac = 55°C)		
	Tac = 55°C	Tac = 65°C	Tac = 75°C	Ua = 1 m/s	Ua = 2 m/s	Ua = 3 m/s
Product temperature	1.1249	1.1996	0.8625	1.3863	1.1249	1.2015
Internal air temperature	0.8034	0.9499	0.8665	0.8589	0.8034	0.9063
moisture content	$3.9665.10^{-4}$	$4.1778.10^{-4}$	$4.7045.10^{-4}$	$5.0070.10^{-4}$	$3.9665.10^{-4}$	$5.0572.10^{-4}$

Table 2.
RMSE values for different variables studied.

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} (X_{cal} - X_{mes})^2 \right)^{1/2} \tag{37}$$

We present in **Table 2** below the values of the mean squared error.

6. Conclusion

In this chapter, the bond-graph approach has been used for modelling a drying system with partially solar heating. This method provides reliable estimates of temperature distributions in the product and the moist air, also the moisture distributions in the product.

The geometry of the dryer, the physical properties of building materials, agricultural product and air are taken into account.

The influence of two aerothermal factors was studied to evaluate the performance of the dryer. The developed model can be adapted to other wet agricultural products as well as to other drying processes.

The challenge for the engineering designer is now to define optimal dryers, which provide a product of constant good quality. For this, the derived model of the tunnel dryer described by equations (1), (34), (35) and (36) will be used subsequently for the control of heat and mass transfer in drying process, which is important to enhance product quality such as colour and flavour.

Acknowledgements

Nomenclature

A	surface area (m^2)
a_w	water activity
C	thermal capacity $(J/°C)$
C_p	specific heat $(J/kg°C)$
c_d	discharge coefficient
D	characteristic diameter of the layer of the product (m)
d	mean thickness of the insulation (m)
g	gravitational acceleration (m/s^2)
h	heat-transfer coefficient $(W/m^2°C)$
k	drying constant (s^{-1})
l	characteristic length (m)
m	mass (kg)
P	saturated water vapour pressure (N/m^2)
$\dot{Q}$	heat flow plate (W)
T	temperature $(°C)$
T_k	air absolute temperature (K)
U	velocity (m/s)
V	volume (m^3)
X	product moisture content $(kg/kg$ dry basis$)$

$\left(-\frac{dX}{dt}\right)$	drying rate (kg/kg dry basis. s)
Nu	Nusselt number
Pr	Prandtl number
Le	Lewis number

Greek letters

υ	kinematic viscosity of air (m^2/s)
ρ	density (kg/m^3)
λ	thermal conductivity ($W/m°C$)
γ	decimal relative humidity

Subscripts

a	air
aux	auxiliary air
am	ambient
c	convection
cd	conduction
e	equilibrium/exit
i	insulation
v	vapour
ma	moist air
$evap$	evaporation
evac	evacuation
pr	product
so	solar air
ha	hot air
wa	wall

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