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Bond Graph Modelling and Simulation of Convective-Radiative Process Drying

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Abstract— **This study is interested in the use of radiative-convective drying method. Agricultural products used are organic products deformable (apple, potato, carrot ...). This method of drying is realized in a climatic wind tunnel, seat of a flow of hot air and in the presence of a radiation source.**

The work presented in this paper focuses on the analysis and modelling of heat transfer during process drying also studying drying kinetics, this was achieved by the bond graph approach. The simulation results obtained from the bond graph model are validated with experimental data from a laboratory set-up.

Keywords— **Bond graph modelling; Simulation; Moisture content; Temperature.**

I. INTRODUCTION

Drying is a procedure that involves removing all or a particular solvent of a substance by adding energy. In physical terms, the drying phenomenon results from a heat and mass transfer to the faith in the material and at the product surface.

Multiple numerical and experimental studies on convective drying were realised [1]. 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 air- product contact [2], [3]. On the other hand, they studied the physical analysis of the dryers and the optimization of their behaviour [4], [5]. We recall that the drying is a complex phenomenon, it includes many other phenomena that emerge from fluid mechanics, thermodynamics and heat and mass transfer [4], [6]. These phenomena are in turn playing a leading role in the drying process.

In this work we focus on the analyzing and modelling of heat and mass transfer during combined drying (convective-radiative) of slices wet agricultural product.

Numerical techniques taking into account the coupled heat and mass transfer mechanisms and adapted to the resolution of the equations formalizing these models. The bond graph approach is well adapted for these tasks. However, it can model multi-disciplinary systems [7], which have highly nonlinear behaviour. This is mainly due to the mutual interaction of several phenomena of various kinds (mechanical, chemical, thermodynamic ....).

II. MATERIALS AND METHOD

The system studied is a laboratory wind tunnel used for drying experiments at maintained conditions. (Fig. 1). It consists of a blower, heaters, tunnel, halogen lamps and instruments for measurement. The airflow was adjusted by the blower speed control. The heating system consisted of two electrical heaters (1000 W and 2000 W) placed inside the duct. The drying temperature inside the tunnel was adjusted by the heater power control. The vein was constructed from plexi-glass as a rectangular tunnel in 0.80 m length, 0.30 m width and 0.25 m height. The drying tray was placed inside the vein. To floodlight the product, the tunnel top plexi-glass material was substituted by an ordinary glass. The spotlight was placed at different levels over the tray.

The incident radiation was measured with the Kip-Zonen solarmeter. The air temperature, relative humidity just above the product thin layer and mass drying sample were measured at short time intervals during the experiments. The velocity of the air passing through the system was measured by a 0–15 m s−1 range anemometer (Model: Testo 435).

The temperature evolutions on the product layer during the drying process were registered at regular intervals with K thermocouples. These registers were located on the bottom, top, and centre of the product layer. Dry-bulb and wet-bulb temperatures of the environmental air were taken. In the measurement of the apple slices temperature, three cop-per constantan thermocouples were used. Measurement of relative humidity and air temperature was made using a Temperature probe (Model: Testo RH635). Recordings were made by connecting thermocouples and temperature probes to a 34970A HP Scientific Data Acquisition System. The mass of the sample was recorded on computer during drying by a top loading digital balance (Model: Mettler) of 300 g weighing capacity and with accuracy of ±0.01 g.

III. A BOND GRAPH MODELLING IN PROCESS ENGINEERING

The dynamic behaviour of the thermo fluid processes is generally described by the non linear differential equations. Their formulation and resolution by the classic methods are limited [8].

With the bond graph methodology, these equations are associated to the storage and the dissipation of energy. Therefore, the bond graph tools permit by its graphic description to explicit the power exchanges in the system, as the energy storage and the thermal dissipation.

The bond graph method was developed as an appropriate tool for modelling all types of the engineering systems. It is based on the topologic representation of different mechanisms regarding exchange, storage and energy dissipation in any thermodynamic system [9].

The use of true bond graph in process engineering, introduces thermal and chemical effort variables (entropy, chemical potential) which are complex and inappropriate to the problems of simulation, because it do not obey simple conservation laws. For their model, we have introduced a pseudo bond graph [7], [10], [11] for which the product of effort and flow has no longer the dimension of power.

A. *Word pseudo bond graph*

The technological level of modelling can be represented by word pseudo bond graph model. In this step, one splits the entire system into simple subsystem as shown in Fig. 2. Where at the entry and the release of each subsystem we have already used the liaison variables corresponding, and this will be based on an energetic description of the process.

B. *Pseudo bond graph model*

If the words of the word pseudo-bond graph shown in Fig. 2 are replaced by the corresponding elements, we obtain the pseudo-bond graph shown in Fig. 3.

The pseudo bond graph model contains seven elements: capacitive elements (**C**), resistive elements (**R**), effort sources (**Se**), flow sources (**Sf**), modulated or controlled flow source (**MSf**), **0** – junctions and **1** –junctions.

C and **R** elements are passive elements because they convert the supplied energy into stored or dissipated energy. **Se**, **Sf** and **MSf** elements are active elements because they supply power to the system and **0**- and **1**-junctions are junction elements that serve to connect **C**, **R**, **Se**, **Sf** and **MSf** and constitute the junction structure of the Pseudo Bond Graph model.

The model has temperature (T) as effort variables and heat flow ($\dot{Q}$), enthalpy flow ($\dot{H}$), radiation flow (I) and mass flow ($\dot{m}$) as many flow variables.

C. *Pseudo bond graph elements and deducted mathematical equations*

1) *Flow sources*

Sf1 and **Sf2** are used as input to the system.

Sf1 represent the radiation flow absorbed by the product and the corresponding flow is:

$$I_{pr} = \alpha_{pr} G A_{pr} \tag{1}$$

α_{pr} is the absorption of the product, G is the radiation rate incident on the product (W/m^2) and A_{pr} is the product area (m^2).

Sf2 represents the hot air mass flow entering the tunnel. The corresponding flow is $\dot{m}_a$ (kg/s).

MSf2 is a modulated or controlled flow source. It represents the air enthalpy flow entering the tunnel. Then, the enthalpy input of the hot air can be calculated as the specific enthalpy associated to the input temperature multiplied by the input mass flow:

$$\dot{H}_{ai} = \dot{m}_a H_{ai} = \dot{m}_a C_{p,a} T_{ha} \tag{2}$$

Where $C_{p,a}$ ($J/kg°C$) is the specific heat of the air and T_{ha} the inlet hot air temperature.

2) *Effort sources*

Se1 is an effort source used in this pseudo bond graph model and it represents the inlet hot air temperature T_{ha} .

Se2 is an effort source and it represents the external temperature of ambient air T_{ex}

3) *C-fields*

The C-fields describe the storage energy phenomena and determine the effort variable or the flow according to the fixed causality using this formulation:

$$e = \varphi_c^{-1}(\int f dt) \tag{3}$$

Cpr models the accumulation of energy at the surface of the product, the product temperature is given by:

$$T_{pr} = \frac{1}{C_{pr}} \int \dot{Q}_{pr} dt \tag{4}$$

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

$$C_{pr} = m_{pr} C_{p,pr} \tag{5}$$

With m_{pr} (kg) is the mass and $C_{p,pr}$ ($J/kg°C$) is the specific heat of the product.

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

$$T_{ma} = \frac{1}{C_{ma}} \int \dot{Q}_{ma} dt \tag{6}$$

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

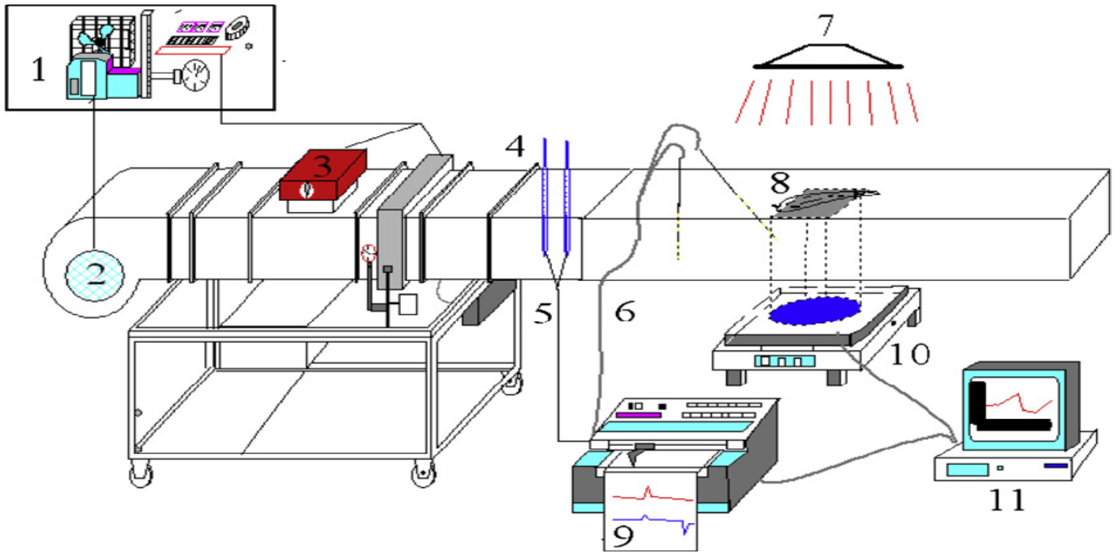

Fig. 1 Schematic diagram of the laboratory apparatus: (1) electric power control, (2) blower, (3) heaters, (4) thermo hygrometer, (5) temperature probes, (6) thermocouples, (7) spotlight Hg, (8) product sample, (9) HP data logger, (10) digital balance and (11) computer.

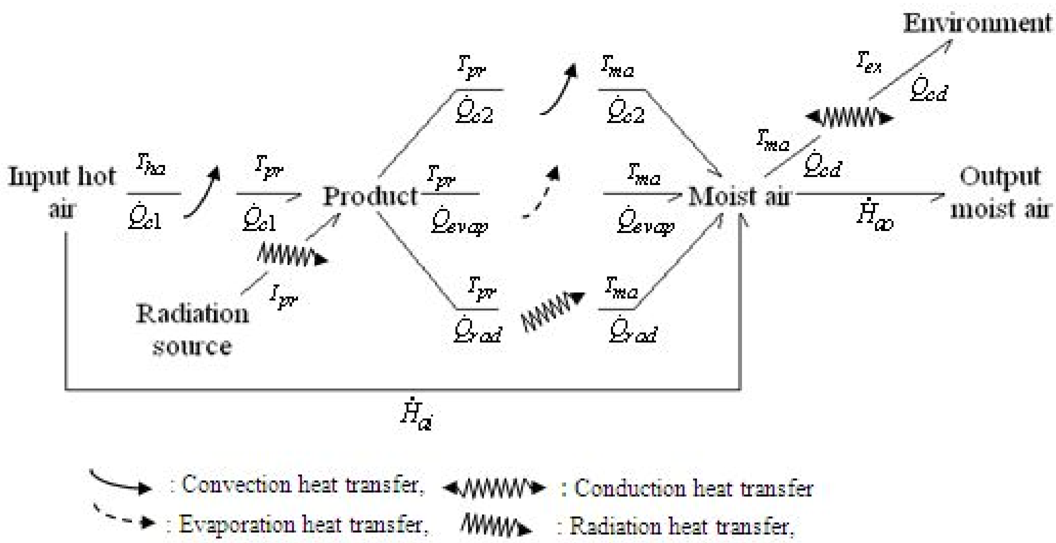

Fig. 2 Word pseudo bond graph model of the process drying.

Where: $C_{ma} = \rho_{ma}\, V_{ma}\, C_{p,ma}$ (7)

With ρ_{ma} (kg/m^3) is the density of the moist air, V_{ma} (m^3) is the volume of the moist air inside the tunnel chamber and $C_{p,ma}$ $(J/kg°C)$ is the specific heat of the moist air.

4) R-fields

In our case, R-fields illustrate the heat transfer phenomena in thermal process, the effort (*e*) or flow (*f*) variable are determined with taking causalities into account and using this formulation:

$$f = \varphi_R^{-1}(e) \quad (8)$$

Besides the thermal resistances *R* are equal to the inverse of heat transfer coefficient *h* (*R=1/h*)

Rc1 models the convection heat transfer phenomena between the hot air and the agricultural product, the convective heat flow is given by:

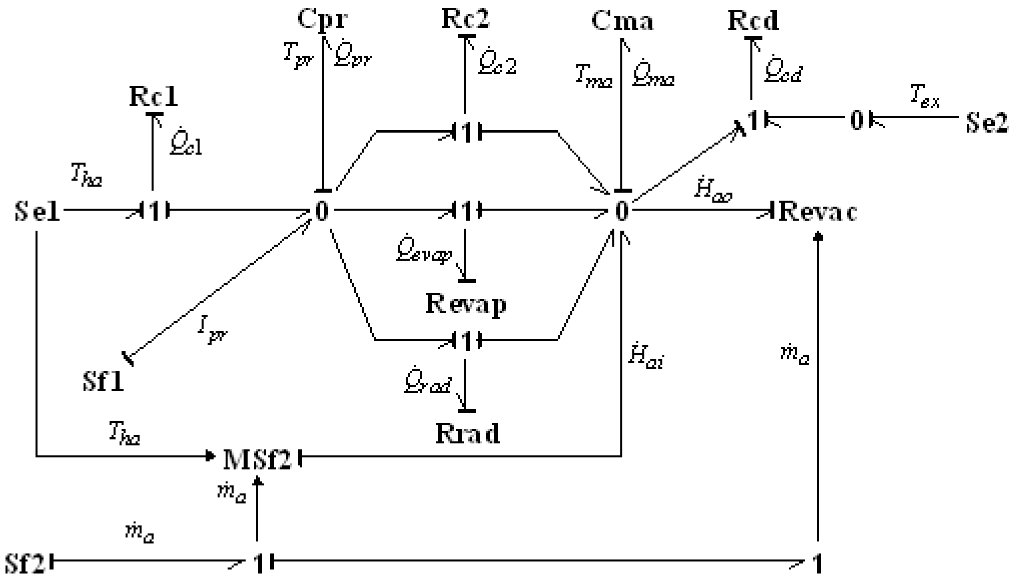

Fig. 3 Pseudo bond graph model of the process drying.

$$\dot{Q}_{c1} = \frac{1}{R_{c1}}(T_{ha} - T_{pr})A_{pr} = h_{c1}(T_{ha} - T_{pr})A_{pr} \qquad (9)$$

A_{pr} (m^2) is the area of product and h_{c1} ($W/m^2°C$) is the convective heat transfer coefficient between the hot air and the agricultural product.

Where: $$h_{c1} = h_c = Nu\frac{\lambda_a}{D} \qquad (10)$$

In which *Nu* is the number of Nusselt established on the basis of Reynolds number (Re), that gives an idea about the flow regime, λ_a ($W/m°C$) is the thermal conductivity of air and *D*(*m*) is the characteristic diameter of the layer of the product. The Reynolds number is expressed as:

$$\mathrm{Re} = \frac{u\ l}{v} \qquad (11)$$

Where:

l : Characteristic length (*m*)

u : Air velocity (*m /s*)

v : Kinematic viscosity of air (m^2/s)

The airflow will certainly be turbulent in the dryer, to calculate the number of Nusselt we use the following correlation [12]:

$$Nu = 0.023.\mathrm{Re}^{0.8}.\mathrm{Pr}^{0.4} \qquad (12)$$

Pr = 0.7 (Prandtl number).

Rc2 models the convection heat transfer phenomena between the agricultural product and the moist air in the tunnel chamber, the convective heat flow is given by:

$$\dot{Q}_{c2} = \frac{1}{R_{c2}}(T_{pr} - T_{ma})A_{pr} = h_{c2}(T_{pr} - T_{ma})A_{pr} \qquad (13)$$

$h_{c2} = h_c$ is the convective heat-transfer coefficient between the agricultural product and the moist air.

Rcd models the conduction heat transfer phenomena between the moist air and the external environment through the chamber wall, the conduction heat flow is given by:

$$\dot{Q}_{cd} = \frac{1}{R_{cd}}(T_{wa} - T_{ex})A_{wa} = h_{cd}(T_{ma} - T_{ex})A_{wa} \qquad (14)$$

h_{cd} ($W/m^2°C$) is the conductive heat-transfer coefficient across the inner wall and estimated by:

$$h_{cd} = \frac{\lambda_{wa}}{d_{wa}} \qquad (15)$$

λ_{wa} ($W/m°C$) is the thermal conductivity of the wall and d_{wa} (*m*) is the average mean thickness of the wall.

Rrad illustrates the radiation heat transfer phenomena from the agricultural product and the moist air in the chamber, the radiation heat flow is given by:

$$\dot{Q}_{rad} = \frac{1}{R_{rad}}(T_{pr} - T_{ma})A_{pr} = h_{rad}(T_{pr} - T_{ma})A_{pr} \qquad (16)$$

h_{rad} ($W/m^2°C$) is the radiation heat-transfer coefficient from the product to the moist air:

$$h_{rad} = \sigma\varepsilon\frac{(T_{pr}^4 - T_{ma}^4)}{(T_{pr} - T_{ma})} \qquad (17)$$

Where $\sigma = 5.67\times10^{-8}$ (W/m^{2}k^4) is the Stefan–Boltzmann constant, ε is the emissivity of thermal radiation of water from surface product.

Revap models the evaporation heat transfer phenomena from the agricultural product and the moist air in the chamber, the evaporation heat flow is given by:

$$\dot{Q}_{evap} = \frac{1}{R_{evap}}(T_{pr} - T_{ch})A_{pr} = h_{evap}(T_{pr} - T_{ma})A_{pr} \qquad (18)$$

$$h_{evap} = 0.016 h_c \frac{\left[P(T_{pr}) - \gamma_{ma} P(T_{ma}) \right]}{(T_{pr} - T_{ma})} \quad (19)$$

h_{evap} ($W/m^2 °C$) is the evaporative heat transfer coefficient [13] and γ_{ma} is the relative decimal humidity and P the saturated vapour pressure in (N/m^2) given by Jain and Tiwari [14]:

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273.15} \right] \quad (20)$$

Revac field is a multi-port element as shown in Fig. 4. It is used as a fictive thermal resistor modulated (using information bond) by the hydraulic flow variable $\dot{m}_a$ to model the enthalpy flow of the moist air leaving the tunnel chamber as:

$$\dot{H}_{ao} = \dot{m}_a H_{ao} = \dot{m}_a C_{p,a} T_{ma} \quad (21)$$

5) (0.1)-junctions

1-junctions correspond to the equality of flows ($\sum_i e_i = 0$)

0-junctions correspond to the equality of effort ($\sum_i f_i = 0$) and represent energy flow balances that are:

- energy balance equation of the product

$$\dot{Q}_{pr} = I_{pr} + \dot{Q}_{c1} - \dot{Q}_{c2} - \dot{Q}_{rad} - \dot{Q}_{evap} \quad (22)$$

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

$$\dot{Q}_{ma} = \dot{H}_{ai} - \dot{H}_{ao} + \dot{Q}_{c2} + \dot{Q}_{rad} + \dot{Q}_{evap} - \dot{Q}_{cd} \quad (23)$$

D. Drying rate equation

The theory of drying is described by Lewis theory [15] based on the analogous of Newton's law of cooling in heat transfer and is often used to mass transfer in a thin layer drying and is as follows:

$(-\frac{dX}{dt})$ is one of the most important parameters used in process drying.

The following drying rate equation was obtained by Lopez et al [16]:

$$(-\frac{dX}{dt}) = k(X(t) - Xe) \quad (24)$$

Where k is the drying constant and it is related to the temperature of the moist air by:

$$k = 0.00719 \exp(-\frac{130.64}{T_a}) \quad (25)$$

$X(t)$ is the instantaneous moisture content and Xe is the equilibrium moisture content of the vegetable or the wet agricultural product, it was calculated by determining experimentally the equilibrium moisture isotherms at 25(°C), 40(°C), 60(°C) and 90(°C). GAB model [17] was selected to predict Xe because it was the model that better fit to experimental data. The following expression was obtained [18]:

$$Xe = \frac{WCKa_w}{(1 - Ka_w)\left[1 + (C-1)Ka_w\right]} \quad (26)$$

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

$$W = 0.0014254 \exp(\frac{1193.2}{T_k}) \quad (27)$$

$$C = 0.5923841 \exp(\frac{1072.5}{T_k}) \quad (28)$$

$$K = 1.00779919 \exp(-\frac{43.146}{T_k}) \quad (29)$$

Where T_k is air absolute temperature (K) and a_w is the water activity. The moisture ratio (reduced moisture) of the wet agricultural product is given by:

$$Xr = \frac{X - Xe}{X_{in} - Xe} \quad (30)$$

X_{in} is the initial moisture content of the product.

IV. RESULTS AND DISCUSSION

For the numerical appreciation of the developed model for the system, the calculations have been made by using the system parameters (Table 1). The software 20-sim was used for all simulations. It is dedicated to the Bond Graph simulation. Its use is rather simple and direct. The wet product dried is tomatoes.

Fig. 4 shows the effect of the radiant source of the variation of the temperature of the moist product.

Fig. 5 illustrates the variation of the reduced moisture content for two mode of process drying. We note that there is almost no influence of the radiant source on the variation of the moisture content.

TABLE I

VALUES OF PARAMETERS USED IN NUMERICAL SIMULATION

Parameters	**Values**	**Parameters**	**Values**
A_{pr}	0.05 (m^2)	M_{in}	6.14(db)
A_{wa}	0.3 (m^2)	ρ_{ch}	1.16 (kg/m^3)
a_w	0.4	λ_a	0.0262 ($W/m°C$)
$C_{p,pr}$	4180 ($J/kg°C$)	λ_i	0.193 ($W/m°C$)
$C_{p,ch}$	1006 ($J/kg°C$)	υ	2.10^{-5} (m^2/s)
D	0.025 (m)	γ_{ch}	0.86 (dec)
l	0.01(m)	α_{pr}	0.57
d_i	0.07 (m)	ε	0.9
m_{pr}	0.2 (kg)	m	0.116 (kg/s)

V. CONCLUSION

In this paper, we have used an unified approach of modelling based on graphic technique known as bond-graph. This technique is systematic and has a sufficient flexibility for thermal system. The developed mathematical model was used to describe adequately the phenomena of convective-radiative process drying applied for wet agriculture product. This model simulates the evolution of drying parameters at different experimental conditions.

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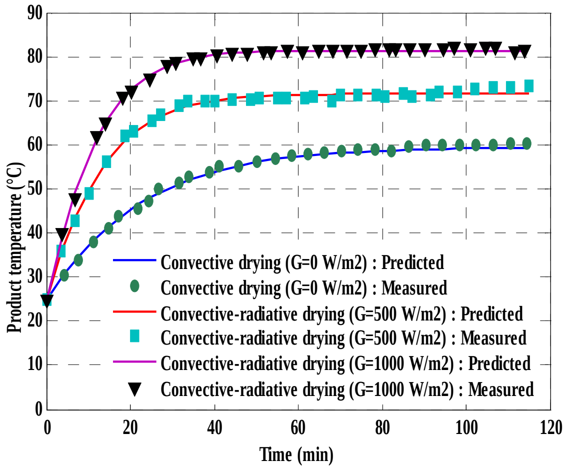

Fig. 4 Effect of the radiation source on the variation of the product temperature (*Tha* = 60°C ; u_a = 2*m/s*).

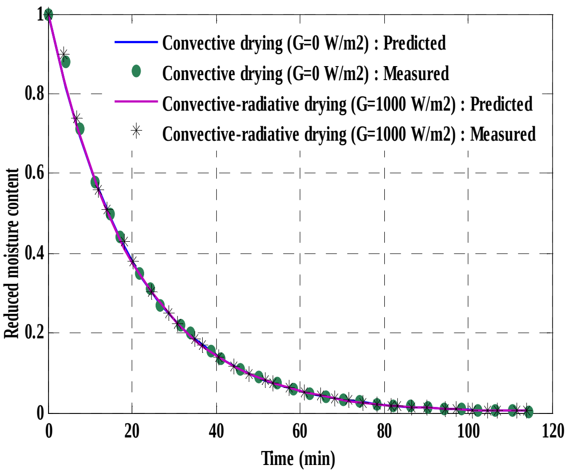

Fig. 5 Effect of the radiation source on the variation of the reduced moisture content (*Tha* = 60°C ; u_a = 2m/s).

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