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Modelling and design of a forced convection indirect solar dryer for food products

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Abstract— **Bacteriological contamination (mold, microbes, etc.), packaging and storage of food products frequently leads to rapid deterioration and consequently losses of these products during the harvest season. To address these problems, the need for solar drying, a renewable energy source that consists of evaporating a certain amount of water from the product, reveals a promising solution, particularly in rural and developing areas. This study focuses on the modelling, design and optimization of the performance of an indirect forced convection solar dryer for food products, in particular, aromatic plants characterized by their final equilibrium moisture content. Indeed, the results of the modelling of solar radiation on the surface of the collector inclined beta = 30° for days with low and high sunlight vary between 521 and 1445 W/m² and the maximum temperatures of the absorber, at the outlet of the collector and in the drying chamber can reach respectively 78 °C, 46°C and 42°C. Thus, for the same conditions, the overall results highlight the following key points: the thermal efficiency of the collector varies between 30% and 45% comparable to that of published indirect solar dryers, a remarkable temperature uniformity inside the drying chamber, essential to preserve the quality of the final product, Optimal humidity dynamics thanks to forced ventilation volume flow from 200 to 400 m^3/h, the drying kinetics in excellent agreement with widely used empirical models for a collector area of 2 to 3 m^2 after a drying time td= 24 hours.**

Keywords—**Solar – Forced convection – Medicinal plants – Drying kinetics – Thermal modelling**

Nomenclature

A_c:	*Area of the collector*	*[m^2]*	T_{do}:	*Outlet drying temperature*	*[°C]*
$c_{p,a}$:	*Specific heat capacity of air*	*[kJ/kg K]*	T_{fi} :	*Inlet fluid (air) temperature*	*[°C]*
$c_{p.p}$:	*Specific heat capacity of the product*	*[kJ/kg K]*	T_{co} :	*Outlet air collector temperature*	*[°C]*
h_c:	*Overall heat transfer coefficient by conduction*	*[W. m^2. K^{-1}]*	T_P :	*Wall temperature*	*[°C]*
I_c :	*Incident solar radiation*	*[W/m²]*	T_{sky} :	*Sky temperature*	*[°C]*
L_v :	*Latent heat of vaporization of water*	*[j/Kg]*	X:	*Moisture content on wet basis*	*[g water/Kg dry air].*
$\dot{m}_a$:	*Inlet mass flow rate of air at the collector*	*[kg/s]*	**Greek symbol**		
m_p:	*Total mass of the product*	*[Kg]*	ε_P:	*Emission coefficient*	*[dimensionless]*
m_w:	*Total amount of moisture to be removed*	*[Kg]*	τ_v :	*Transmittance of the top glazing*	*[dimensionless]*
Q_g:	*The total flux received by the solar collector*	*[W]*	α_{ab} :	*Solar absorptance*	*[dimensionless]*
Q_u:	*Rate of useful energy to heat the air*	*[W]*	η_c:	*Collector thermal efficiency*	*[%]*
T_{di} :	*Inlet drying temperature*	*[°C]*	σ:	*Stefan-Boltzmann constant*	*[W/ m²K^4]*

I. Introduction

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The loss of food products during drying processes, whether natural or artificial, is a problem of concern [1]. Precise control of storage parameters, including temperature and humidity, is essential to maintaining the quality of these products [4]. Inadequate packaging of artisanal food products frequently leads to rapid deterioration due to bacteriological problems. This deterioration affects not only the quality of the products, but also the statistics of harvesting and production in tonnes of dried products [5]. Solar drying by natural or forced convection is the only way to preserve food, with solar energy being the most widely used [6]. Fruits and vegetables are an important source of these nutrients for the human diet, as they are very rich in vitamins and minerals. However, most of these products are harvested in harsh conditions, characterized by very high humidity and temperatures, which makes them quickly perishable. Indeed, they are subject to various contaminations (mold, microbes, etc.) and must therefore be sold or consumed very quickly [5,6]. The present study focuses on the modelling and design of an indirect forced convection solar dryer for food products (FCISD) based on an in-depth understanding of its thermal behaviour [2]. Many products, especially agricultural products, contain a significant amount of water in the form of moisture. To preserve them in the long term, it is necessary to evaporate a significant amount of this moisture using solar dryers, and more specifically indirect forced convection dryers. The control of the various parameters, such as temperature and humidity, ensures better quality and prevents product degradation. Mastering solar drying parameters is one of the most important tools for reliable sizing, design and energy optimization, adapted to the variable local climatic conditions and the actual characteristics of the product. Indeed, the thermal performance of the solar drying system is based on that of the solar collector. Therefore, several studies have been conducted to improve the performance of the solar dryer. Among the solutions: Abhay Lingayat et al have designed and developed an indirect solar dryer with forced convection intended for drying agricultural products consisting of a plane-to-air solar collector with the V-plate of the absorber whose total surface area of the collector is 2 m^2, a drying chamber of $V = 0.4\ m^3$ dimensions (Length, width and height) 1 m × 0.4 m × 1 m and a chimney for the evacuation of humid hot air. In this case, an experimental study was carried out on bananas chosen as a dried, sensitive and rapidly deteriorating product, to study its drying characteristics. The results showed that the optimization of the collector area depends on the air temperature and the physical characteristics of the product [7]. Pardhi and Bhagoria designed, constructed, and studied a prototype of a mixed-energy forced-convection solar dryer. Tests of both smooth and rough solar collector plates demonstrated poor thermal performance. The results also show that for drying 3 kg of grapes from an initial moisture of 81.2% to a final moisture content of 18.6% a maximum capture surface $A_c = 1.03\ m^2$ was required for a period of 4 days compared to 8 days of natural drying for the same conditions [8].

II. DESCRIPTION OF THE DRYING SYSTEM

The indirect forced convection solar dryer studied is a thermo-energy system designed to ensure a fast, hygienic and perfectly controlled drying of food products. It consists of three main subsystems: solar air flat-plate collector, a drying chamber with several racks and a forced ventilation module assuring a constant and adjustable air flow figure 1. The overall operation of the system is based on the forced convection of air previously heated by solar energy. Its functional architecture is broken down into four successive stages: the incident solar radiation is absorbed by the black-painted absorbent plate. On the other side, the ambient air with the environmental parameters enters the collector, where it is heated by contact with the hot absorbent plate, and then circulates through the air duct to the drying chamber, so the hot air at the outlet of the solar collector is then blown into the drying chamber by the fan to remove moisture from the product. Finally, the moisture-laden air is exhausted through a chimney or an adjustable ventilation grill to the outside.

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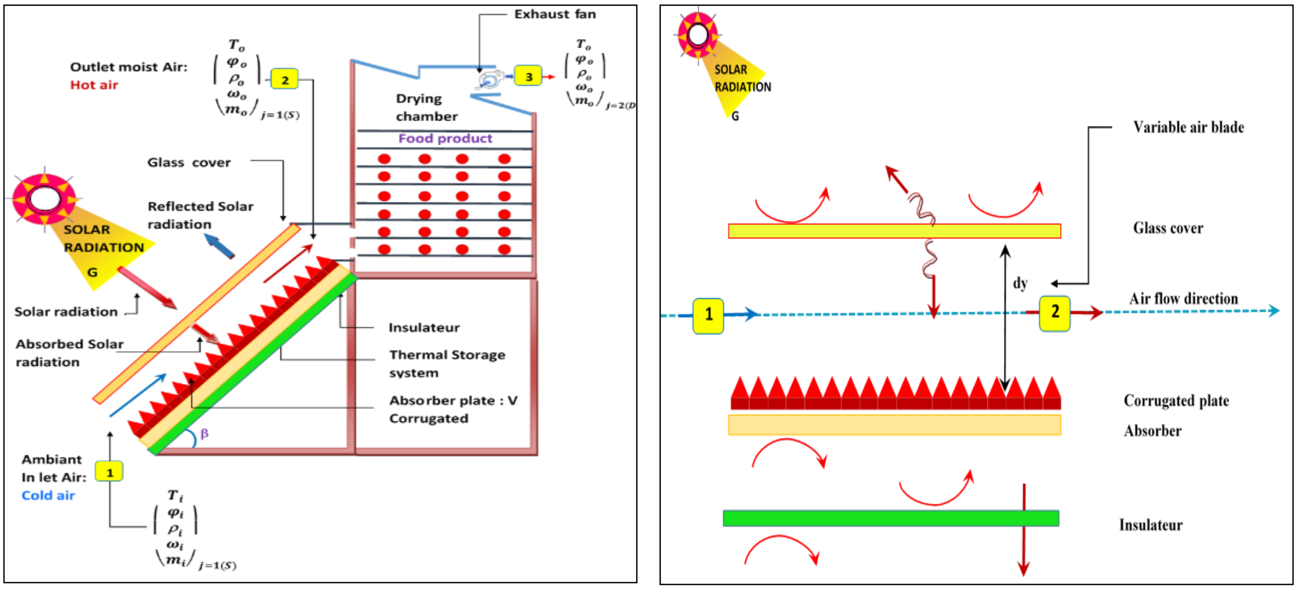

(a) (b)

Fig. 1 Schematic Diagram (a) of the forced convection indirect solar dryer (FCISD) (b) of the plan air solar collector

III. MATHEMATICAL MODEL

The mathematical model developed aims to predict the thermo-hygrometric behaviour of the indirect forced convection solar dryer (FCISD). It is based on the establishment of energy and mass balances for the solar collector, the drying chamber and the product itself [1]. The mathematical formulation of the equations of the energy and mass balances in the system components is based on the following general assumptions [3]: air is considered to be an ideal gas with constant thermophysical properties, the air flow in the collector and the drying chamber is one-dimensional, the heat transfer by internal radiation within the collector follows the Stefan-Boltzmann law, The moisture content of the product is evenly distributed throughout its volume and the product is modelled as a homogeneous, isotropic material of regular geometry..

A. *Solar Collector Thermal Model:*

The overall heat balance at the level of the flat plate solar air collector is given by equation (1), the incident solar flux is the sum of the useful energy needed to heat the air and the total heat losses by convection, conduction and radiation.

$$Q_g = A_C\,(\tau_v\alpha_{ab})I_c = \dot{m}_a\,c_{p,a}\left(T_{co} - T_{fi}\right) + h_c\,A_c\,(T_P - T_{amb}) + \varepsilon_P\,\sigma A_c\left(T_P^4 - T_{sky}^4\right) \qquad (1)$$

The instantaneous thermal efficiency of the collector is given by equation (2):

$$\eta_c = \frac{Q_u}{Q_g} = \frac{\dot{m}_a\,c_{p,a}\left(T_{co} - T_{fi}\right)}{I_c\,A_c} \qquad (2)$$

B. *Thermo-hygrometric model of the drying chamber:*

The equations for thermal heat transfer between the product and its environment are given by the laws of conservation of energy. Indeed, part of the energy received is stored in the walls, the other is used to evaporate the water from the product to an equilibrium content [6]. However, the variation in the internal energy of the product is the sum of the amount of latent heat responsible for the vaporization of the water of the product and the convective heat exchanges between the air and the product, equation (3).

$$A_s h_{cf}(T_a - T_p) = \dot{m}_a\,c_{p,a}\,(T_{di} - T_{do}) + \dot{m}_w\,L_v \quad (3)$$

Where: As: the total surface area of the product exposed to hot air [m^2], $\dot{m}_w$˙: the mass flow of evaporated water. [Kg/s].

The mass balance of water vapour is given by equation (4)

$$\dot{m}_w = \dot{m}_a(\omega_{out} - \omega_{in}) \quad (4)$$

Where ω is the specific humidity (moisture ratio) of the air [g of water/kg of dry air].

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C. Thermal Product Modelling:

the product is subjected to a combined heat-mass transfer. Its heat balance is written:

$$\dot{m}_p C_{Pp} \left(\frac{dT_p}{dt}\right) = A_s h_{cf} \left(T_a - T_p\right) - \dot{m}_w L_V \quad (5)$$

Moisture loss is governed by an internal diffusion equation:

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial x} \quad (6)$$

Where X is the water content and D_{eff} is the effective diffusivity.

D. Kinetic Drying Model:

the drying kinetics are described by an empirical model. The Page model, which is typically the most accurate for food and beverage products, is expressed as follows:

$$M_R = exp(-kt^n) \quad (7)$$

Where: k: temperature-dependent drying constant, n: an exponent characteristic of the product type. Other models may be used for comparison.

The page template		Newton (Lewis) Model		Henderson–Pabis Model	
$M_R = exp(-kt^n)$		$M_R = exp(-kt)$	(8)	$M_R = a.exp(-kt)$	(9)

These models are fitted to the experimental data to extract the characteristic drying parameters of the product.

IV. NUMERICAL RESOLUTION METHOD

The time-dependent system of equations, established in the previous section, is solved numerically using MATLAB and an implicit finite-difference scheme. The method consists of simultaneously integrating the energy and mass balance equations of the solar collector, the drying chamber and the product, considering the daily variation of solar radiation in fig. 4. The differential equations are solved using an implicit Euler scheme, ensuring numerical stability even with small time steps. The time domain is discretized as follows:

$t_0=0$, $t_{(i+1)} = t_i + \Delta t$ $\quad$ i=1…, N with Δt varying between 1 and 5 minutes.

V. RESULTS AND DISCUSSION

This section presents a detailed analysis of the thermal, energy and hygroscopic performance of the indirect forced convection solar dryer. The results were obtained from the numerical resolution of the previously established thermodynamic model and cover the following aspects:

(i) the dynamics of solar radiation and the effect of the inclination angle of the collector, (ii) the thermal behaviour of the solar collector, (iii) the thermo-hygrometric distribution inside the drying chamber, (iv) the drying kinetics of the product and the evaluation of the model parameters, (v) the influence of the mass of the product and the surface area of the collector on the overall drying performance.

Figure 2 shows the variation of the global incident radiation (w/m^2) as a function of time (hours) for the city of Tunis (latitude 33°) for different angles of inclination from 15° to 70° (June 21 and December 21) with clear sky. For an angle of inclination of 15°, the maximum solar irradiation reached is 1445 w/m^2 on June 21 compared to 521 w/m^2 on December 21.

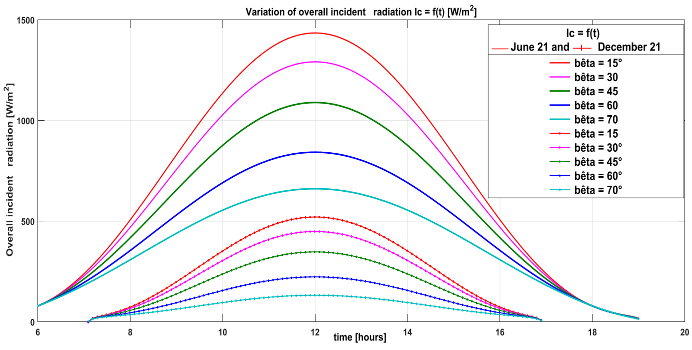

Fig. 2 Variation of global incident radiation (w/m^2) as a function of time (hours) and inclination angle β.

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Figure 3 shows the variations in the instantaneous efficiency of the solar collector as a function of time that increases over time for different volume flows of the air at the inlet of the solar collector. It is noticeable that as the flow rate increases, the yield increases. From a certain value of the flow rate, it increases slightly to a maximum value η=65% this is since the exchanges between the air, and the absorber are no longer in equilibrium.

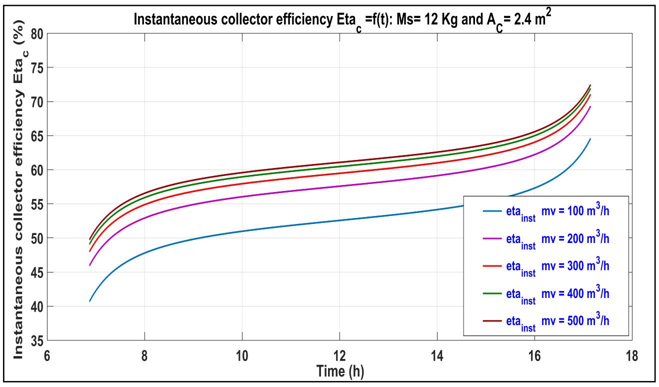

Fig. 3 Variation of the instantaneous efficiency as a function of time (hours)

Figure 4: For a constant volume flow rate of the order Mv = 400 m^3/h, all temperatures are variable and follow the shape of the curve of the incident solar radiation, as a function of time (h). When the temperature reaches a maximum in broad daylight, each temperature reaches a peak: the temperature of the absorber T_abs=78 °C, the temperature of the air at the outlet of the solar collector T_c_out = 47 °C.

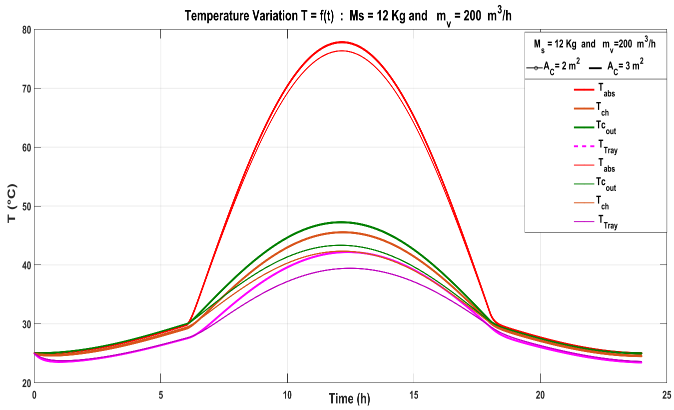

Fig. 4 Variation of the absorber, collector outlet air, dry air chamber and average tray temperatures as a function of time (hours)

Figure 5 shows the evolution of the temperature of the drying chamber as a function of time for different thicknesses of the thin-film product, it rises rapidly at the beginning of drying td = 6 h before stabilizing. It is also found that thicker products absorb heat more slowly, leading to a drop in temperature and consequently a longer drying time that affects energy consumption. On the other hand, for products cut into a thinner layer, heat transfer with air is ensured more quickly and drying is achieved in a shorter time.

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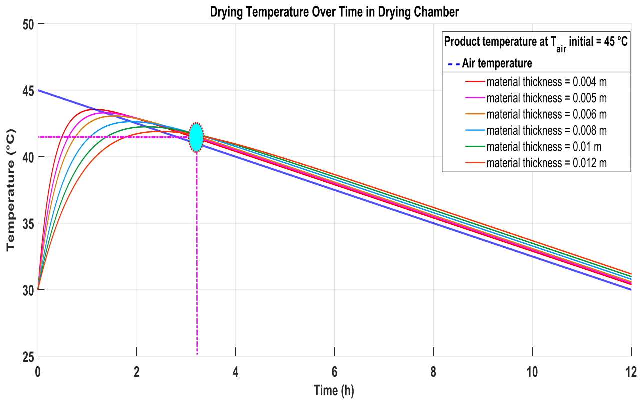

Fig. 5 Drying Temperature Over Time in Drying Chamber for different material thickness

VI. CONCLUSION

The indirect forced convection drying system studied is described by the equations for the conservation of the heat and mass balances as well as by the heat transfers between the different elements of the system. This work has made it possible to develop a complete thermal and hygroscopic model of an indirect forced convection solar dryer for food products. The model is based on energy and mass balances applied successively to the solar collector, the drying chamber and the product, followed by numerical resolution in MATLAB [9]. The results show that the system has good thermal performance, not least thanks to the stable output temperature of the collector (42–50 °C), which is ideally suited for drying temperature-sensitive products. The analysis shows that the optimal surface area of the collector depends mainly on the mass of the product, its initial moisture content and the intensity of the solar radiation. For a load of 12 kg of product, a collector area of 2.45 m² allows a final humidity level of around 12% to be achieved within 24 hours, confirming the effectiveness of the system in similar climatic conditions. The drying chamber has excellent thermal homogeneity and a constant reduction in relative humidity, validating the relevance of forced convection to maintain regular drying kinetics and prevent moisture stagnation. The simulation of the drying kinetics using Page's model shows an exceptional agreement with the expected profiles, reaching a coefficient of determination $R^2 > 0.995$.

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