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Design of Continuous Forced Convection Indirect Solar Dryer with Supplementary Heating for the Drying of Agricultural Products: Maize, Mahogany Nuts, Shea Nuts, Mangoes By-products

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Abstract: In this work; we were interested in a drying system with displacement of the material to be dried. The practical aspect of this study is the design of a continuous forced convection indirect solar dryer with auxiliary heating to reduce upstream or downstream failure or in the processing environment of agricultural products. In the rest of our work, we focused on the drying of maize, mahogany nuts, shea nuts, by-products resulting from the processing of mangoes. The parameters to be followed in this design are the flow rate and temperature of the coolant. The choice of devices of this equipment is made according to these two parameters. The particularity of this design is that the electrical elements will be powered by photovoltaic energy which is interconnected with conventional energy to avoid any form of load shedding. At the end of our study, this resolution of the failure in the processing chain of agricultural products will increase the value added of the agricultural sector.

Keywords: Continuous Indirect Solar Dryer, Forced Convection, Agricultural Products & By-Products, Auxiliary Heating

1. Introduction

Drying is an effective way of preserving fruits and vegetables. Traditional solar drying (direct sun exposure) is one of the primary means of drying but has some disadvantages due to bad weather. These bad weather deteriorate the quality of the dried products.

In order to overcome this disadvantage, it would be obvious to opt for solar dryers to maintain the intrinsic qualities of dried products. This drying system is also a step in the transformation of certain products in the agri-food, textileindustries, etc.

Nowadays, a lot of research is done on the " sun " energy source. Solar energy is evolving to such an extent that it is obvious to make integrated renewable energy design. The continuous forced convection indirect solar dryer is the drying method used in our study. In this type of dryer there is a simultaneous movement of the dried product and heat. The coolant used here for drying is hot air.

The aim of this work is to develop a continuous forced convection indirect solar dryer as well as its use for the drying of by-products derived from the processing of mangoes.

2. Materials and Methods

a) Description of the drying system

The continuous forced convection indirect drier system with supplementary heating has been realized taking into account those already existing in particular the dryers described by [7-12, 17]. This drying device regulates the temperature and the air flow intended for drying.

The heat transfer fluid is conveyed to the drying chambers using a centrifuge. The regulation of the temperature is ensured by solenoid valves and temperature probes. In the event of a temperature drop (below the recommended temperature) of the coolant in the drying chambers, the pre-installed heating elements start to maintain the desired temperature [14-16].

Condensate discharge is provided by automatic drain valves.

Movement and drying of the product are continuous. The product is moved by worm. The decrease in the mass of the product at each drying chamber and the passage time in each chamber depend on the nature of the product [2, 3, 5, 6].

b) Choice of system devices and dryer model [1, 19-23]

i. The coolant production system

1) The compressor or the blower:

The compressor or blower is an apparatus for producing compressed air for use. Compressed air is one of the oldest forms of energy that man has used. It is an energy offering many advantages and makes it possible to solve, in a simple and rational way, the problems of automation.

2) The solar thermal plate:

The solar thermal plate absorbs solar radiation in a disordered manner using an absorber which is generally surface. And the collector called solar concentrator, forms a block with the heat exchanger, generally coils in which the compressed air passes to be loaded with calories to become the coolant (heat transfer fluid).

3) The heating resistor:

The heating resistor is an electrical resistance connected to conventional electrical energy or photovoltaic energy in order to produce heat to compensate for the deficit or to ensure the production of coolant in case the solar thermal is deficient or unproductive.

4) The disinfectant filter:

The filter removes compressed air from all impurities and condensed water in suspension to protect equipment in the installation.

Depending on the filter cartridge chosen for the filter, the impurities retained will vary between 0.01 µm and 40 µm. It is therefore important to regularly empty the bowl of the recovered condensation and to clean the cartridge of impurities that could clog its pores.

The pressure regulator, or expansion valve, ensures that the working pressure is as regular as possible as long as the supply pressure is higher than the required pressure.

In summary, the heating system used in this study is a combined system of solar thermal and heating resistance that will serve to overheat the compressed air produced. In this system the heating resistor will be used as compensation in case of failure to reach the ideal temperature between [θ°C; θ'°C] with θ°C<θ'°C [18] or replacement of the solar source.

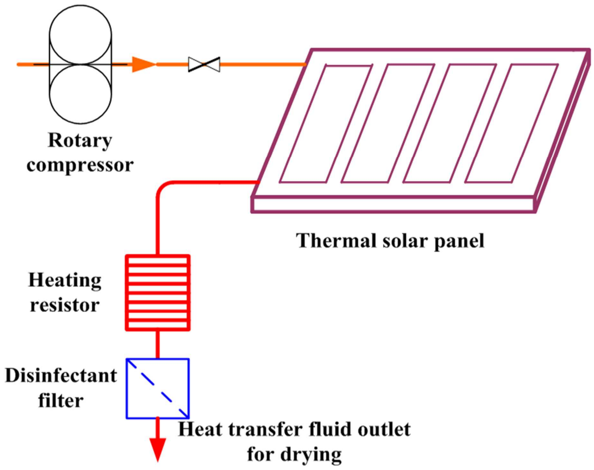

Figure 1. *Synoptic of the heat transfer fluid production system.*

ii. The conveying device

A geared motor is a motor coupled to a gearbox. It is a variable speed reducer which makes it possible to vary the rotation frequency of the drive motor and to increase the output torque of the gearbox. The passage time of the product in the ducts will be a function of the number of rotation of this geared motor.

The worm is a part having a threaded portion and a head for rotating, so as to ensure penetration into a pipe called conduct.

The geared motor and worm assembly allows the conveying of the material during drying.

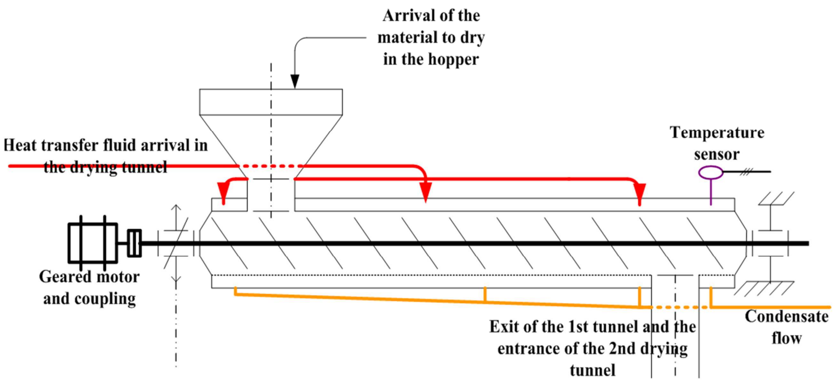

Figure 2. *Kinematic chain of the conveying device.*

iii. The electric power supply system

1) Solar photovoltaic:

Photovoltaic solar energy refers to electricity produced by transforming part of the solar radiation with a photovoltaic cell. Several cells are interconnected and form a photovoltaic solar panel (or module). In the event of a deficit, this energy will be offset by conventional electricity.

2) The control box:

The box [24] will be used to fix the various control modules of the equipment namely the motorized and purge valves, the temperature probes, the geared motor, the compressor or the blower, the solar photovoltaic interconnection system and conventional electricity, and the heating resistor.

It is a box of characteristics IP 20-IK 08 with reversible curved door in silkscreened safety glass, key lock 2433 A. The pivoting side panels can be dismantled from the inside without tools.

3) The regulator:

The regulator used is a power regulator [24] powered by 400 V-50 Hz. Their combination with 400 V-50 Hz fixed batteries makes it possible to adapt the compensation to the needs of the operation.

This type of controller controls the connection and disconnection of the stands to maintain the target power factor.

4) The batteries:

The batteries used in our study are fixed batteries [24] three phases 400 V-50 Hz. These batteries will compensate the needs of the operation. We have constant load installations operating 24 hours a day, vacuum compensation of transformers or individual motor compensation.

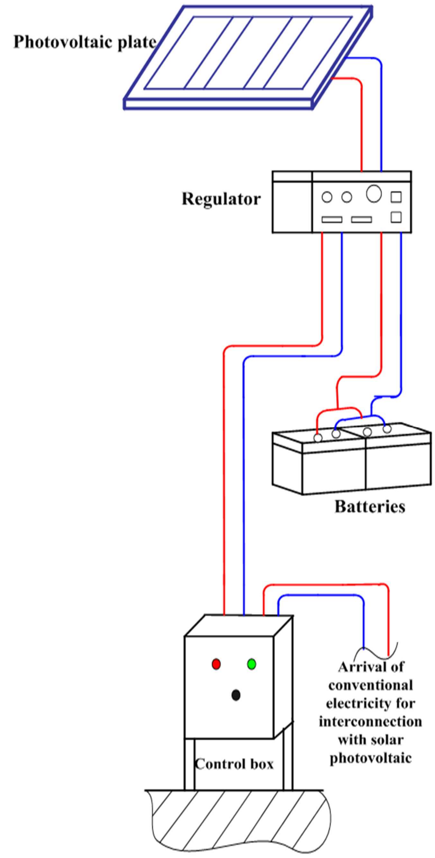

Figure 3. *Diagram of the power supply device.*

iv. Modeling of the dryer

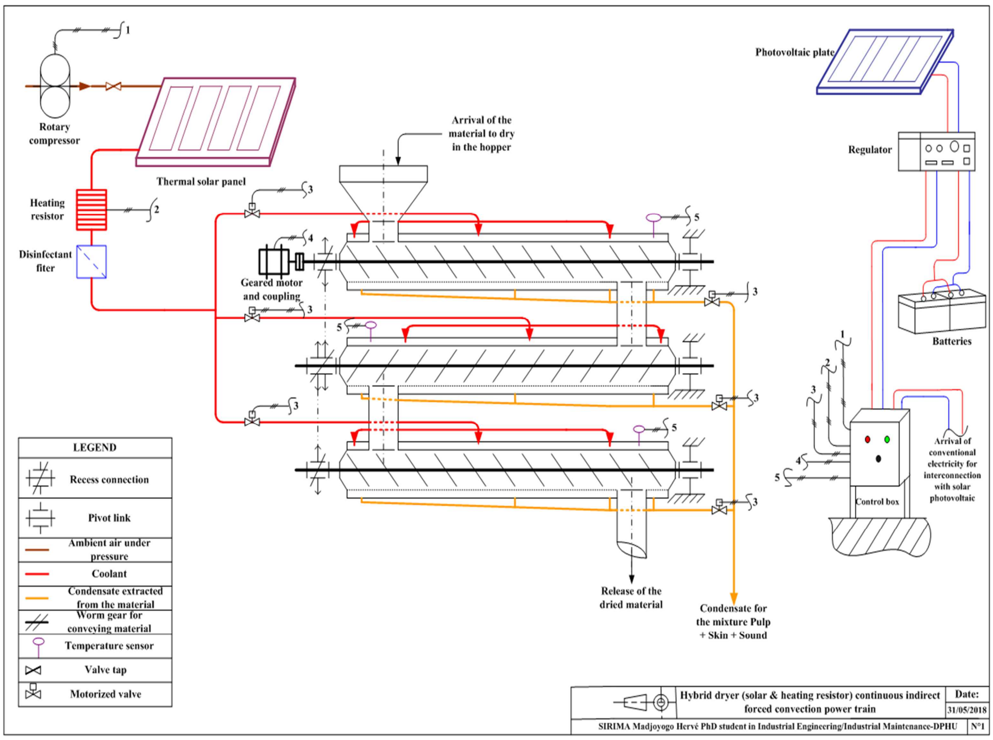

Figure 4. *Hybrid dryer (solar& heating resistor) continuous indirect forced convection power train.*

3. Thermal Balance

The drying is done at constant temperature and flow rate of the heat transfer fluid at the entrance of the dryer, therefore we will limit ourselves to the analysis of the behavior of the drying unit equipped with the auxiliary heating. The global consideration of the transfer phenomena of the coolant and the product by the system as well as the physical quantities used are macroscopic quantities and not local quantities.

a) Thermal balance at the sources producing coolant (heat transfer fluid)

The energy balance at the producing sources leads us to determine the power produced at each source while taking into account the variation of their use as a function of time. We will have:

1) In the production of solar thermal:

$$Q_{p1} = M_a.C_{pa}.\ (T_{as}\text{-}T_{ae})$$

with:

Q_{p1}: Power produced by the source in Joule (J)

M_a: Mass flow rate of air in kg/s

C_{pa}: Thermal capacity of the air in J/kg.°C

T_{as}: Temperature of the air at the exit of the producing source (Solar thermal).

T_{ae}: Air temperature at the input of the producing source (Solar thermal).

The efficiency of the solar thermal source is summarized in the following formula:

$$\eta_1 = Q_{p1} / (Ap.Ir)$$

with:

Q_{p1}: quantity of heat produced at the collector (W),

A_p: Area of the solar plate (m^2),

I_r: Intensity of solar radiation incident on the collector (W/m^2).

2) Inthe production of the heating resistor:

$Q_{p2} = RI_2.Tr$ with:

Q_{p2}: Power produced by the source in Joule (J)

R: System resistance in ohm (Ω)

I: Intensity crossing the resistance in ampere (A)

T_r: Heating time (s).

The efficiency of the heating resistor source is determined by the following relation:

$$\eta_2 = \frac{Qp2}{Qp2+Pp}$$

with:

P_p: Lost power

3) In the production of solar thermal-heating resistance:

This situation happens in the case where the heating resistor comes in addition to the solar source. All this is made possible thanks to the programming and automation of the system. The power produced is:

$$Q_p = Q_{p1} + Q_{p2} = M_a.C_{pa}.\ (T_{as}\text{-}T_{ae}) + RI_2.T_r$$

b) Thermal balance at the conveying ducts of the coolant

We have heat transfer by conduction with a hollow cylinder. The thermal conductivity will be deduced taking into account the distances separating the source of heat transfer fluid and the drying tunnels. To do this, it would be important to have a very low coefficient of conductivity to avoid the formation of a considerable volume of condensates during the transfer "*confers calculation of λ*."

The drying temperature will be set within a tolerance range of [θ°C; θ'°C]. For the determination of λ we will take the temperature already fixed.

$$\emptyset = 2\pi L\lambda\Delta T\ /\ (\text{Log}\ (R_2/R_1)) \Longrightarrow \lambda = \emptyset\ (\text{Log}\ (R_2\ /\ R_1))/\ 2\pi L\Delta T$$

∅: Power in Watt (W)

λ: Coefficient of thermal conductivity in W / m.°K

L: Distance between the heating element and the drying tunnels in m

ΔT: Heat transfer medium temperature in Kelvin (°K)

R_1: Inner radius of the coolant conduit in mm

R_2: Outside radius of the coolant conduit in mm

We therefore need a pipe of thermal conductivity coefficient λ calculated above or a pipe whose thermal conductivity is close to this value.

c) Thermal balance at the drying tunnel

The thermal balance at the drying tunnel is done by taking into consideration some hypotheses to focus the analysis on the heat transfer system:

1) Radiative exchanges inside drying ducts are neglected.
2) The by-products (mango processing waste and mangoes unsuitable for consumption) of the mango are at the same temperature and have the same water content.
3) The walls of the drying duct have uniform and constant temperatures.
4) With regard to the coolant, the convective exchanges are predominant while those by conduction are negligible.
5) The problem is unidimensional, that is to say along the axis OZ; the variation of the temperature is considered uniform in the XOY plane, this result is proved experimentally.
6) The temperature variation of the material to be dried is a function of time.

Table 1*. Identification of different variables.*

Designations	Symbols
Coefficient taking into account the radiative and emissive properties of the body (Ar)	A
Convective heat exchange coefficient (W/m².K)	h
Thermal conductivity of liquid	λl
External diameter of the tube (duct)	Dext

Designations	Symbols
Inner diameter of the tube (duct)	Di
Diameter of the worm	Darbre
Heat flow that attacks the drying duct	Φ
Heat flow actually received by the material in each drying pipe	Φ'
Heat flow received through the surface S1 (non-cracked surface)	$\Phi1$
Heat flow actually received through the surface S1 (non-cracked surface)	$\Phi'1$
Heat flow received through surface S2 (cracked surface)	$\Phi2$
Width of projections	e
Length of protrusions	l
Length of the duct (tunnel) drying	L
Liquid density	ρ
Nusselt number	$\overline{Nu}$
Reynold number	Re
Area attacked by the coolant	S
Unslit area	S_1
Area occupied by the projections (Direct contact zone between the coolant and the raw material)	S_2
External body temperature of drying pipe	T_{pext}
Temperature received by material	T_{pint}
Dynamic viscosity of the liquid	μ
Average speed of the liquid	U_m
Volume of drying pipe	V_{pipe}
Material volume	$V_{material}$
Worm volume	V_{vsf}

We are in the case of a forced convection with a cylinder perpendicular to the flow of the fluid.

1) Nusselt number: $\overline{Nu} = A.Re^m = (h.D_i) / \lambda_l$

2) Reynold number: $Re = U_m.D_l. (\frac{\rho}{\mu})$

Note that on the surface S_2 the heat transfer fluid will directly attack the raw material so the heat flux received by said material is finally:

$$Qp = \emptyset = \Phi = \Phi1 + \Phi2$$

$$\Phi1 = \Phi.\frac{S1}{S} = \emptyset.\frac{S1}{S}\ \Phi2 = \Phi.\frac{S2}{S} = \emptyset.\frac{S2}{S}$$

$$\left.\begin{array}{l} Nu = A.Rem = \frac{(h.Di)}{\lambda l} \\ Re = Um.Dl.\left(\frac{\rho}{\mu}\right) \end{array}\right\} = Nu = A.\left(Um.Dl.\left(\frac{\rho}{\mu}\right)\right)m = (h.D_i)/\lambda_l \Rightarrow h = \lambda_l.\left(\frac{A}{Di}\right).\left(U_m.D_l.\left(\frac{\rho}{\mu}\right)\right)^m$$

$$\Phi = \lambda l.\left(\frac{A}{Di}\right).\left(Um.Dl.\left(\frac{\rho}{\mu}\right)\right)m.S.(Tpext - Tpint)\ \text{car}\ \Phi = h.S.(Tpext - Tpint)$$

$$S = Dext.L$$

$$S = 140*8000$$

$$S = 1\ 120000\ mm^2$$

$$S_1 = S - S_2 = Dext.L - \Sigma\ (l.e)$$

$$S_2 = \Sigma\ (l.e) = 28*(50*1)*80$$

$$S_2 = 112000 mm^2$$

$$S_1 = 1120000 - 112000$$

$$S_1 = 1008000\ mm^2$$

$$V_{pipe} = S_{base}.L = \pi r^2.L = \pi.L.(Di^2)/4$$

$$V_{vsf} = \pi.L.(Dshaft^2)/4$$

$$V_{material} = \pi.\frac{L}{4}.(Di^2 - Dshaft^2)$$

Finally, the heat flux actually received (Φ ') by the material in each drying pipe is given by the following formula:

$$\Phi' = \Phi'1 + \Phi2$$

The heat fluxΦ2 is received directly by the material on each duct. We will have:

$$\Phi 2 = [\text{Ma.Cpa. (Tas} - \text{Tae)+ RI2.Tr} - \Sigma \text{ (convective losses of the ducts)}].\frac{S2}{S}$$

$$\Phi 2 = [\text{Ma.Cpa. (Tas} - \text{Tae)+ RI2.Tr} - \Sigma \text{ (convective losses of the ducts)}].\frac{S2}{S}$$

The heat flux Φ1 is indirectly received by the material through the surface S1 which is not cracked. We will have:

$$\Phi 1 = [\text{Ma.Cpa. (Tas} - \text{Tae)+ RI2.Tr} - \Sigma \text{ (convective losses of the ducts)}].\frac{S1}{S}$$

$$\Phi 1 = [\text{Ma.Cpa. (Tas} - \text{Tae)+ RI2.Tr} - \Sigma \text{ (convective losses of the ducts)}].\frac{S1}{S}$$

So, we will have to determine the temperature received by the material through S1.

The temperature (Tpint) received by the material through the surface S1 is thus obtained by posing the following equality:

$$\lambda\text{l. }(\frac{A}{Di})\text{. (Um.Dl. }(\frac{\rho}{\mu})\text{) m.S. (Tpext} - \text{Tpint)} = [\text{Ma.Cpa. (Tas}-\text{Tae) +RI2.Tr}-\Sigma \text{ (convective losses of the ducts)}].\frac{S1}{S}$$

$$\text{Tpint} = \text{Tpext} - [\text{Ma.Cpa. (Tas}-\text{Tae) +RI2.Tr}-\Sigma \text{ (convective losses of the ducts)}].\frac{S1}{S}/\ \lambda\text{l. }(\frac{A}{Di})\text{. (Um.Dl. }(\frac{\rho}{\mu})\text{) m.S}$$

Finally, we get the following formula.

$$\text{Tpint} = \text{Tpext} - [\text{Ma.Cpa. (Tas}-\text{Tae) +RI2.Tr}-\Sigma \text{ (convective losses of the ducts)}].\frac{S1}{S}\ /\ \lambda\text{l. }(\frac{A}{Di})\text{. (Um.Dl. }(\frac{\rho}{\mu})\text{) m.S}$$

4. Conclusion

The experimental analysis carried out in this work is a contribution to the improvement of the drying systems in order to have a continuous industrial system. It saves considerable time on drying time and a continuous forced convection system that can be arranged upstream or downstream or in the middle of another agricultural product processing line depending on the type of product.

Our drying system considerably increases the value added of the agricultural sector, despite some shortcomings that we hope to improve very soon.

In addition, we first of all, in this study, diagnosed the different types of existing driers, and then we proposed a new model, of which, we were obliged to study the possibility of implementation. Thus, we proceeded to the modeling of the drying system.

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