Engineering, 2023, 15, 13-23
https://www.scirp.org/journal/eng
ISSN Online: 1947-394X
ISSN Print: 1947-3931

Experimental Study and Modeling of a Convective Dryer for Fruits and Vegetables

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How to cite this paper: Sinon, S., Tera, S., Haro, K., Djanfar, E.-M., Sanogo, O. and Kam, S. (2023) Experimental Study and Modeling of a Convective Dryer for Fruits and Vegetables. *Engineering*, **15**, 13-23.
https://doi.org/10.4236/eng.2023.151002

Received: November 17, 2022
Accepted: January 27, 2023
Published: January 30, 2023

Abstract

The present work deals with the study of the thermal performances of a convective dryer for fruits and vegetables. This dryer, operating with energy generated from the combustion of biomass in a boiler connected to a water/air heat exchanger could be a solution to the problematic of energy related to drying. An experimental and theoretical study is carried out on the temperature profile inside the dryer. For this purpose, 10.3 kg of tomatoes were dried on the experimental setup. The operation lasted about 16 hours and reduced the moisture content from 93.8% to 12% in wet basis. The overall thermal efficiency of the convective dryer during the trial is 10.76%. For the theoretical study, the dryer components (boiler, water/air exchanger and drying chamber) are first modeled individually; the different sub-programs are then coupled to form the convective dryer program. The method of global heat balances combined with the one called "*ε-NUT*" is used. The set of equations is discretized using the implicit method of finite differences, then solved with the Gauss algorithm in Fortran 90. The theoretical results obtained are in good agreement with those measured.

Keywords

Energy, Drying, Biomass, Boilers, Fruits and Vegetables

1. Introduction

The total production of fruits and vegetables is estimated at 434 kt in 2019 in

Burkina Faso [1]. In the period from 2009 to 2019, it has increased by 26% for fruits and 21% for vegetables. According to the Food and Agriculture Organization of the United Nations, about 52% of fruits and vegetables are lost between harvest and consumption [2]. These losses are largely due to a lack of adequate preservation of these highly perishable products.

Drying techniques can provide a satisfactory solution for the preservation of fruits and vegetables to reduce their post-harvest losses. Drying, as well as dryer technologies, have been the subject of several studies ([3] [4] [5] [6] [7]). The dryers are diversified, ranging from direct dryers to hybrid dryers with the use of various energy sources [8].

Solar dryers, which are widely used, are limited because they operate only in the presence of sunlight. The profitability of butane gas dryers is threatened by price volatility and recurrent shortages of this energy source and the use of fossil fuel is known to have undesirable impacts on environment and climate change.

Burkina Faso has a large biomass potential, ranging from crop residues to household waste, which can offer an interesting solution to the problem of energy related to the drying of agricultural products. Indeed, the use of biomass as a boiler fuel coupled with a water/air heat exchanger could be a credible alternative to the use of butane gas which is currently the main source of energy of the country for drying operations; this energy source, which is available and inexpensive, will reduce the cost of drying operations and post-harvest losses.

2. Experimental Setup

Figure 1 shows the dryer that is the subject of our study. It is a convective dryer consisting essentially of a drying chamber, a water/air heat exchanger and a biomass boiler.

The boiler is water tube type, heated by the combustion of biomass. The inner and outer coaxial vertical tubes have diameters of 0.416 m and 0.736 m respectively. Three horizontal tubes, each with a diameter of 0.184 m, are connected to the inner wall of the inner vertical tube. The boiler walls consist of two coaxial mild steel vertical tubes with a height of 1.5 m and have a volume of 250 L. The

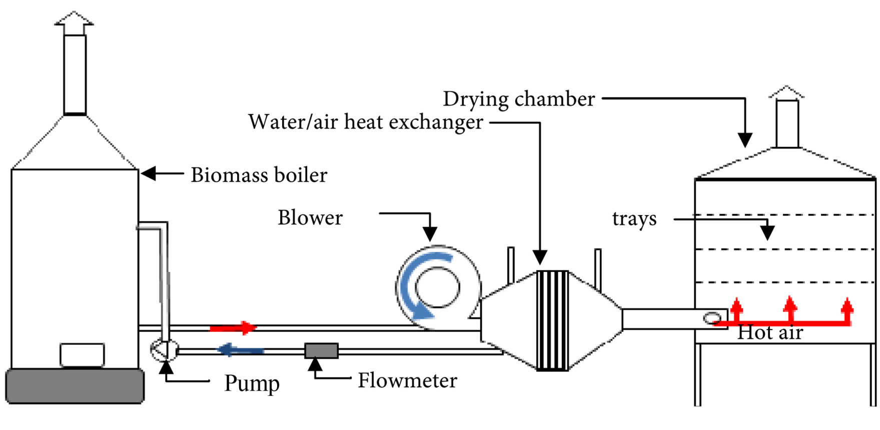

Figure 1. Schema of the experimental set-up.

wall thickness of the different tubes (vertical and horizontal) is 8 mm. A 4 m high convergent pipe is connected to the upper end of the coaxial vertical pipes and serves as a smoke exhaust stack as shown in **Figure 1**.

The heat exchanger is a water/air type. It consists of 4 copper serpentine tubes with a diameter of 16.3 mm, thickness 1 mm with continuous rectangular aluminum fins of thickness 1 mm; the whole is stored in a steel box.

The drying chamber has a size of 2 m × 2 m × 1.6 m respectively for length, width and height. It contains 06 trays of 1.7 m^2 each. The walls are thermally insulated and composed of aluminum sheet, wooden plywood, polystyrene and steel sheet from the inside to the outside.

The product to be dried is tomato with an initial mass of 10.3 kg distributed at 1.72 kg per tray. The tomatoes are first washed and sorted and then sliced into rounds of about 1 cm thickness. The hot air feeding the drying chamber is obtained by forced convection heat transfer by means of a blower with a maximum flow rate of 0.075 $kg \cdot s^{-1}$, between cold air and hot water (about 85˚C) through the water/air heat exchanger. The hot water comes from the biomass boiler via a pipe. The hot water is circulated in a closed circuit between the boiler and the water/air heat exchanger by a pump. The water in the boiler is heated with the flue gas energy content generated by the combustion of the biomass.

In order to ensure a better stability of the drying conditions and a homogenization of the temperature inside the drying chamber, the air blower is switched on 30 minutes before the introduction of the trays loaded with tomato slices. A sample of tomato slices is marked on each tray to monitor the evolution of the parameters of all the slices drying on the rack. The weighing is performed outside the drying chamber; the time interval between two weightings is 30 minutes during the first 04 hours, then 1 hour during 3 hours and reaches 1h30 towards the end of the drying. During a drying operation, temperature, mass and humidity are the parameters measured.

3. Modeling of the Convective Dryer

3.1. Biomass Boiler

The method chosen for the modeling of the boiler is the so-called global method ([9] [10]) which consists in making global energy balances at different levels of the boiler while assuming a unidirectional flow, constant thermophysical properties. The basic equation for this method is defined by (1):

$$m_i c_{pi} \frac{\mathrm{d}T_i}{\mathrm{d}t} = \sum_{i,j} K_{ij} S_i \left(T_j - T_i\right) + \phi_i \tag{1}$$

With:

m_i : Mass of component i (kg);

c_{pi} : Specific heat of component i (J/kg·K);

T_i, T_j : Temperatures of components i, j (K);

K_{ij} : Overall heat transfer coefficient between media i and j ($W/m^2 \cdot K$);

S_i : Area of medium i (m^2);

ϕ_i : Source or sink of heat (W).

3.2. Water/Air Heat Exchanger

The ε-NUT (Efficiency-Number of Unit and Transfer) method is considered for the theoretical study of the exchanger. Indeed, knowing the efficiency of the exchanger and the global coefficient of heat transfer between the two fluids (water and air) involved, this method allows the evaluation of the temperatures of the hot water and the drying air at the exchanger outlet. We assume that the data of the water at the inlet of the exchanger are those of the biomass boiler outlet, the heat flow given by the hot water is entirely received by the air during the heat transfer at the water/air heat exchanger. We also assume that the heat losses of the two fluids and those of the materials of which the water exchanger is made are considered negligible. The global heat balance is defined by the Relation (2):

$$\phi_{ech} = \dot{m}_{water} c_{p_{water}} \left(T_{enter}^{water} - T_{out}^{water} \right) = \dot{m}_{air} c_{p_{air}} \left(T_{out}^{air} - T_{amb} \right) \quad (2)$$

The efficiency is given by the Relation (3):

$$\varepsilon_{ech} = \frac{\dot{m}_{water} c_{p_{water}} \left(T_{enter}^{water} - T_{out}^{water} \right)}{\left(\dot{m} c_p \right)_{min} \left(T_{enter}^{water} - T_{amb} \right)} = \frac{\dot{m}_{air} c_{p_{air}} \left(T_{out}^{air} - T_{amb} \right)}{\left(\dot{m} c_p \right)_{min} \left(T_{enter}^{water} - T_{amb} \right)} \quad (3)$$

Efficiency is formulated differently in the Relation (4) [11]

$$\varepsilon_{ech} = 1 - \exp\left[\frac{NUT^{0.22}}{C_r} \times \left\{ \exp\left(-C_r \times NUT \right)^{0.78} - 1 \right\} \right] \quad (4)$$

With:

$$C_r = \frac{\dot{m}_{air} c_{p_{air}}}{\dot{m}_{water} c_{p_{water}}} \quad (5)$$

$$NUT = \frac{U \cdot S_{air}}{C_{min}} \quad (6)$$

The overall heat transfer coefficient between the two fluids (water and air) is given by the Relation (7):

$$U = \left[\frac{1}{h_i} \frac{S_{air}}{S_i} + \frac{S_{air}}{2\pi \times \lambda_{cuivre} \times L_{tb}} \ln\left(\frac{d_{e1}}{d_i} \right) + \frac{S_{air}}{2\pi \times \lambda_{alu} \times L_{tb}} \ln\left(\frac{d_{e2}}{d_{e1}} \right) + \frac{1}{\eta_g \times h_a} \right]^{-1} \quad (7)$$

3.3. Drying Chamber

Regarding the modeling of the drying chamber, the data of the drying air at the inlet of the drying chamber are those at the outlet of the water/air heat exchanger, the method used is to cut the drying chamber into fictitious slices in the direction of the drying air flow where a heat balance is applied on each component [5]. We also assume that the moist air is considered as a mixture of perfect gases (dry air and water vapor), the air flow is unidirectional and uniform (from the bottom to the top of the drying chamber), the heat transfer by rack-to-product conduction is neglected, the heat transfer by radiation inside the drying chamber is neglected, the temperature and water content of the product are assumed uniform for each rack. For each component of the drying chamber in a fictitious wafer, the energy balance is written as follows:

- Tomato slices

$$m_{pr}Cp_{pr}\frac{\partial T_{pr}}{\partial t}=S_{pr}h_{pr\_air}^{conv}\left(T_{air}-T_{pr}\right)-P_{ev} \tag{8}$$

- Internal face of the wall

$$m_{pi}Cp_{pi}\frac{\partial T_{pi}}{\partial t}=S_{p}K_{p}\left(T_{pe}-T_{pi}\right)+S_{p}h_{pi\_air}^{conv}\left(T_{air}-T_{pi}\right) \tag{9}$$

- External face of the wall

$$m_{pe}Cp_{pe}\frac{\partial T_{pe}}{\partial t}=S_{p}K_{p}\left(T_{pi}-T_{pe}\right)+S_{p}h_{pe\_amb}^{conv}\left(T_{amb}-T_{pe}\right)+S_{p}h_{pe\_ciel}^{ray}\left(T_{ciel}-T_{pe}\right) \tag{10}$$

- Drying air

$$m_{air}Cp_{air}\left[\frac{\partial T_{air}}{\partial t}+U_{a}\frac{\partial T_{air}}{\partial z}\right]=S_{pr}h_{pr\_air}^{conv}\left(T_{pr}-T_{air}\right)+S_{p}h_{pi\_air}^{conv}\left(T_{pi}-T_{air}\right) \tag{11}$$

Evaporative power is defined by the Relation (12):

$$P_{ev}=m_{s}L_{vap}\left(T_{pr}\right)\frac{\mathrm{d}X}{\mathrm{d}t} \tag{12}$$

With:

$$L_{vap}\left(T_{pr}\right)=4186.5\left[597-0.56\left(T_{pr}-273.15\right)\right]\quad [12] \tag{13}$$

Drying characteristic curve model is chosen to describe the drying process of tomato slices based on the study of BOUGHALI [13]:

$$f\left(X_{r}\right)=\frac{-\frac{\mathrm{d}X}{\mathrm{d}t}}{\left(-\frac{\mathrm{d}X}{\mathrm{d}t}\right)_{0}}=0.03972+2.48916X_{r}-3.71419X_{r}^{2}+2.31832X_{r}^{3} \tag{14}$$

With:

$$X_{r}=\frac{X-X_{0}}{X_{eq}-X_{0}} \tag{15}$$

3.4. Calculation of Drying Efficiency

The parameters taken into account to calculate the drying efficiency are the mass of the dry product, the evolution of the water content as a function of time, the flow rates of the two fluids (water and air) and the mass of biomass used.

Based on the relationship of Prasad [14], the drying efficiency relates the amount of energy required to evaporate a certain amount of water from a product $\left(m_{sech}\times L_{vap}\times\frac{\mathrm{d}X}{\mathrm{d}t}\right)$ to the amount of energy supplied to the dryer $\left(\eta_{boiler}\times\varepsilon_{exchn}\times\dot{m}_{comb}PCI\right)$ by the combustion of the biomass. This relation can be expressed through Equation (16):

$$\eta_{evap} = \frac{m_{sech} \times L_{vap} \times \frac{\mathrm{d}X}{\mathrm{d}t}}{\eta_{boiler} \times \varepsilon_{exchn} \times \dot{m}_{comb} PCI} \quad (16)$$

With:

$$\eta_{chaud} = \frac{\dot{m}_{water} c_{p_{water}} \left(T_{out}^{water} - T_{enter}^{water} \right)}{\dot{m}_{comb} PCI} \quad (17)$$

$$\varepsilon_{ech} = \frac{\dot{m}_{air} c_{p_{air}} \left(T_{air} - T_{amb} \right)}{\left(\dot{m} c_p \right)_{min} \left(T_{enter}^{water} - T_{amb} \right)} \quad (18)$$

4. Results and Discussion

4.1. Boiler Performance

Figure 2 shows the evolution of the experimental efficiency and the calculated efficiency of the biomass boiler over time during a test. The experimental efficiency varies during the test between 0% and 62.52% with many fluctuations due to the instability of the flue gas and hot water temperature at the boiler outlet whereas the calculated efficiency varies between 0% and 62.78%. However, the analysis of the profile of the two curves shows that the calculated values of the efficiency remain mostly above the measured one. This difference could be explained by certain losses which were not taken into account during the theoretical study, in particular the heat losses by convection-radiation at the level of the opening of the combustion hearth and at the level of the more important smoke.

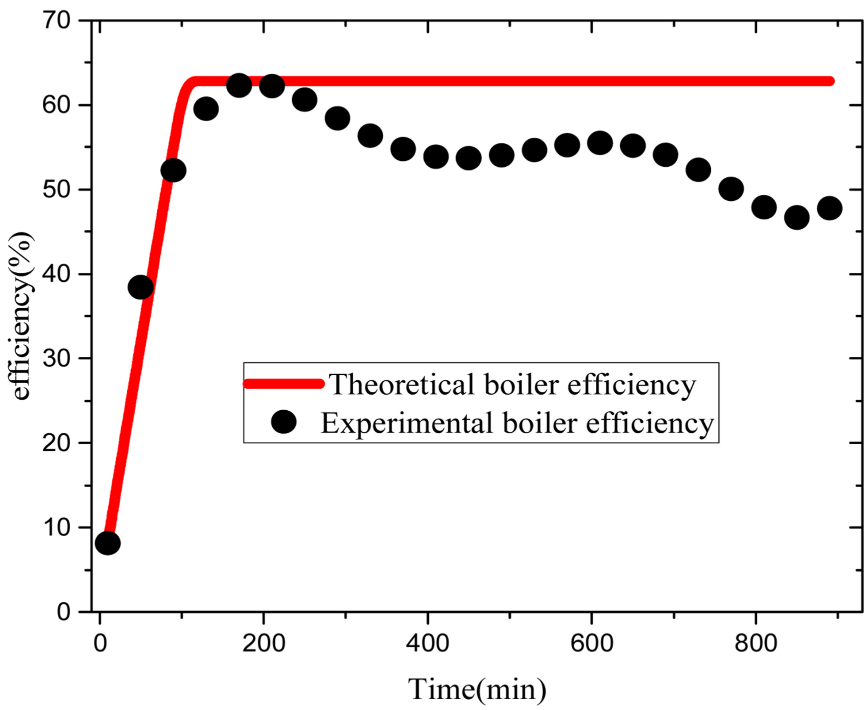

Figure 2. Evolution of the boiler efficiency during a test.

4.2. Performance of the Water/Air Heat Exchanger

Table 1 shows the calculated thermal performance of the water/air heat exchanger. These performances are evaluated from the efficiency of the heat exchanger with mass flow rates of 0.320 kg/s, 0.075 kg/s for hot water and air respectively; inlet temperatures of 80˚C and 35˚C for hot water and air respectively, the value obtained for this performance criterion is 66.35%. In the test with the same inlet conditions, the heat exchanger has an average efficiency of about 57.07%.

4.3. Drying Kinetics of Tomato Slices

Figure 3 illustrates the theoretical and experimental evolution of the water content of tomato slices in the convective dryer as a function of time for a drying air speed of 2.75 m/s, a temperature of 65˚C and a relative humidity of 12%.

The analysis of the theoretical and experimental drying kinetics curves indicates very similar profiles at the beginning, towards the end of drying; and a deviation in the middle of drying. This discrepancy is probably due to the theoretical approach where average values of drying air speed and temperature are used. The theoretical drying time is 13 h 20 min; the experimental one is 16 h

Table 1. Performance of the water/air heat exchanger.

Fluids	$\dot{m}\left(kg\cdot s^{-1}\right)$	$c_p\left(J\cdot kg^{-1}\cdot{}^{\circ}C^{-1}\right)$	$T_{enter}\left({}^{\circ}C\right)$	$T_{out}\left({}^{\circ}C\right)$	measured efficiency (%)	calculated efficiency (%)
Water	0.24	4206	91.3	87.3	57.07	66.35
Air	0.075	1005	29.8	64.9		

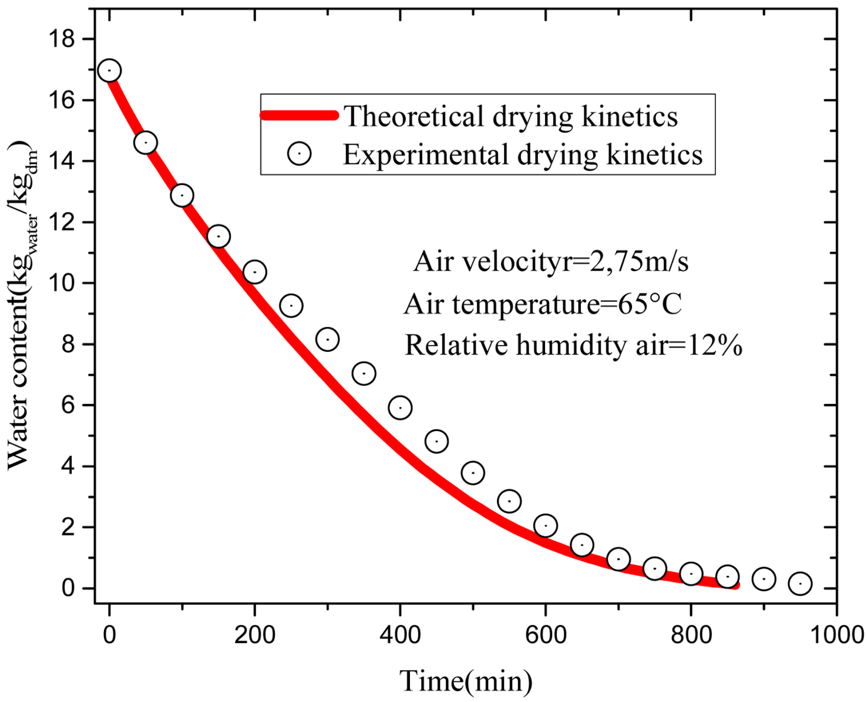

Figure 3. Experimental and theoretical drying kinetics.

10 min with a final relative humidity of 12% for the tomato slices. This final moisture content is close to the 11% obtained by Doymaz [15]. A phase shift of 02 h 50 min between the theoretical and experimental drying time observed, could be explained by a variation of parameters such as temperature and speed to which is added an imperfection of the insulation of the drying chamber, during the experimental study.

4.4. Drying Efficiency

The profile of the experimental and calculated global thermal efficiency of the convective dryer during the drying of tomato is presented in **Figure 4**. This evolution is obtained under the following conditions:

- Hot water flow = 0.32 kg·s^{-1};
- Air flow = 0.075 kg·s^{-1};
- Air temperature = 65˚C;
- Relative humidity of the air = 12%.

The analysis shows us two curves with the same decreasing pattern; however, a difference is noted between them: this is explained by the fact that during the experimental study of drying, many heat losses are recorded through imperfections in the thermal insulation of the walls and the frequent opening of the drying chamber to monitor the drying parameters, while during the theoretical study, the only heat losses taken into account are those related to the walls, the others being neglected. During tomato drying, the experimental and theoretical yields vary respectively from 10% to 25% and from 14% to 28%. These experimental yields are in the same order of magnitude as the 11% yield obtained by

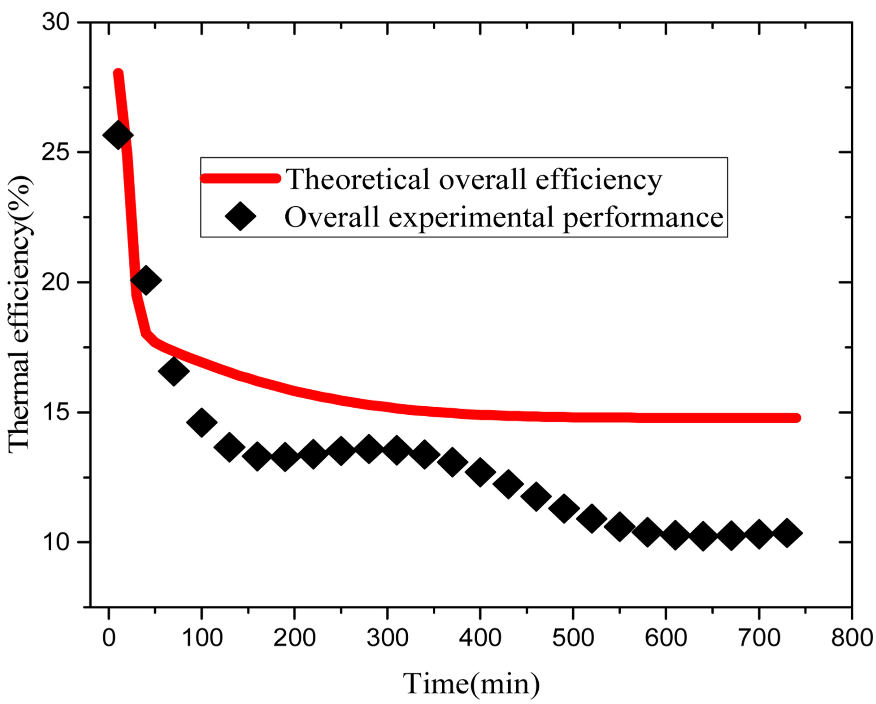

Figure 4. Experimental and theoretical global thermal efficiency and convective dryer.

Madhlopa and Ngwalo [16] when drying pineapple in an indirect dryer fueled by biomass combustion. They are better than that obtained by Prasad [17] when drying Tinospora cordifolia (medicinal plant) in a solar-biomass hybrid dryer operating in biomass-fired mode, which was 7.5%.

5. Conclusions

This study evaluated the performance of a convective dryer supplied with energy by the combustion of biomass in a boiler coupled with a water/air heat exchanger. The heat production unit (boiler-water/air heat exchanger couple) is able to provide hot air with a temperature ranging from 50˚C to 60˚C. The study also shows that the dryer is efficient for drying operations. Indeed, the drying of 10.3 kg of tomato with an initial moisture content of 93.8% (wet basis) took about 16 hours of time with a final moisture content of 12%. During tomato drying, the overall thermal efficiency of the dryer was approximate.

Theoretical study was used to simulate the operation of the convective dryer. The simulated results represented by the different curves are in good agreement with those measured. It should be noted that there are sometimes discrepancies between the simulated results and those measured due to losses recorded at certain levels of the convective dryer.

We plan to conduct more tests on the convective dryer and make the necessary modifications to improve its performance. Research is also planned to determine the quality of the dried product and also for an economic study to optimize the profitability of the convective dryer.

Acknowledgements

The authors wish to express their gratitude to the International Scientific Program (ISP), University of Uppsala, Sweden for its financial support through the project. BUFO1.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Highlights

- Realization of the convective dryer;
- Experimental evaluation of the dryer performance;
- Modeling the operation of the dryer.

Nomenclature

cp	:Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$);
$\frac{dx}{dt}$	:Dring rate ($kg_{eau} \cdot kg_{ms}^{-1} \cdot s^{-1}$)
h	:Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
K:	:Global heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
L_{tb}	:Length of the serpentine tube (m)
L_{vap}	:Latent heat of vaporization ($J \cdot kg^{-1}$)
m_{sech}	:Mass of the dry tomato (kg)
m:	:Mass (kg)
NUT	:Number of units and transfers
PCI	:Lower calorific value ($J \cdot kg^{-1}$)
P_{ev}	:Evaporative power (W)
S	:Area (m^2)
T_{enter}^{water} ; T_{out}^{water}	:Respectively the inlet and outlet temperatures of the hot water (K);
T:	:Température (K)
X_r	:Reduced water content
$\dot{m}$	:Mass flow rates ($kg \cdot s^{-1}$);

Greek Symbols

ϕ_i	:Source or sink of heat (W)
ϕ_{ech}	:Flow exchanged between the two fluids; (W);
ε_{exchn}	:Efficiency of the exchanger (%)
η	:Thermal efficiency (%)

Indices

g	:fins;
pr	:Product