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Dehydration of Agro Products in a Hybrid Solar Dryer Controlled through a Fuzzy Logic System

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Abstract

Drying is one of the most energy-intensive processes in agro-products industry. For this reason, using solar energy appears as an attractive not polluting alternative to be used in drying processes. However, the daily and seasonal fluctuations in the radiation level require using energy accumulators with phase change materials (paraffin wax), to have a continuous drying processes. In hybrid solar dryers with energy accumulation system, a control system is essential to coordinate the control valves that allow the income of air that comes from the solar panel or from the energy accumulator. In this work, we implemented an advances multivariable control system that uses fuzzy logic in the hybrid solar dryer. The dryer includes an energy accumulator panel with paraffin wax as phase change material. The input variables were ambient temperature and solar radiation, both not controllable. The controlled variables were the opening level of the solar panel and accumulator energy valves. The control program consisted in an algorithm implemented with the "Fuzzy" toolbox in Matlab. Data were acquired with OPTO 22. The control system performed adequately when used to dehydrate mushroom slices and plums. Closing or opening the respective valves as a response to the variations of solar radiation and ambient air temperature allowed optimizing the use of solar energy.

Keywords

Hybrid Solar Dryer, Fuzzy Logic, Control System, Mushroom, Plums

1. Introduction

1.1. Drying of Agro-Products

The main goal of drying of foodstuff is to reduce the moisture content of the solid up to a level where microbial

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growth and enzymatic reactions are minimum. Agro-products represent a significant part of the seasonal crops. In order to extend their shelf life, drying is a mayor technology; however, it implies high energy consumption [1]. The energy necessary for drying usually comes from fossil fuels, whose price is continuously rising. Drying consists in heat transfer from the heating source to the humid substrate, resulting in water transfer from the inner of the substrate to the surface, and then to the surrounding air [2]. The heat and mass transfer rates are closely related with the flow rate, temperature and relative humidity content of the drying air [3].

1.2. Solar Drying

Solar drying is the use of solar radiation as unique or partial energy source, in a drying process. Since ancient time, humanity used solar radiation to dehydrate and preserve food, initially by exposing directly the products to the sun. Using solar energy reduces the energy cost and additionally the CO_2 emission. In solar drying, the drying rate depends on non controllable external factors such as solar radiation, ambient air temperature, wind speed and relative humidity of the air. Besides it depends also on the substrate characteristics such as initial moisture content, physical properties and surface exposed to the drying air [4]. Direct exposure to sun is a very simple drying method, but does not allow managing the weather conditions, and therefore does not yield homogeneous and adequate quality products. In addition, since foods are exposed to radiation without any shield, contamination with insects, dust and microorganisms is frequent [3]. Some of those disadvantaged can be avoided with indirect solar dryers, where heating of the drying air occurs by passing through a solar panel and then coming in a drying chamber. Nevertheless the hindrance of solar radiation variations remains.

Solar dryers have lower operation costs with respect to conventional dryers, being an economically feasible alternative to conventional drying systems [5]. Using solar energy in a drying process of agroproducts can result in a reduction in energy consumption between 27% and 80%, depending on the type of dryer and the meteorological conditions [6]-[8].

Optimization of the cost associated to the usage of solar dryers requires an analysis of the local sola radiation, temperature and air relative humidity. The optimal drying period is of 8 hours for drying temperatures between 30˚C and 70˚C [9].

Smitabhindu [10] calculated the annual cost of drying per dry product unit (banana), optimizing of the geometry and operational parameters of the drying system aiming to minimize the drying cost.

1.3. Thermal Energy Accumulation

Thermal energy storage allows using solar energy in low or null radiation periods. This energy accumulation can be performed by storing sensible and/or phase change heat. Phase change heat present advantages due to its high heat density and a minimum temperature variation during charge and discharge periods [11].

Phase change materials (PCM) receive great attention in recent years for using them to store solar energy for industrial and household applications.

The latent heat of the accumulation system stores energy during fusion and delivers it during solidification of PCM. These materials are classified in organic and inorganic PCM. Organic PCM have the advantage of keeping their properties independently of how many times they melt or solidify [12].

In recent years several publications inform the use of PCM in solar equipments for drying of agroproducts [13] [14]. These systems have a higher energy accumulation capacity with respect to systems that store sensible heat [15] [16].

The choice of the most appropriate PCM should consider the cost, thermal conductivity (in liquid and solid phase), the energy storage capacity and the phase change temperature [17]. For drying of agroproducts, the preferred PCM is paraffin wax [15] [18].

In order to enhance thermal conductivity of paraffin wax, the encapsulation of PCM has been studied using different geometries being spherical the most promising [15] [19].

1.4. Fuzzy Logic

Classic automatic systems operate according to logic of fixed values, and do not allow representing intermediate values which are commonly found in real processes. Fuzzy logic theory permits automating the control of real processes through computer algorithms. In this work, an automatic system to control valves was implemented based on fuzzy logic theory.

Control strategies based on fuzzy logic is currently in development. Levente and Hungerbuhler [20] succeeded in the application of neural networks and a fuzzy model to quantify drying time and its variation during a production period.

Atthajariyakul and Leephakpreeda [21] determined the optimal drying conditions of rice in a fluidized bed, using a fuzzy logic control system, achieving a high quality substrate and an efficient energy consumption. Alvarez [22] applied a fuzzy logic system to drying of tobacco leaves, with good results.

2. Experimental

The hybrid solar dryer (HSD) (**Figure 1**) consisted of a 3 m length and 1 m width solar panel, composed by a glass sheet (2.5 mm thickness) and a black wavy zinc plate. To increase the expose surface 40 zinc fins (3 cm height and 3 m length) were introduced, then the total surface exposed to solar radiation was 10 m^2. Below this zinc plate it was placed a thermal insulating material (50 mm thickness). The air passes through the free space (30 to 50 mm height) between the glass and the zinc plate until reaching the mixing point with the recycled air (**Figure 2**). After that, the air enters the drying chamber (0.5 m × 0.5 m × 1.2 m), where it distributes to pass over 10 perforated plate trays made of stainless steel (0.45 m × 0.5 m), located in two sections of 5 trays each one (**Figure 3**).

The solar energy accumulator (**Figure 4**), placed beside the solar panel, contained 14 (kg) of paraffin wax (PCM) distributed in 100 copper pipes (inner diameter of 14 mm) with aluminum fins in order to favor heat transfer to the drying air. Fusion temperature of paraffin wax is 56˚C and a latent heat of 213 (kJ/kg). This panel is thermally isolated and the upper side has a 7 mm thickness glass cover.

The valve (6) regulates the air flow from the solar panel and valve (7) regulates the flow from the solar energy accumulator.

3. Implementation of OPTO22 Control System

OPTO22 allow monitoring data in real time by the PAC Display Configurator, which develops a graphical inter-phase [23].

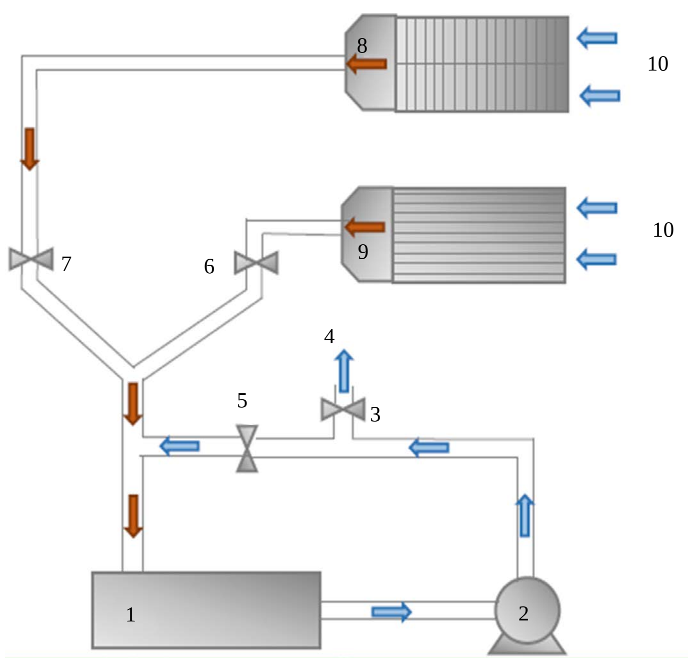

Figure 1. Hybrid-solar dryer. 1) Chamber drying; 2) Centrifugal fan; 3) Vent valve; 4) Vent; 5)Recirculation valve; 6) Panel valve; 7) Accumulator valve; 8) Solar energy accumulator; 9) Solar panel; 10) Air fresh inlet.

Figure 2. Solar panel.

Figure 3. Drying chamber with mushrooms.

Figure 4. Solar energy accumulator.

Implementation of the Valves Opening Controller

The control system regulates the air flow rate from the solar panel and form the energy accumulator. When radiation level and ambient temperature are high, the drying air is heated only by the solar panel; while simultaneously the PCM in the energy accumulator melts, thus storing the energy. As radiation decreases, the energy input from the solar panel is insufficient to heat the drying air. Then it is necessary to use the accumulated energy. To accomplish this, the fresh air passes through the accumulator [24].

The control program consisted in an algorithm implemented with the "Fuzzy" toolbox in Matlab™. The necessary rules were based on previous experimental data obtained with the hybrid solar dryer. **Table 1** shows nine rules that combine the radiation variable and ambient temperature, both in three levels (high, medium and low). Also the valves of the solar panel and the accumulator were adjusted to high, medium or low levels (**Table 1**).

Among the membership functions offered by Matlab we selected trapezoidal (trapmf), Gaussian (gaussmf) and triangular (trimf). The membership function and the parameters of each input and output variable were selected based on empirical knowledge of the hybrid solar dryer.

Each variable has its own membership function. Radiation is an input variable that fluctuates between 0 and 10000 (0 - 1200 (W/m^2)). The parameters are given in **Table 2**.

The ambient temperature is an input variable and fluctuates between 0˚C and 40˚C. The parameters are given in **Table 3**.

Panel valve and accumulator valve are output variables that fluctuate between 0 and 100. The parameters are given in **Table 4**.

Table 1. Rules for the fuzzy logic controller.

Radiation	Air temperature	Panel valve	Accumulator valve
High	High	High	Low
High	Medium	High	Low
High	Low	High	Low
Medium	High	High	Low
Medium	Medium	High	Low
Medium	Low	High	Low
Low	High	High	Low
Low	Medium	Medium	Medium
Low	Low	Low	High

Table 2. Membership function for radiation.

Level	Type	Parameters
Low	trapmf	[−200; −100; 200; 3000]
Medium	gaussmf	[1000; 4000]
High	trapmf	[5000; 7000; 20,000; 25,000]

Table 3. Membership function for ambient temperature.

Level	Type	Parameters
Low	trapmf	[−10; −5; 20; 25]
Medium	trimf	[22; 25; 28]
High	trapmf	[25; 30; 45; 50]

Figure 5 depicts a scheme that represents the main steps of the control system. First, OPTO22 takes in the variables values and send them to the Matlab algorithm. After that, the control strategy is built in Simulink™, which sends the signals that order the opening of the valves. Finally, OPTO22 operates as final control element.

4. Results

4.1. Control of the Valves Opening

Figure 6 shows the behavior of the accumulator and panel valves as a function of solar radiation and ambient temperature in time. These data correspond to January 22th, 2013, starting at 9:30 (corresponding to time 0 hours) and 21:30 (corresponding to time 12 hours), in a sunny day with a maximum solar radiation of 900 (W/m^2) and a maximum ambient temperature of 30˚C.

In the first 8 hours the solar panel valve was completely open, while the accumulator valve was completely closed. In this period the paraffin wax melted owing to the solar energy absorption. From the 8th hour until the 10th hour the panel valve begins to close and the accumulator valve opens gradually. In this period the stored energy is withdrawn by the drying air. Then the drying air temperature equals ambient temperature.

Table 4. Membership function for panel valve and accumulator valve.

Level	Type	Parameters
Low	trimf	[−40; 0; 20]
Medium	trimf	[10; 50; 90]
High	trimf	[80; 100; 140]

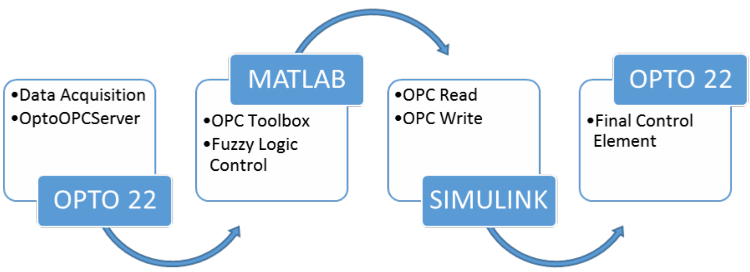

Figure 5. Fuzzy logic control system.

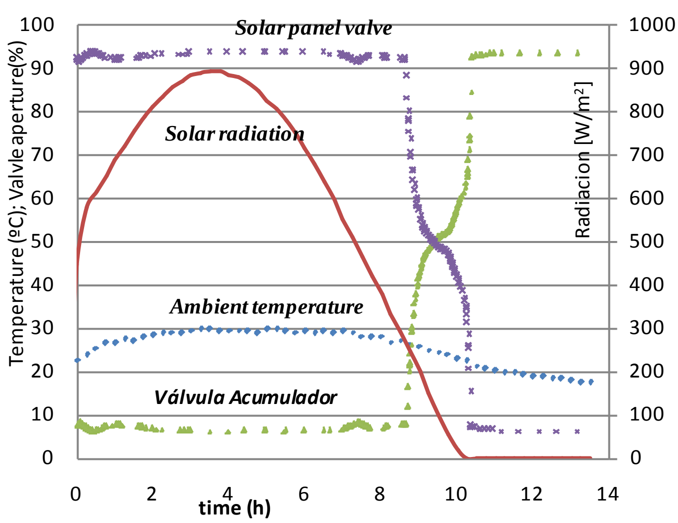

Figure 6. Behavior of the accumulator and panel valves in a sunny day.

Figure 7 shows the behavior of the accumulator and panel valves in a partially cloudy day. These data correspond to January 21th, 2013, from 9:30 to 21:30, where radiation reached 400 (W/m^2) and an ambient temperature of 27˚C.

The opening of the valves followed a trend according to solar radiation level. After the first hour of drying, solar radiation decreased sharply, observing a notorious change in valve opening. From the 6th hour onwards radiation decreased up to 300 (W/m^2) and again the valves change their opening level.

4.2. Mushroom Drying

In order to evaluate the performance of the hybrid solar dryer using the fuzzy logic control system, 8-mm mushroom slices were dehydrated using only solar energy. Initial load was 15 (kg) and the drying period was 11 hours, diminishing the moisture content from 93% to 6% (**Figure 8**).

The fuzzy logic controller adequately controlled air flow rate (**Figure 9**). During the first 8 hours, fresh air was heated only with the solar panel, and afterwards during the 3 final hours the drying air was heated with the panel and solar accumulator, as shown in **Figure 6**.

Figure 10 shows that in the solar panel the air reaches a maximum temperature of 70˚C and an average temperature of 58˚C during the first 8 hours. After that, the accumulator valve starts to open, thus increasing the temperature of the fresh air that passes through the accumulator panel in 15˚C above the ambient temperature. The stored energy allowed heating the air during 3 hours. Finally, **Figure 11** shows the drying kinetics of mushroom slices.

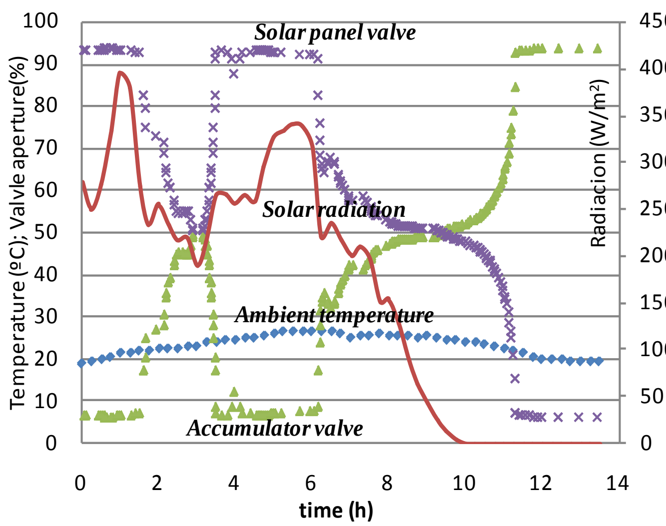

Figure 7. Behavior of the accumulator and panel valves in a partially cloudy day.

(a) (b)

Figure 8. Mushrooms. (a) Fresh; (b) Dehydrated.

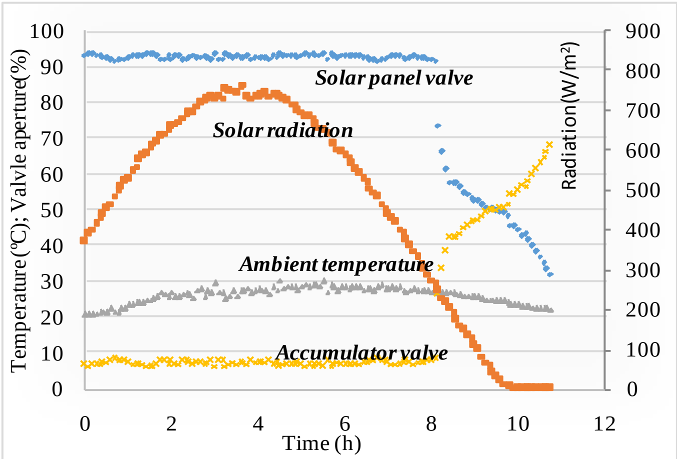

Figure 9. Behavior of the accumulator and panel valves during mushroom drying.

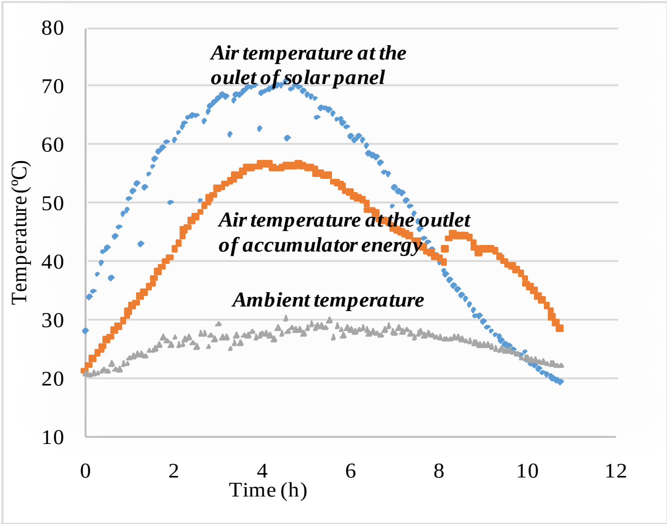

Figure 10. Temperature in the outlet of the solar panel and energy accumulator, during mushroom drying.

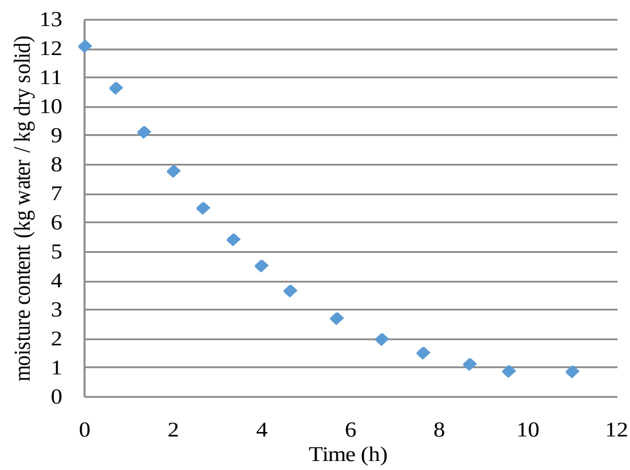

Figure 11. Drying kinetics of mushroom slices, using control system.

4.3. Plum Drying

Charges of 10 kg plums were dehydrated using only solar energy to heat drying air. The total drying period was 10 hours, coinciding the first 7 hours with the highest solar radiation period, and after that (the last 3 hours) the energy was taken from the solar accumulator. The initial moisture content of plums was 80%, reaching a 71% after 10 hours of drying. Plum skin avoided a higher moisture loss in this period. Since the final moisture is too high for preservation, the drying process should continue in the following days.

As shown in **Figure 12** and **Figure 13**, fuzzy logic controller used to regulate the fresh air flow together with worked adequately together with the sir humidity controller at the outlet of the drying chamber. This allowed an efficient use of solar energy. In this application, the air flow controller showed a similar behavior to that observed in mushroom drying.

Figure 13 shows that during the first 7 hours, the air at the outlet of the solar panel reached a maximum temperature of 72˚C, and an average of 59˚C. After that the solar accumulator valve begins to open, thus increasing the fresh air temperature in 13˚C above the average ambient temperature.

The fluctuations of the air temperature at the outlet of the solar panel (**Figure 10** and **Figure 13**) obey to the regular opening of the drying chamber for sampling.

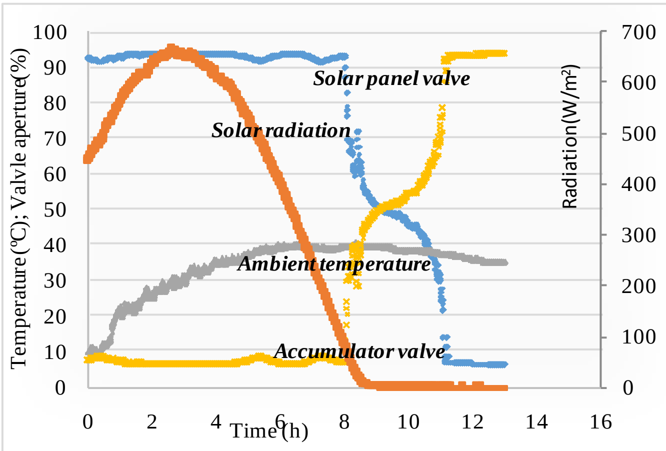

Figure 12. Behavior of the accumulator and panel valves during plum drying.

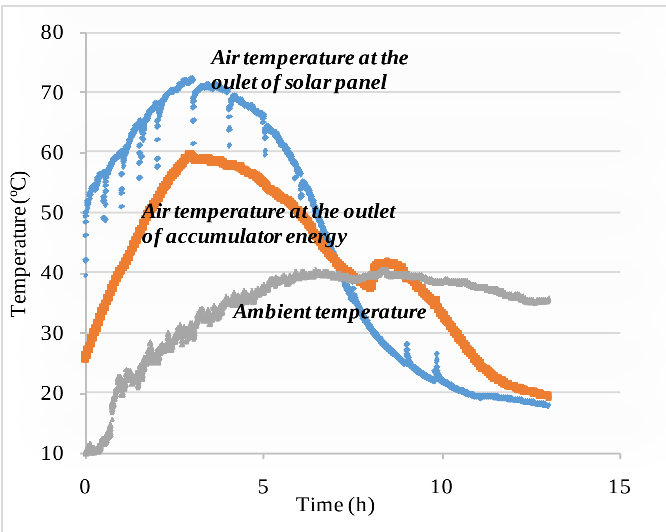

Figure 13. Air temperature in the outlet of the solar panel and energy accumulator during plum drying.

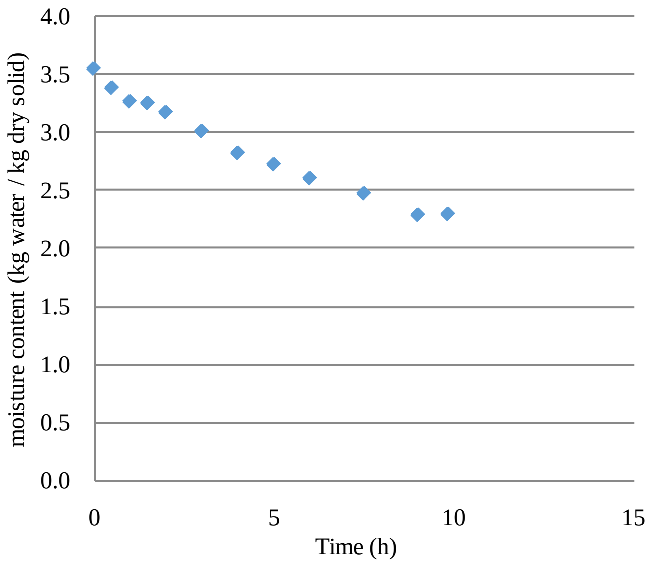

Figure 14. Drying kinetics of plum.

Comparing mushroom (**Figure 11**) and plum (**Figure 14**) drying, the first reached lower final moisture content due to the plum skin that acts as an impermeable barrier, obstructing water pass.

5. Conclusions

We implemented an advanced control system based on fuzzy logic in a hybrid solar dryer to control the opening of solar panel valve and energy accumulator valve in function of solar radiation and ambient temperature.

The fuzzy logic controller performed adequately during the drying of mushroom slices. This resulted in an increase of thermal efficiency of the process. During 11 hours of drying, the moisture content of slices mushroom diminished from 93% to 6%. During 10 hours of drying, the moisture content of plum diminished from 80% to 71%.

The communication system based on OPC technology works in a very good way for programming fuzzy logic control implemented in Matlab with the data acquisition program OPTO22.

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