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Application of a multi-model control with TS fuzzy switching to an indirect solar dryer operated in natural convection

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Abstract: The modeling techniques are usually required to develop and analyze the performance and to predict the response of solar devices under intermittent solar radiation. This work concerns a solar dryer without any secondary energy input. The device consists on a flat plat solar collector (1m*2m), and a drying chamber (1m*1m*1m). In addition to moisture, the temperature of the drying chamber is one of the principal important parameter that affects the drying rate, the quality of dried product and the efficiency of the process. Experimental measurements of the temperature inside the drying chamber were conducted in natural convection at various solar radiation throughout the winter and summer seasons. The highest chamber temperature reached was 61°C in a clear sky in winter day (Ta=25°C) and 68°C during sunny day in summer (Ta=32°C). Linear models of the solar dryer at every atmospheric condition were estimated and the error was estimated at 2%. The TSK-Fuzzy inference system is used to estimate accurately the real-time parameters of the global solar dryer model. The fuzzy model planned for this study gives a good prediction of the drying chamber temperature. The error remains under 1°C and confirms the pertinence of the identified TS model for such process.

Key words: Renewable energy, natural convection, solar dryer, fuzzy, modeling, solar collector.

1. Introduction

Drying technology is used for many products and in many processes. In agriculture, drying is usually needed to preserve food, fruits, seeds, medicinal plants, vegetables and industrial manufacturing as well. These products are very rich in various vitamins and mineral salts and are the major source of these nutrients for the human alimentary.

These products are harvested with a very high rate of moisture which leads to lose a large amount of them by decay. Whatever, to preserve these products we should reduce their amount of moisture. Solar drying is one of the most important potential applications. In addition, more than 80% of the food is being produced by small farmers in developing countries and especially in the Maghreb [1]. In these countries, small producers need agriculture equipment with autonomous energy and with low investment and maintenance and easy to operate. Solar dryers are suitable for this issue [2].

On the other hand, the preservation of the quality becomes more and more important in the processing of agriculture product [3]. Drying was practiced since the ancient time and direct solar drying was used for drying food [4]. This method is practiced by simply exposing the product to direct radiation of sunlight. Thus, the product is posed directly on the floor or on mats, on the rocks and on the roofs houses. However, in this method color, quantity and quality of the product degraded. This process is not very hygienic. Now this technique is avoided by using an indirect solar dryer where the air is heated by a solar collector separated or combined with a drying chamber, the product remains in shadow and isolated from the sunlight. The drying process occurred by the exchange of water between products and hot air. This indirect solar dryer represents a promoter solution view to its ability to keep the products to be dried away from dust and preserves not only their color but also their active principles in order to maintain its position and conquer new markets.

Let's present here the main works achieved in modeling methods for drying process. Scientist are widely interested in modeling of the solar dryers as the number of published paper on the subject do not cease increasing since the last decade, especially those related to indirect solar dryers. Modeling techniques are very important for a description of systems behavior in experiments. Indirect solar dryers are modeled in various techniques as follow [5]: computational fluid dynamics (CFD), artificial neural network, an ANFIS, FUZZY, thermal modeling, mathematical modeling, drying kinetics model etc.

CFD is related to fluid mechanics, it is a software that is used to simulate the interaction of air flow and movement inside the drying chamber [6] and to predict the drying efficiency [7].

Thermal modeling analysis of a range of parameters such as air velocity, solar radiation and the pressure drop of the absorber is studied by [8]. Perforation and the pitch diameter were also considered for the study of thermal modeling of a solar dryer [9].

In other works, MR Equations (Root Mean Square Error and Reduced Chi-Square [10]) are used to calculation of the moisture ratio in a drying process at various relative humidity of the drying air [11]. Dejchanchaiwong, R., Arkasuwan, A. in [12] established a mathematical modeling to investigate the performances of a mixed mode and indirect solar dryers for natural rubber sheet drying.

The drying kinetic modeling is completely applied in drying constant for the case of food drying; it has been depended to a constant relative humidity, measured the condition of the temperature and associated to the parameters of the drying chamber [13]. The kinetic modeling is tested to dry apricot [14], black tea [15], and plum [16].

Whereas, Fuzzy modeling is done in many various field as for heat solar systems. Fuzzy logic modeling is based on input and output data, applied for non-linear multi-input and multi-output systems. Fuzzy modeling is enhanced considerably since the first established and using by Zadeh [17]. The advantage of fuzzy logic is to accurately predict the results with minimum error. The fuzzy model is also being extended to different places consistent to different weather conditions, mainly ambient temperature, solar radiation, and relative humidity [18]. Fuzzy model was used to predict the performance of a solar crop dryer [19]. In previous work, [20, 21] a fuzzy control algorithm is experimented on the reformulated solar dryer model for prediction of energy efficiency of a solar dryer. A fuzzy model was also developed to determine and calculate the temperature of jaggery and the moisture evaporated from the air of greenhouse, on the basis of intensity of solar radiation and ambient temperature.

In this paper, fuzzy (Tkagi-Sugeno) is proposed to predict the thermal properties of air heated by solar collector in the drying cell. The Fuzzy rules are generated by the temperature measurements in the drying chamber for various solar radiations and ambient temperatures.

After a brief presentation of the solar dryer, experimental measurements in the drying chamber related to different solar radiation and ambient temperature are presented. Then, TSK inference system for predicting the model parameters of solar dryer is developed. Lastly, the performances of the TSK system are investigated experimentally under different operational conditions to validate the model.

2. Experiments

The solar collector consists of two parts: the solar collector, where the air used in the drying process heated, and the drying chamber where the material to be dehydrated is placed in trays. Air is heated throughout the day in the solar collector.

2.1. Solar collector

The solar collector is a finned plate solar air heater, the absorber's length is L=2m and its width is W=0.95m and it is made from aluminum, the top side of the absorber is painted with matt black glycerophtalic lacquer, the number of fins is 24 and they are made from aluminum with 0.001 thick. The glass cover is 0.003m thick with a separation of 0.05m with the absorber. The collector is stationary, with a tilt angel of 30° with respect to horizontal. The bottom and sides are isolated with the mineral fiber, 0.05m thick **(Fig.1).**

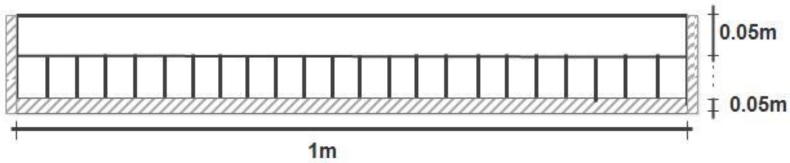

Figure 1: Frontal section of the solar collector

2.2. Chamber drying

The drying chamber was built with a steel structure, the walls were made from a steel sheet metal and were isolated by mineral fiber, the total capacity of the drying chamber **(Fig.2)** is 4 trays and each galvanized steel mesh tray has a drying area of $0.94m^2$.

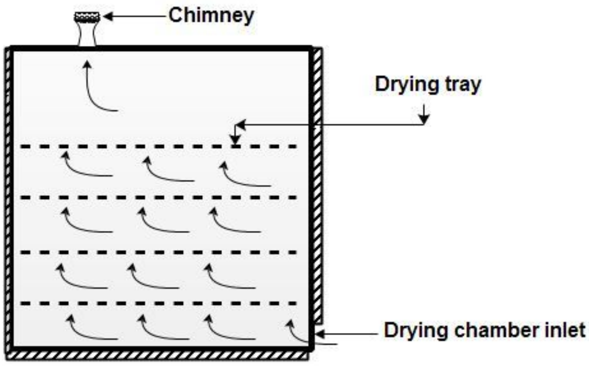

Figure 2: Diagram of drying chamber

3. Materials and methods

Temperature, relative humidity and solar radiation were recorded every 10 min during two hours (11h-13h), in order to guaranty a probably constant ambient temperature and solar radiation. Temperature sensors (TM110 pt100, 0.5°C accuracy) were placed outside and inside the chamber drying. Three pt100 sensors were distributed in the middle of drying chamber. Two other pt100 sensors were utilized for measuring the ambient temperature. Four hygrometer sensors (HM-110, 0.5% accuracy) are used for measuring relative humidity. Two of them are used for the ambient relative humidity measurement, and two others are used in the drying chamber. Incidence global solar radiation was recorded locally using a Keep and Zonnen pyranometer with a sensitivity of 14.69 E10^{-3} mV. Experimental setup is shown in the next pictorial view **(Fig.3)**.


Figure 3: view of the experimental setup of the solar dryer

4. Results and discussion

4.1 Behavior of the solar dryer in winter season

Measurements carried out in winter season (12 and 16 on December 2016 and 5, 18, 19 and 25 on January 2017) in order to study the behavior of our dryer under various weather conditions. At first, the temperature of the drying chamber was considered the principal parameter to control. In the solar air heater, the temperature grows up in the same trend as the global irradiance incident on the collector. The dyer remains in shadow for 10 min and immediately exposed to solar radiation for 2 hours at 11 am. The highest air temperature reached in cell chamber was previously spotted between 11am and 13 pm. During this period, solar radiation and ambient temperature can be assumed constants.

In winter, the highest drying temperature reached is 61°C under solar incidence 960W/m^2 for the ambient temperature of 25°C **(Fig.4 a)**, and 57°C at a solar radiation of 800W/m^2 and 25°C ambient temperature **(Fig.4**

b). The ambient relative humidity recorded is 54% and the drying chamber relative humidity decreased from 36% to 5% under the growing temperature **(Fig.6 b)**.

In a partly cloudy day, The drying chamber temperature reached 47°C and 42°C under solar radiation and ambient temperature of 660W/m^2, 25°C and 460W/m^2, 23°C respectively **(Fig.4 c ,d)**, and the relative humidity inside the chamber drying decreased from 35% to 10% under increasing temperature **(Fig.6 d)**.

Experimental measurements are carried out also in a period of inclement weather, and air temperature inside the drying chamber was recorded is 15.5°C with an irradiance of 60W/m^2 and an ambient temperature of 12°C as shown in **(Fig.5 b)**. The ambient relative humidity recorded is 78% and the drying chamber relative humidity decreased from 68% to 58% **(Fig.6 b).**

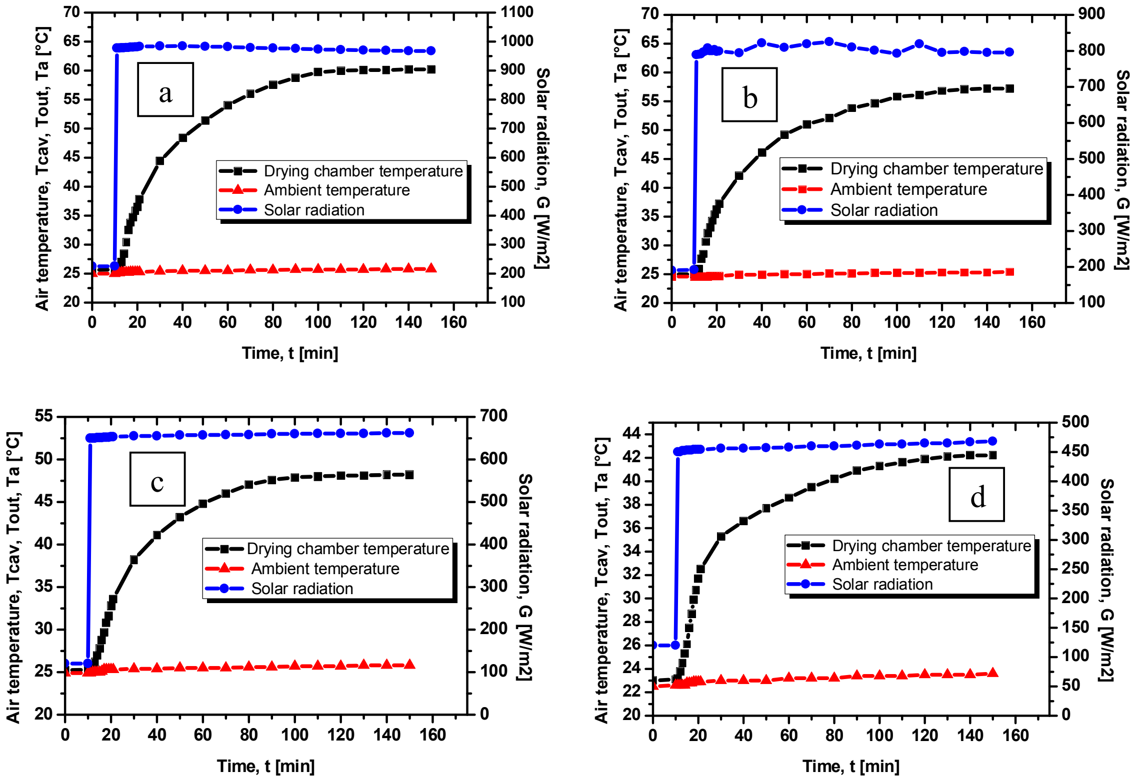

Figure 4. Solar intensity and temperature variation inside the dryer. (a) sunny day, (b) clear day, (c) partly cloudy day, (d) cloudy day.

Measurements are also carried out in a sunny day at a solar radiation of 1000W/m^2 and a low ambient temperature of 15°C in order to figure out the behavior of the dryer in such a weather conditions **(Fig.5 a)**. It's observed that the highest temperature reached inside the drying chamber is 57°C.There is a significant temperature difference (42°C) between drying chamber and ambient temperature.

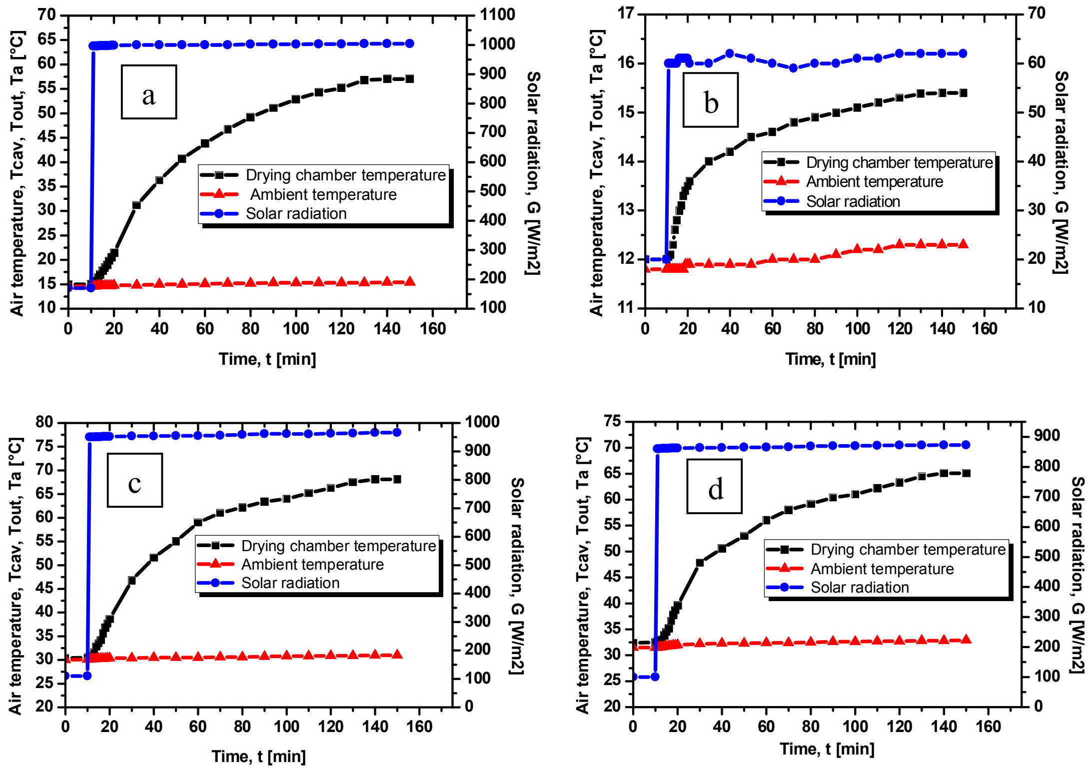

Figure 5.Solar intensity and temperature variation inside the dryer. (a) sunny day, (b) inclement day

4.2 Behavior of the solar dryer in summer season (Table)

Experimental measurements are also performed for 19, 20 days on August 2016 during the summer season. As shown in **(Fig.5 c)** and **(Fig.5 d)**. The experimental results are shown in Table 2.

Table 2. Drying chamber temperature on the basis of solar radiation and ambient temperature.

Solar radiation	Ambient temperature	Ambient relative humidity	Drying chamber temperature
960W/m^2	32°C	36%	68°C
860W/m^2	30°C	39%	65°C

The average ambient relative humidity recorded was 39% and the drying chamber relative humidity decreased from 28% to 3.5% as shown in **(Fig.6 a)**.

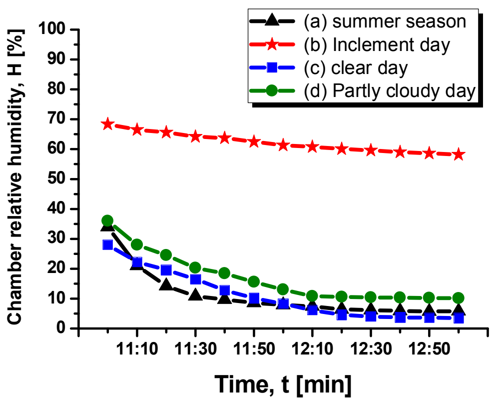

Figure 6. Drying chamber relative humidity variation.

5. Solar dryer modeling

According to several experimental measurements conducted on the solar dryer at various weather conditions, it's obviously observed that the behavior of the dryer operated in natural convection is directly affected by solar radiation and ambient temperature as input variables.

5.1 The linear solar model

The dryer dynamic response can be represented by different types of models. It depends on the weather condition.

Table 1. Second order model parameters based on weather condition

Natural convection								
C_i	Solar radiation / ambient temperature							
	$1000W/m^2$ 15°C	$960W/m^2$ 25°C	$800W/m^2$ 25°C	$660W/m^2$ 25°C	$460W/m^2$ 23°C	$60W/m^2$ 12 °C	$950W/m^2$ 32°C	$860W/m^2$ 30°C
a	$1.823\ 10^{-5}$	3.609e-5	4.98e-5	3.33e-5	6.516e-5	0.0001021	2.142e-5	2.138e-5
b	1.939e-8	4.82e-8	7.006e-8	6.421e-8	4.263e-8	6.286e-8	1.458e-8	9.799e-9
c	0.001602	0.003186	0.004236	0.003574	0.00325	0.004067	0.001371	0.001244
d	$4.358.10^{-7}$	1.251e-6	1.703e-6	1.804e-6	9.81e-7	1.038e-6	3.513e-7	2.332e-7

The approximation of a high order system by one of a lower order is highly advantageous as it reduces the computation time of the transient response and thus useful for the controller design and control system analysis [22]. The cost and the complexity of the controller increase in direct proportion to the system order.
Using the experimental setup described previously, some experimental measurements were needed to give a general idea about the influence of different inputs (solar radiation, ambient temperature) on the behavior of the solar dryer, also to evaluate the simplest representation that should be associated to the dryer. Several measurements were conducted on the dryer in a clear day, partly cloudy day, cloudy day and inclement day in natural convection as shown in (**Fig. 6, 5**). In each case, the obtained response is similar to that of a second order response where the parameters (a, b, c, d) change according to solar radiation, ambient temperature.

The solar dryer system is a complex non-linear system [23]. However for each weather condition and operating mode, the dryer can be represented by a second order system as shown in **Fig. 7**, where G is the solar radiation and Ta is the ambient temperature.

The model represented here is based on a relative simple linear model which is sufficient to represent the dynamics of the dryer response in each weather condition. The measured inputs and outputs were loaded into the system identification Toolbox of Matlab environment (using ident) in order to identify the transfer function coefficients. The system identification provided using Matlab allows the building of mathematical models of a dynamic system based on measured data.

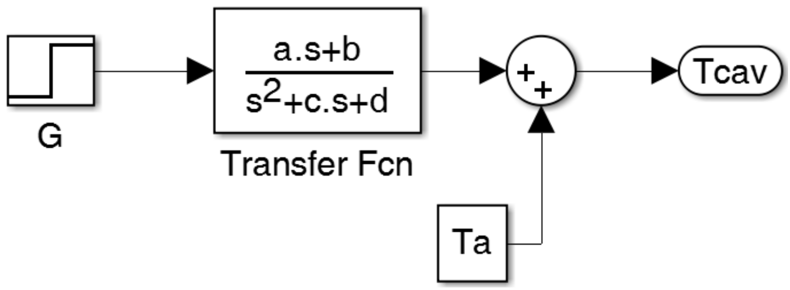

Figure 7. Simplified representation of the solar dryer at each weather condition.

The coefficients (a, b, c, d) were computed using the measured data obtained for different solar radiation and ambient temperature. Table. 1 gives the identified coefficients of the second order transfer function for eight solar radiations and ambient temperatures. From Table. 1 the non-linear evolution of the coefficients (a, b, c, d) can be remarked, which confirm that is impossible to represent the solar dryer by the same second order model for different weather conditions. To overcome this problem a Takagi-Sugeno fuzzy system is proposed to be used in order to obtain a global model of the dryer.

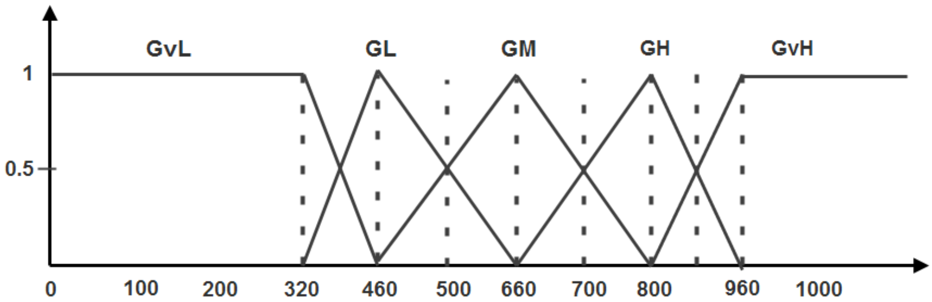

Figure 8. Generated member functions for solar radiation

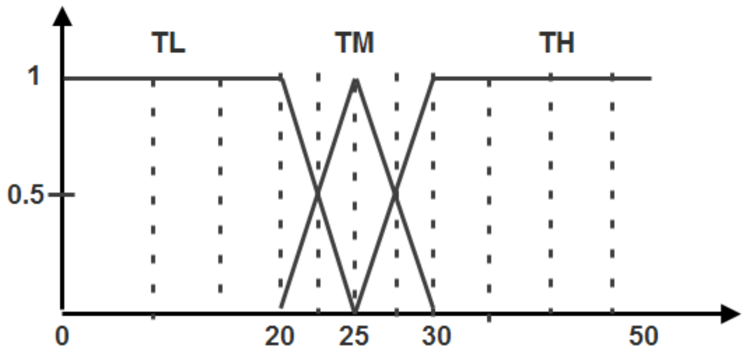

Figure 9. Generated member functions for ambient temperature

5.2 Takagi-Sugeno fuzzy model

In the last decade, the application of artificial intelligence in modeling to other scientific and engineering disciplines has been successfully explored. In the case of solar dryers still an opportunity to develop such models reliability [24]. Fuzzy modeling is supposed adequate for situation where there is a large uncertainty or unknown variation in the dryer parameters. The Takagi-Sugeno (TS) fuzzy model is a notable way to describe a non-linear dynamic system using local linear models.

We present this paper to introduce The TS fuzzy systems approach in order to develop explicit models of the dryer taking into account the non-linear relationships between the dryer two inputs (solar radiation, ambient temperature) and the output (drying chamber temperature). A TS fuzzy model using fuzzy if-then rules is built from obtained parameters of a linear model for some weather conditions.

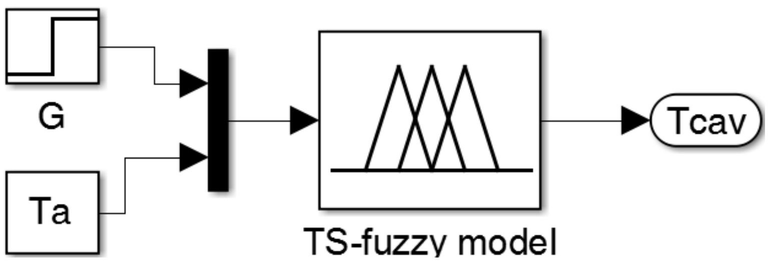

Figure 10. TS Fuzzy model of solar dryer.

Figure. 8 shows the five generated membership functions corresponding to the dryer parameter (G) characterizing solar radiation. The generated membership functions corresponding to the fuzzy sets of the dryer parameter (Ta) characterizing variation of the ambient temperature is shown in (**Fig. 9**). Using the fuzzy rules, the appropriate TS fuzzy model's output (drying chamber temperature) is estimated according to the associated linear model. (**Fig. 10)** shows the used simulink block to represent the studied dryer.

The application of fuzzy modeling provides a good estimation of the dryer behavior for all combinations of solar radiation and ambient temperature. This implies that for any weather condition variation, the TS fuzzy model approximates the appropriate linear model of the system. The TS fuzzy inference engine combines the local linear models according to input vectors in order to find a proper model of the system capable of generating the appropriate output.

6. Experimental validation of the solar dryer model

The reliability of the model performances was evaluated by comparing the predicted drying chamber temperature with experimentally measured one.

To inspect the validity and effectiveness of the proposed model, experimental measurements were conducted during the first and 20 January 2017 days. The first day corresponds to an inclement weather at a solar radiation of 250W/m^2 and an ambient temperature of 12°C, **(Fig.11 b)**. Whereas the second day is related to a sunny day with a solar radiation of 820W/m^2 and ambient temperature of 25°C **(Fig.11 a)**. The experimental measurements of the drying chamber temperature are compared with the predicted by the proposed model.

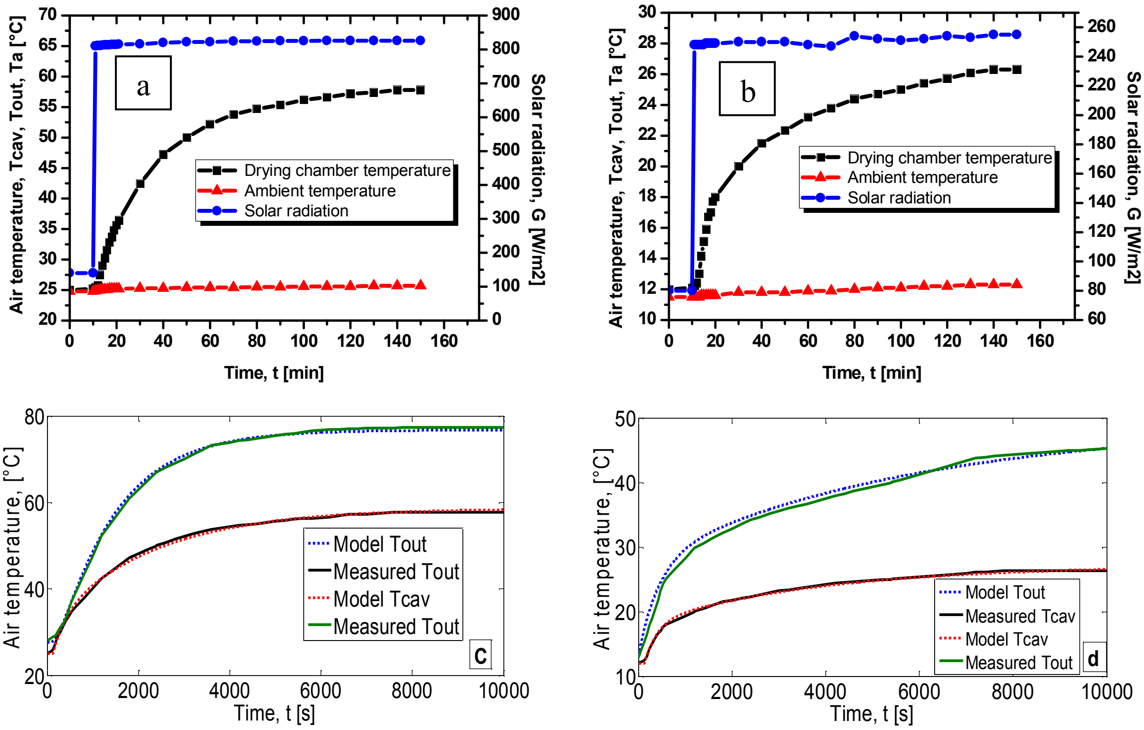

Figure 11. Validation of the constructed model of the dryer for different weather condition. (a,c) clear day, (b,d) inclement day.

The resulting drying chamber temperature versus time plot at various weather conditions are given in **(Fig. 11 c).** In this figure, solid lines present the predicted response and the dashed lines present the experimental ones. The simulation results and the experimental ones are in close accord confirming the appropriate approximation of the identified TS fuzzy model. The same deduction is available in the inclement day weather **(Fig. 11 d).** These results confirm the pertinence of the identified TS fuzzy model.

Conclusion

In this study, an indirect solar dryer behavior operated in natural convection at various weather conditions has been reported. In order to well describe the solar dryer behavior, several experimental measurements were conducted in the drying chamber on the basis of solar radiation and ambient temperature. Linear models of the solar dryer are further estimated using system identification toolbox in Matlab, at each weather condition. Error estimations were 2%. TSK-fuzzy system has been proposed to accurately estimate the dryer model parameters at each case. The TS fuzzy was validated by comparing the predicted drying chamber temperature against the experimental one. Two response models reveal the best curve fitting for the experimental drying chamber temperature. The error remaining under 1°C and thus confirming the pertinence of the identified TS model. It may be concluded that the predicted drying chamber temperature adequately explained the solar dryer behavior at various weather condition throughout the seasons of the year. The fuzzy system model leads to judge either such a drying temperature is sufficient for drying a wide variety of vegetable products with high humidity content, without incurring thermal damages.

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