Development of a Household Scale Solar Dryer: Performance Evaluation and ARX Modeling

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Abstract

This paper compared the results of an actual experimental study and an ARX modeling study on the performance of a household scale solar dryer. This is a low-loading capacity dryer for drying bananas for household consumption and not for commercial production. The ARX model is simple but is more complete than a normal auto-regressive models because it can be based not only the previous time-series data, but also on exogenous variables. The ARX model prediction of the moisture content of the bananas compared with the experimentally measured values was good. Hence this model can be applied in predicting operational performances and in designing the controllers for drying processes.

Keywords:

Household Scale Solar Dryer, Drying of Banana, ARX Modeling, Experimental Performance

1. Introduction

Solar drying of agricultural products can be an efficient way for removing moisture from wet products [1-2]. An equipment which uses solar energy for drying products is commonly called "solar dryer". In the past 60 years, many types of solar dryer have been developed [3-10]. In terms of loading capacity, these dryers can be broadly divided into two categories [11]. The first category includes small-scale solar dryers with low loading capacity (a few kilograms), and the second category are the large-scale solar dryers with high loading capacity (more than 100 kg). For the low loading capacity dryers, their developers usually claim that the solar dryers can still be used in the field despite of the low capacity [7]. The small-scale solar dryers are impractical for applications in the field due to the limited capacity [12]. In addition, the technical designs are usually not suitable even for drying for family consumption.

In Thailand, the number of middle-class people is rapidly increasing [13]. These people usually use refrigerators to preserve food. Some also use drying to preserve food. Some people dry fish, which can then be cooked later. But usually, food drying is not only for preservation, but also for modifying the taste and texture of food to make them more delicious. In many places, excess fresh bananas are dried to be eaten as snacks, mainly for household consumption. Natural sun drying is usually employed for drying fish, bananas, and other food products in this country.

Natural sun drying is cheap; however, the products being dried usually get damaged by rainfall, and by the feeding of insects and animals.

To solve these problems, it is necessary to develop an efficient dryer for household use. But previous development work on solar dryers for a household use are extremely limited [14]. Very few household dryers are in use today. As Thailand is in the equatorial zone with abundant solar radiation, the use of solar dryers to dry products for household consumption has high potential.

Modeling can be an important tool for developing efficient dryers. There are several studies done on modeling the solar drying of fruits [15-16]. Modeling methods include classical mathematical modeling, artificial neural network and ARX modeling.

The ARX modeling has an advantage as it is based only on experimental data, but requires less experimental data, as compared to other similar methods. The ARX modeling is common in control engineering design work. Recently ARX modeling has been used for short-term electric load forecasting, and in prediction of thermal and cooling loads in buildings [17-19]. Casanova-Pelaez et al. [20] reported an ARX model to help control the drying process for olive pomace using an industrial furnace. To the best of our knowledge, no study on ARX modeling of drying of fruits in solar dryers has been reported.

In this study, we developed a household scale greenhouse solar dryer for bananas. The actual performance of this dryer was then evaluated with the use the ARX model.

2. Materials and methodology

2.1. Design of the dryer

The dryer proposed in this work is for a middle-class family living in a city or a town and they could buy fresh banana from a fruit market to make dried banana for household consumption, not for industrial production of dried banana for sale and a middle-class family has generally limited space for placing a dryer. According to our observation, a middle-class family in Thailand want to make 1-1.5 kg (1-2 dried banana packages) of dried banana for household consumption which come from about 4 kg of fresh banana (1-2 hands of banana).

Based on this information, we set up the loading capacity of the dryer at 4 kg with the dryer designed mainly for drying bananas for household consumption. Based on information on commercially-sold dried bananas, the initial moisture content of fresh bananas is 70% (w.b.) and that of the dried bananas is 20% (w.b.) [21]. From these data, the mass of water to be removed from banana is approximately 0.9 kg, and thermal energy needed for this is 2.35 MJ/kg of water.

The area for receiving solar radiation (A_c) can be approximately calculated from the equation proposed by Janjai and Keawprasert [22] below:

$$A_c = \frac{Q_{drying}}{\eta H_T N_d} \quad (1)$$

Where η is the efficiency of the dryer to convert solar radiation into thermal energy, H_T is yearly average daily solar radiation on horizontal surface, N_d is the number of days required to dry banana and Q_{drying} is thermal energy required for removal of water from the product. η is assumed to be 0.05, H_T is equal to 18.2 MJ m^{-2} day^{-1} [23] and N_d is 4 days, the normal practice for banana drying. With these values, Eq. (1) gives the value of A_c to be 0.44 m^2.

Due to the availability of the materials for constructing the dryer, the dryer was built with a width of 0.75 m and length of 1.20 m. To prevent the spoilage of the product being dried during adverse weather conditions, an 800 W infrared radiation (IR) electrical heater was installed inside the dryer to supply thermal energy if there will be adverse weather conditions.

As a ventilation system is needed for the dryer, two 12V DC (14.4 W) fans powered by a 10 W-solar cell module were used to suck humid air inside the dryer to the outside environment. The dryer was covered with a solid polycarbonate sheet with a thickness of 3 mm.

The sheet has visible transmittance of 0.85 and its transmittance for infrared radiation is 0.2. With this high solar radiation transmittance and low infrared transmittance, good greenhouse effect was consequently created inside the dryer. The floor of the dryer was made of a black-painted iron sheet with insolator at the outer surface of the sheet.

A product tray was placed 5 cm above the floor. The whole dryer was placed on top of a rolling cart. A picture of the dryer is shown in Fig. 1 and its schematic diagram shown in Fig. 2.

Fig. 1 Pictorial view of the dryer.

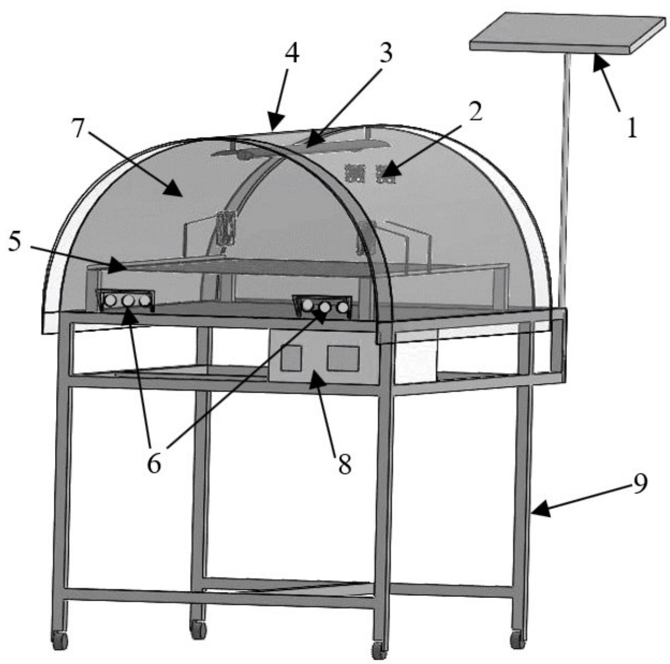

Fig. 2 The schematic diagram of the dryer: 1. Solar cell module 2. DC fans 3. Infrared heater 4. polycarbonate cover 5. trays 6. air inlet 7. Door 8. Electrical controller 9. Rolling cart.

2.2. Actual Experimental Study

The household solar dryer was placed on the rooftop of the Science Building 3 of Silpakorn University in Nakhon Pathom, Thailand. Twenty-four sets of solar drying experiments for bananas were conducted from 5 June to 8 November 2019 to demonstrate and test the performance of the dryer. The results were then compared with the results of the ARX modeling study.

The fresh bananas used for the experiments were bought from a market in Nakhon Pathom. For each set of experiment, bananas were first placed inside a room at an ambient condition to achieve the equilibrium moisture condition at ambient temperature and relative humidity, before starting the solar drying experiment. About 4 kg of peeled bananas were placed on the tray inside the dryer at 8 AM. Drying was done till 6 PM. Control samples consisting of 1.5 kg of bananas, with initial moisture content under similar ambient condition as those dried inside the solar dryer, were put outside for normal sun drying.

Solar radiation was measured using a pyranometer having an accuracy of ± 0.5% (Kipp & Zonen, model CM 11). Drying temperatures were monitored by using a thermocouple (K type) connected to a data logger (Yokogawa, model DC100) with the data sampling interval of 10 minutes. The relative humidity of the air was periodically measured by hygrometers (Electronik, model EE23, accuracy ± 2%). The weights of the bananas were recorded using an electronic balance (Kern, model 474-42, accuracy ± 0.1 g) at intervals of one hour. The moisture content of the bananas was determined using the air oven method at a temperature of 103 °C for a period of 24 hours.

2.3. ARX Modeling Study

ARX means Auto-Regressive with eXogenous input. The modeling study considers a black box, which can be viewed in terms of the input, output, and transfer characteristics even without the knowledge of the internal working processes.

Although classical mathematical models can be used to simulate a solar dryer, the ARX model was to provide a better insight and greater understanding of the drying process, as it is difficult to determine the system parameters for modeling a dryer. The ARX approach, being commonly used in control engineering for the design of controllers, can be used to model a dryer. This approach is simple and does not require the estimation of the system parameters.

But the ARX modeling is more complete than a normal auto-regressive models because it can be based not only the previous time-series data, but also on exogenous variables. An adequate ARX model combines a set of exogenous input variables and previously measured time-series data.

In this study, the input variables are solar radiation, ambient air temperature, ambient air relative humidity, and the output variable is the moisture content. Drying experiment numbers 1, 5, 9, 18 and 22, obtained by random selection, were used for the ARX modeling.

Let $y(k\Delta t) = y_k$ be a sequence Y of output variables sampled at a constant interval of time Δt, $u(t) = u_k$ is the corresponding input U. For the case of banana drying in the solar dryer proposed in this study, the *z-transform* between the input and output sequence is provided by the following equation.

$$A(z)\, y(t) = B(z)\, u(t) + e(t) \qquad (2)$$

Where z is a delay operator, $A(z)$ is the coefficient of $y(t)$, $B(z)$ is the coefficient of $u(t)$ and $e(t)$ is a sampling noise.

After selecting the model orders and defining the structure of the ARX model, the estimations of the parameters were carried out with a MATLAB using the Levenberg-Marquardt algorithms [24] to search for the parameters which minimizes the errors between the measured values ($y_m(t)$) and the simulated data ($y_s(t)$). Thus, it essentially requires minimization of $e(t)$ as given by

$$min\ e\ (t)=min\left[y_m(t)\ -\ y_s(t)\right] \tag{3}$$

From the above-mentioned procedure together with the experimental data, the following equations were obtained.

$A(z) = 1 - 0.9135\ z^{-1} - 0.07895\ z^{-2} - 0.1957\ z^{-3} + 0.2289\ z^{-4}$

$B1(z) = 0.4704\ z^{-1} - 0.2736\ z^{-2} - 0.02617\ z^{-3} - 0.1809\ z^{-4}$

$B2(z) = 0.03932\ z^{-1} - 0.01066\ z^{-2} - 0.006375\ z^{-3} - 0.003974\ z^{-4}$

$B3(z) = -0.007693\ z^{-1} + 0.0005098\ z^{-2} + 0.0005927\ z^{-3} + 0.002978\ z^{-4}$

$B4(z) = 0.2071\ z^{-1} + 0.05039\ z^{-2} + 0.006179\ z^{-3} - 0.1632\ z^{-4}$

The rest of experimental results were compared with those obtained from the model. The suitability of the model was also evaluated using the values of the root mean square difference (RMSD) and mean bias difference (MBD).

The RMSD is a measure of the closeness of the predicted values and experimental data. It is defined as the square root of the mean square between the experimental points and the predicted values. The RMSD relative to the mean measured data in percent (RMSD) is given by

$$RMSD=\frac{\sqrt{\frac{\sum_{i=1}^{N}\left(M_{i,model}-M_{i,measure}\right)^2}{N}}}{\frac{\sum_{i=1}^{N}M_{i,measure}}{N}}\times 100 \tag{4}$$

Where $M_{i,\ model}$ is moisture content obtained from the ARX model and $M_{i,\ measure}$ is moisture content obtained from the measurement of the i^{th} data and N is the total number of the data.

The MBD is a measure of the average discrepancy between the experimental points and the fitted curve and the MBD relative to the mean measured data in percent (MBD) is given by

$$MBD=\frac{\frac{\sum_{i=1}^{N}\left(M_{i,model}-M_{i,measure}\right)}{N}}{\frac{\sum_{i=1}^{N}M_{i,measure}}{N}}\times 100 \tag{5}$$

3. Results and Discussion

Twenty-four set of drying experiments on the drying of bananas using the solar dryer, were conducted to assess the performance of the dryer. The experimental results were then used in the ARX modeling study.

3.1. Experimental performance of the dryer

The results are also shown in graphs in Fig. 3 to 6 below. The variations of the solar radiation during the drying period are shown in Fig. 3. There was almost no fluctuation in solar radiation as there were no clouds and rainfall. The solar radiation increased sharply from 350 to 900 W/m^2 at noon and after noon, the solar radiation decreased sharply till the sunset.

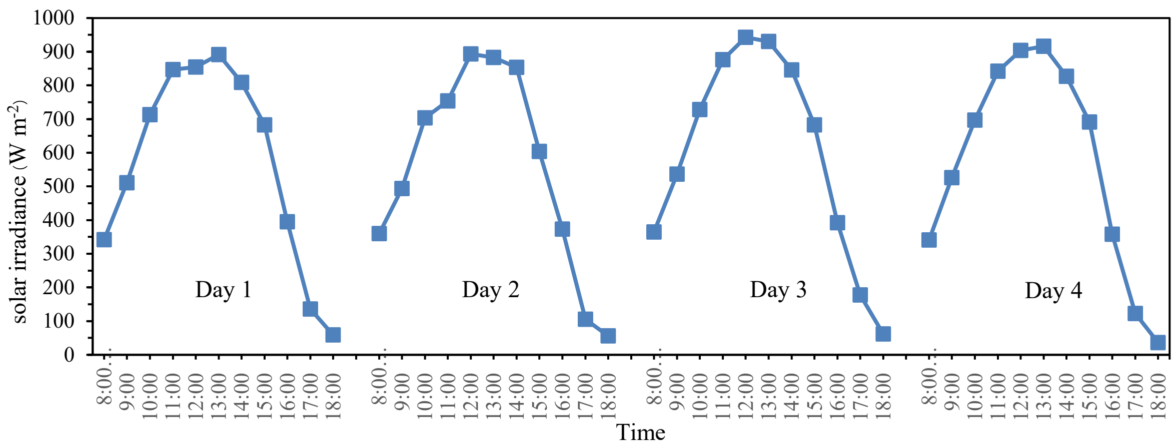

Fig. 3 The variations of the solar radiation during the drying period.

Fig. 4 shows the variations with time of the ambient air temperature and the drying air temperature inside the dryer. There are significant differences between the inside air temperature of the dryer and the outside air temperature. The inside air temperature increased from 55°C in the morning to 65°C at noon. The inside temperature is always much higher than the outside temperature. This is a good indication of the air temperature inside the dryer that has the sufficient potential for faster drying of products compared to natural sun drying.

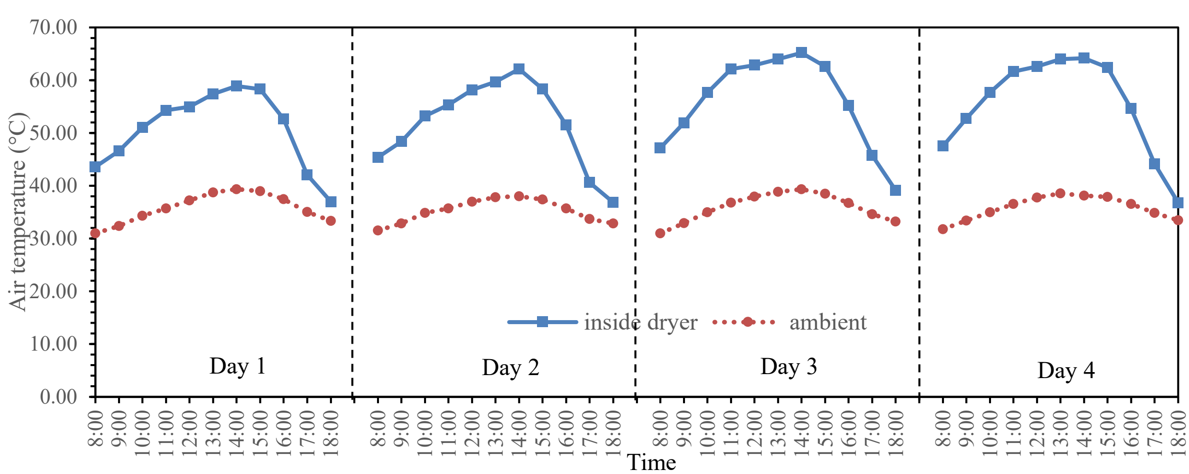

Fig. 4 The variations of the ambient air temperature and the drying air temperature inside the dryer with time.

The variations of the relative humidity of the air inside the dryer and the ambient air outside the dryer are shown in Fig. 5. The relative humidity (%) of the air inside the dryer decreased from 55% in the morning to 3% at noon, while the relative humidity of outside ambient air decreased from 70% to 30%. The relative humidity inside the dryer was always lower than the relative humidity outside the dryer, and the decrease in humidity was much more prominent inside the dryer at noon. This shows that the relative humidity inside the dryer has more potential for faster drying, as compared to natural sun drying.

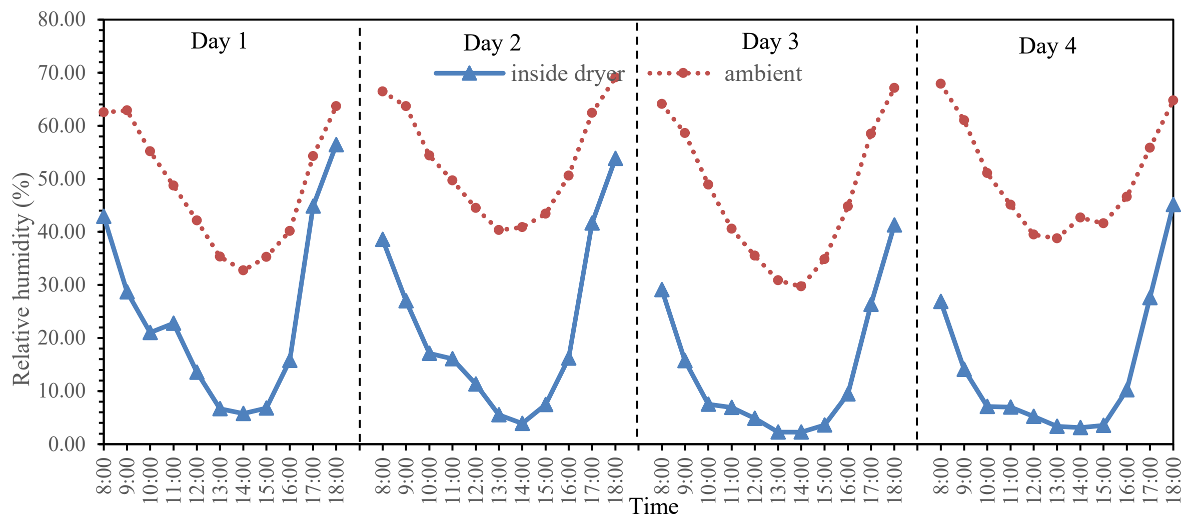

Fig. 5 The variations of the ambient air relative humidity and the drying air relative humidity inside the dryer with time.

Fig. 6 shows the comparison of moisture content changes of bananas inside the household solar dryer and those under the natural sun drying. Bananas inside the household solar dryer was dried to final moisture content of 13% (w.b.) within 4 days from an initial moisture content of 69% (w.b.), but for natural sun drying, the moisture content of similar samples reached 13% (w.b.) within 8 days. Thus, there is a considerable reduction in drying time using in the household solar dryer.

The bananas dried in the solar dryer was good quality dried bananas. The bananas were completely protected from rain and insects.

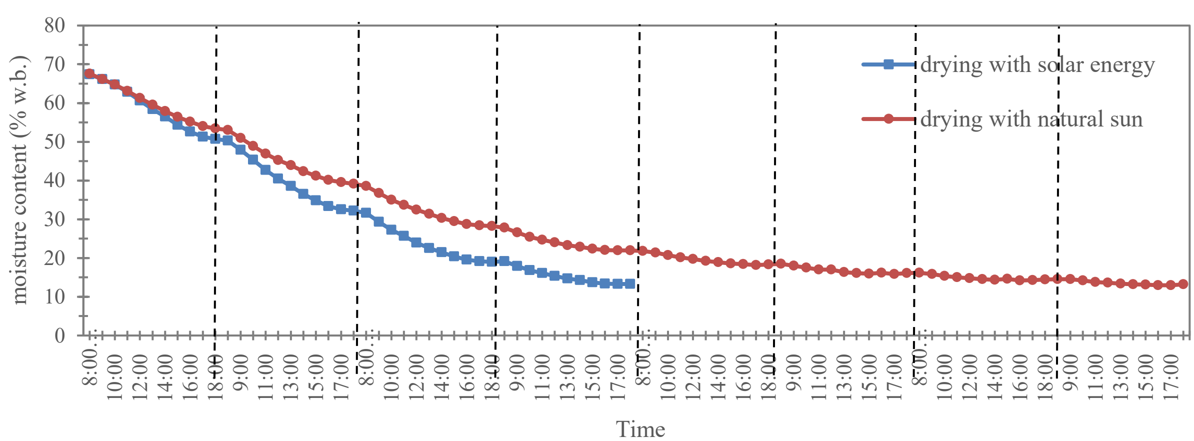

Fig. 6 Comparison of the variations of moisture content of banana inside the small household solar dryer and under natural sun drying for the typical result.

The results in terms of mass of dried banana and duration of drying from all experiments are shown in Table 1. It is observed that the mass of fresh bananas of 4 kg was reduced to 1.4-1.7 kg within four days, which is shorter than the drying time under natural sun drying.

Table 1 Results of all drying experiments.

Experiment No.	**Duration of experiment**	**Mass of dried banana obtained from experiment (kg)**	**Drying time for natural sun drying (day)**
1	7-9 Jun 2019	1.70	7
2	10-13 Jun 2019	1.50	8
3	14-17 Jun 2019	1.50	8
4	21-24 Jun 2019	1.50	8
5	25-28 Jun 2019	1.60	8
6	29 Jun - 2 Jul 2019	1.50	8
7	3-6 Jul 2019	1.50	5
8	7-10 Jul 2019	1.50	6.5
9	11-13 Jul 2019	1.50	8
10	15-18 Jul 2019	1.40	8
11	19-22 Jul 2019	1.40	8
12	23-26 Jul 2019	1.50	4
13	29 Jul - 1 Aug 2019	1.50	8
14	2-5 Aug 2019	1.50	8
15	6-9 Aug 2019	1.60	4
16	13-16 Aug 2019	1.55	8
17	19-22 Aug 2019	1.50	8
18	23-26 Aug 2019	1.50	6
19	2 - 5 Oct 2019	1.60	8
20	8 - 11 Oct 2019	1.60	7
21	17 - 19 Oct 2019	1.50	7
22	21 - 23 Oct 2019	1.50	7
23	25 - 27 Oct 2019	1.60	4
24	5 - 8 Nov 2019	1.60	3.5

3.2. ARX modeling of solar drying performance

The predicted results from the use of the ARX model in the drying of bananas in the household solar dryer were compared with the actual experimental results, and are shown in Table 2.

Table 2 Discrepancy in terms of root mean square difference (RMSD) and mean bias difference (MBD) between moisture contents predicted by the ARX model and those obtained from experiments.

Experiment No.	MBD (%)	RMSD (%)
2	-0.49	2.80
3	-0.42	2.94
4	-2.47	9.93
6	0.25	2.46
7	2.25	8.94
8	-0.50	2.81
10	-0.32	6.49
11	-1.51	7.44
12	-0.19	1.23
13	0.89	5.36
14	2.18	8.80
15	1.46	5.99
16	-0.68	3.86
17	0.61	3.77
19	-1.31	5.87
20	-1.06	4.80
21	0.09	2.27
23	0.31	2.37
24	0.66	3.81
Combined data	**0.033**	**5.33**

The prediction values of the model were evaluated based on RMSD and MBD. The RMSD of the prediction values for the moisture content for a loading capacity of 4 kg was 1.23 - 9.93%, MBD was -2.47 – 2.18%. These values of MBD and RMSD were small. Thus, the RMSD of the values from the model were within the acceptable limit of 10% [25]. The model predictions of the moisture content values were good.

In terms of usefulness of the model, the performance of the dryer depends on environmental parameters such as the solar radiation, ambient air temperature and relative humidity of the location where a dryer is intended to be installed. The ARX model, which uses these parameters, can be used to predict the performance of the dryer at any location before the actual installation of the dryer with a sufficient accuracy.

4. Conclusions

Results from the experiments showed that the dryer performed well. The ARX model predictions of the moisture content of the bananas were compared with the experimentally measured values. The comparison between the predicted and measured values was good.

The model study includes the appropriate variables, which make it easily implementable and computationally efficient. The ARX model does not require any system parameters estimation. Hence this model can be applied in predicting operational performances and designing controllers for drying processes. The ARX model is a simple method for system identification without the need for doing much calculation.

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