Performance and ARX Modelling of a Solar Vapour Compression Refrigeration System

Somjet Pattarapanitchai[1], Serm Janjai[1,*], Sattra Sirikaew[1], Bilash Kanti Bala[2]

[1]Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand

[2]Department of Electrical and Electronic Engineering, Prime University, Mirpur-1, Dhaka 1216, Bangladesh

[*]**Corresponding author's email:** serm.janjai@gmail.com

Received: 28 July 2021, Revised: 1 December 2021, Accepted: 22 February 2022

Abstract

This study presents an experimental performance and an Auto-Regressive with Exogenous variable (ARX) modelling of a solar photovoltaic (PV) operated vapour compression refrigeration system. The system is composed of a conventional refrigerator and PV modules. The performance of the system was evaluated in terms of its cooling effect suitable for storage of food and agricultural products. The performance analysis clearly shows that a DC electric motor operated by solar PV with storage of electrical energy in batteries can be used for domestic applications using an environment-friendly renewable resource of solar energy. The ARX modelling of the system was performed. The agreement between the ARX simulated cooling temperature inside the cooling chamber and the measured cooling temperature inside the cooling chamber was good, with the discrepancy in terms of root mean square difference and mean bias difference being less than 10%. This finding suggests that ARX modelling provides a simple method for evaluating the system performance. The vapour compression solar refrigeration system can be used for cooling household products where electricity is unreliable or the electrical grid system is non-existent.

Keywords:

Solar Vapour Compression Refrigeration System, PV Module, Cooling, Food and Agroproducts, ARX Modelling

1. Introduction

Refrigeration systems are made for cooling and dehumidifying purposes. Refrigeration is a process of removing heat from a body to lower its temperature below that of its surroundings [1-2]. Domestic household refrigeration system is for cooling food products such as fruits, vegetables, fresh fishes, and meat for their preservation for several hours and even for a few days. The most common refrigeration system used for domestic purposes is the vapour compression refrigeration. This system uses electricity to run the compressor to achieve refrigeration. Vapour compression refrigeration systems require a large amount of electricity [3]. Electricity cost to run the refrigeration system is therefore high. To decrease electricity cost, an alternative cheaper energy source can be considered.

Electricity from renewable energy, like solar PV systems, can be can be used to run the compressors of vapour compression refrigeration systems, which might be designed to operate at low voltage direct current using DC series/ brushless electric motors. The cost of electricity can be significantly lower than electricity from the grid.

Tropical and subtropical regions have plenty of solar radiation to run such solar PV-powered refrigeration systems as described previously. The use of solar PV-powered refrigeration systems can be a good cheaper alternative solution to the problem of preservation of food products. There can be a big demand for household solar PV-powered refrigerators for the preservation of food products in these areas. The use of solar PV-powered vapor compression refrigeration systems can meet the capacity requirements of households for efficient preservation of food products. Also, as there are many places in the developing countries where power supply is still intermittent and irregular, solar PV-powered vapor compression refrigeration systems can also be the solution for cold storage of vaccines and lifesaving drugs [4].

Several performance studies of solar PV-powered vapor compression refrigeration systems in locations where local electrical grid is not available, but refrigeration need is critical. Some of these recent studies are summarized below:

Hammad and Tarawneh [5] reported an acceptable arrangement for a 60-W solar PV-powered DC refrigerator showing the good utilization of direct solar radiation for cooling purpose. The refrigerator capacity, the coefficient of performance and cooling temperatures were acceptable and satisfactory. The performance of the DC refrigerator powered by PV panels was the same as the performance of a refrigerator powered by normal electricity.

Aktacir [6] did an experimental study of a multi-purpose PV powered refrigeration system and observed that the refrigerator temperature reached down to -10.6°C, with a daily energy demand of 347.7 Wh. The use of solar energy reduced the operating cost. This system can be used where local electrical grid is not available, but where refrigeration is required.

Ekren et al. [7] reported that a small household refrigerator with a DC motor operated compressor can be operated with PV power without any inverter. The performance of coefficient of the refrigeration system was 0.67 during no storage and the exergetic coefficient of refrigeration was 0.859%.

Sharma et al. [8] reported a comparative performance analysis between a solar PV-powered vapor compression refrigeration system and a vapor absorption refrigeration system. The results showed that though the vapour absorption refrigerator takes more time to decrease the temperature of the cabinet in comparison to the vapor compression refrigerator yet it consumes less power.

Mba et al. [9] developed a computer model for a PV-powered refrigeration system. This computer model consisted of sub-models for a solar PV panel, a battery, an inverter, a controller, and a vapour compression refrigerator unit. Modelling was done using MATLAB to simulate the system performance and the simulation can be run for different types of solar PV panels.

Su et al. [10] proposed a dynamic model to simulate a variable speed PV-powered refrigerator and they used the simulation results to investigate various performance parameters of the refrigerator.

Gao et al. [11] presented a dynamic model of a PV direct-driven refrigeration system and validated it with experiments. The performance of the system as predicted from the model and those obtained from the experiments were in good agreement. Using the model, two control methods, namely the MPPT (Maximum Power Tracking) method, and the CSP (Compressor Speed Prediction) method were compared and they found out that the MPPT method was more efficient than the CSP method.

In general, mathematical modelling of a solar PV-powered refrigeration systems is useful for predicting performance of systems prior to real installation. There are several approaches for the modelling. Classical mathematical modelling is still the basic tool for performance prediction of refrigeration systems. Several studies have been reported on experimental and analytic modelling of solar refrigeration systems [5, 12-14] and classical modelling is quite complicated and it requires estimation of system parameters.

However, some techniques do not require the estimation of the parameters for modelling, such as Auto-Regressive with Exogenous variable (ARX) [15] and artificial neural network (ANN) [16] techniques. As an alternative to analytical modelling and as a qualitative tool, the ARX modelling enables the conduct of very fast and simple simulations without the estimation of the parameters. In addition, the ARX modelling technique does not require the formulation of an analytical description. Instead, a black-box model is constructed based on time series data combined with exogenous variables. In general, ARX modelling require relatively less experimental data for modelling as compared to similar modelling approaches.

Several other studies have been reported on the design on solar PV powered vapor compression refrigeration systems and limited experimental studies simulating performance of such vapor compression refrigeration systems were performed. But to the best of our knowledge, no study has been reported on ARX modelling and simulation of vapor compression solar refrigeration systems. Therefore, the objectives for this study are to investigate the performance of a solar PV-powered vapor compression solar refrigeration system and conduct an ARX modelling of this system.

2. Methodology

2.1. Description of the system

A vapour compression refrigeration system was installed at premises of the solar energy field laboratory of the Faculty of Science of Silpakorn University, Nakhon Pathom, Thailand (13.82°N, 100.04°E). Fig. 1 shows the basic refrigerator unit and its corresponding schematic diagram. The basic refrigerator unit (Fig 1) consists of a compressor, condenser, expansion valve and an evaporator.

Fig. 2 shows a more detailed schematic diagram of the **solar PV-powered vapor compression refrigeration system**. The system consists of two 300 W solar PV modules, two 12 V batteries with the capacity of 200 Ah (each), the refrigerator unit and a charge controller. If electricity from the modules is sufficient for the refrigerator unit, this electricity will be used directly to supply the refrigerator unit and the rest will be installed in the batteries. In case that the electricity from the modules is not sufficient, the electricity from the batteries will be supplied to the refrigerator unit. The use of electricity is controlled by the charge controller. This charge controller helps maintain the power supply within the current and voltage ranges tolerated by the refrigerator unit and prevents overcharge of the batteries. The batteries have capacity to run the refrigerator for two days without solar radiation.

The internal volume of the refrigerator unit is 169 liters. From the specification of the unit the power required for this volume is 120 W. But, according to our experiments, the average electricity consumption of the compressor of this unit is 60 W. Environment-friendly R290 is used as a refrigerant. The refrigerator unit, charge controller and batteries are accommodated in a hut (Fig. 3) where roof is used to place the PV modules.

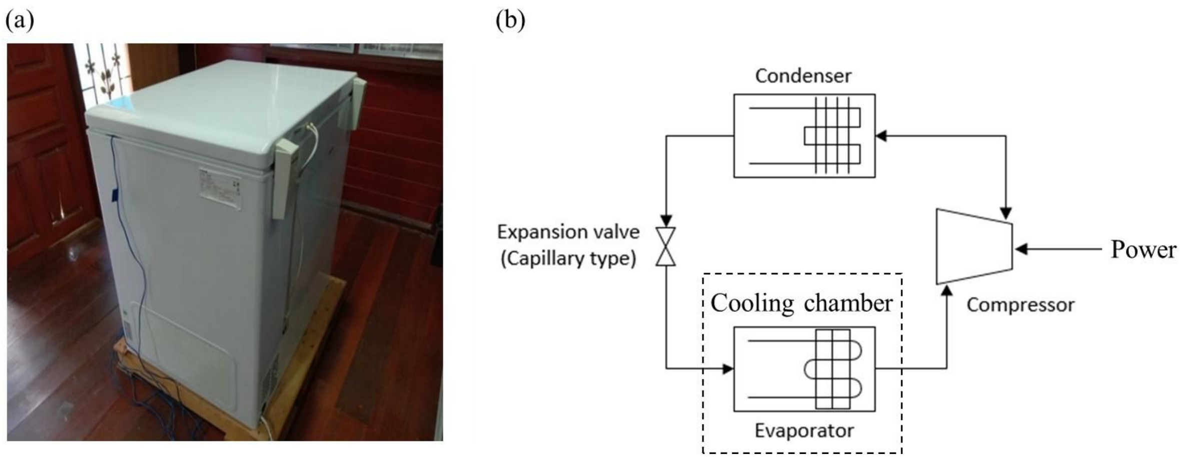

Fig. 1 Vapour compression solar refrigerator unit: (a) pictorial view and (b) schematic diagram.

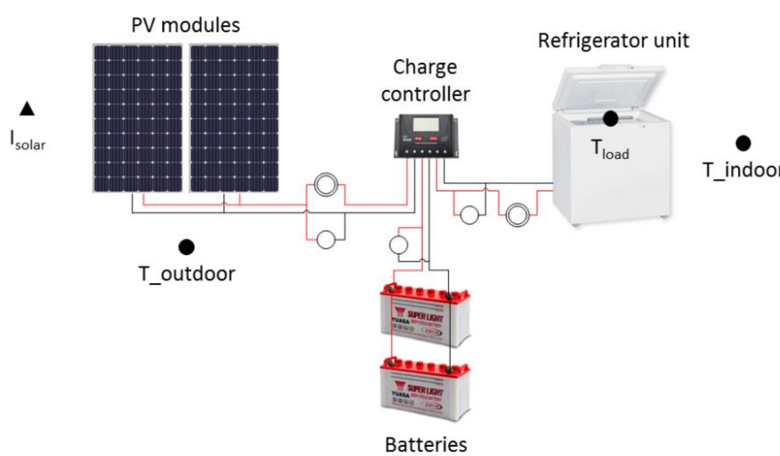

Fig. 2 Schematic diagram of the solar PV-powered vapor compression refrigeration system with the measurement points (• is position of temperature measurement, ▲ is position of solar radiation measurement, ◎ position of current measurement and ○ position of voltage measurement.)

2.2. Experimental investigation of system performance

2.2.1. Experimental setup

The solar PV-powered vapor compression refrigeration system was placed on the premises of the solar energy field laboratory at the Faculty of Science, Silpakorn University at Nakhon Pathom, Thailand. The system was used to generate experimental data to investigate the performance of the system, to conduct modelling using the ARX approach, and to validate this modelling approach.

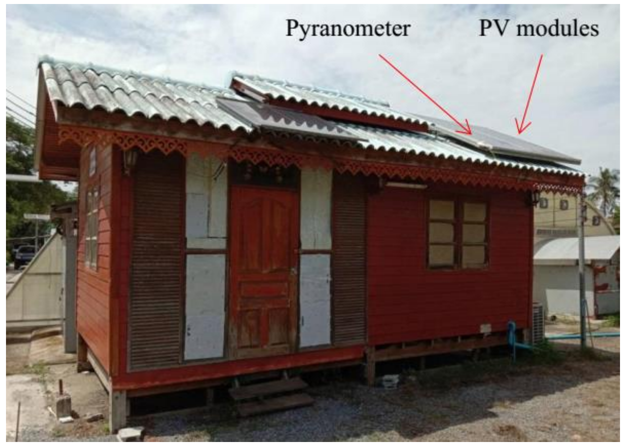

Fig. 3 A hut for accommodating the solar refrigeration system.

The study was done in a small hut with the solar PV modules on the top of the roof of the hut and a refrigerator unit inside the hut (Fig. 3). Ten experiments were performed from June to August 2019, using different volumes of water (10, 20, 30, 40, 50, 60, 70, 80, 90, 100 liters) as cooling load. Water was chosen as cooling load because the refrigeration system was to simulate the preservation of fresh fruits and vegetables, which usually have moisture content more than 50% (wb).

The temperature inside the refrigerator unit was set to 2˚C. Solar radiation was measured using a pyranometer having an accuracy of ± 0.5% (Kipp & Zonen, model CM 11) placed on the rooftop of the hut. The refrigerator unit was installed inside the hut. Outdoor temperature, indoor temperature, temperature of the water inside the refrigerator unit were monitored by using thermocouples (K type) connected with a data logger (Yokogawa, model DC100). Only one sensor was used for measuring indoor temperature because it is an air conditioned room and the temperature of the air is quite uniformed. Voltage and current from the solar PV modules were measured by a DC voltmeter and a DC ammeter (Fulke, model 45), respectively, All measurements were performed every 1 minute. The position of the measurement points are shown in Fig. 2.

2.2.2. Uncertainty analysis

Uncertainty analysis refers to the uncertainty or error in experimental data. In general, there are two types of error, namely, systematic error and random error. Normally, the systematic error in the experimental data is a repeated error of constant value, while the random error is due to imprecision. The systematic error can be removed by proper calibration, but the random error cannot be removed, but the imprecision due to the random error can be numerically defined. The data collected for solar radiation, outdoor and indoor temperatures were recorded during calibration. While the mean value of the measurements and standard deviation of the random errors of the data on the temperatures and solar radiation were determined.

The variable x_i that has an uncertainty dx_i is expressed as [17-19]

$$x_i = x_{mean}(measures) \pm dx_i \qquad (1)$$

where x_i is actual value, x_{mean} is mean measured value (mean value of the measurements) and dx_i is uncertainty in the measurement. There is an uncertainty in x_i that may be as large as dx_i. The value of dx_i is the precision index that is usually taken as 2 times of the standard deviation and it encloses approximately 95% of the population for a single sample analysis. In this study, statistical analysis was performed to estimate standard error between the ARX predicted cooling temperature and experimentally determined values and correlation coefficient.

2.3. ARX modeling [15] of the solar PV-powered vapor compression refrigeration system

There are several approaches for modelling solar energy systems such as follows; classical mathematical approach [20], ARX approach [15], Auto-Regressive Moving Average with eXogenous inputs (ARMAX) approach [15], Nonlinear Auto-Regressive eXogenous (NARX) approach [15], and Box-Jenkins (BJ) approach [15].

The classical mathematical models [20] can be used to simulate the performance of a solar PV-powered vapor compression refrigeration system (our system). These models provide better insight and greater understanding of the transfer process, but the models are usually complicated, and it is difficult to determine model parameters even for a household type vapor compression refrigeration system. So, this is not appropriate for our system.

For ARMAX approach [15], we need to average the series of the output in the past which is not necessary because the tendency of the output (cooling temperature) is quite known i.e., decreasing temperature with time). Therefore, this approach is also not appropriate for our system.

For NARX [15], it is usually employed for a system whose output varies with a lot of fluctuations. But in our case, the output varies systematically with time. Therefore, this approach again does not fit to our system.

The BJ model [15] is an auto-regressive model whose value of outputs in the past and average value of output in the past are used in the model and exogenous input variables were not used. As the inputs (e.g. solar radiation and load) of our system are very important and they should be used, thus, the BJ approach is also not appropriate for our system.

In this study, the ARX approach was thus chosen to model our system. The system is considered as a black box which can be viewed in terms of input, output, and transfer characteristics without any knowledge of internal working processes. Additionally, ARX approach works well in other energy systems [15, 21].

ARX modelling approach is commonly employed in control engineering for designing a controller. It can be also used for predicting the performance of other systems. To the best of our knowledge, ARX approach has not been used to model solar-powered refrigeration systems. Therefore, the ARX approach was selected in this study.

The ARX method is more complete than the autoregressive model, since it is based not only the previous time-series output data, but also on the exogenous variables which are the previous time-series input data of those variables. A complete ARX model combines a set of exogenous input variables and previously measured time-series data. This approach is appropriate for our system which has systematic variation of the output (cooling temperature).

According to ARX approach, let $y(k\Delta t) = y_k$ be sequence "y" of output variables sampled at a constant interval of time Δt, $u(t) = u_k$ is the corresponding input u (k = 1, 2, 3, …). In this study, the input variables are solar radiation (u_1), indoor temperature (u_2), outdoor temperature (u_3) and load (the amount of water) (u_4). Outdoor temperature influences directly the indoor temperature through the heat transfer between indoors and outdoors, and the indoor temperature directly affects the temperature of water inside the cooling chamber because there is heat transfer through the walls of the cooling chamber. Therefore, the outdoor temperature affects indirectly the temperature of water inside the cooling chamber.

The *z-transform* between the input and output sequence provides the following different equations. In this study, the cooling water temperature inside cooling chamber of the refrigeration unit is the output variable, $y(t)$ that depends on the pervious time series data and exogenous variables, solar radiation u_1, indoor temperature u_2, outdoor temperature u_3, and volume of water inside the cooling chamber u_4 and it is expressed generally as:

$$A(z)y(t) = B(z)u(t) + e(t) \tag{2}$$

where $A(z)$ is the coefficient of $y(t)$, $B(z)$ is the coefficient of $u(t)$, z is a delay operator and $e(t)$ is a model error.

In this study, the ARX modeling was built from the experiments using the loads of 10, 30, 50, 70 and 100 liters of water. The experiments using the loads of 20, 40, 60, 80 and 90 liters of water were employed to test performance. From the experiments, with data collection of every 1- minute, the coefficient of the output variable ($A(z)$) and coefficients of the exogenous variable ($B(z)$) were obtained. Based on the theory of ARX modelling [15] and experimental data, $A(z)$ and $B(z)$ can be written as follows.

$$A(z) = 1 - 2.464z^{-1} + 1.94z^{-2} - 0.4762z^{-3} \tag{3}$$

$$\left.\begin{aligned}
B1(z) &= -0.00002652z^{-1} + 0.00009677z^{-2} - 0.00009708z^{-3} + 0.00009383z^{-4} - \\
&\qquad 0.000127z^{-5} - 0.00002673z^{-6} + 0.0001651z^{-7} - 0.00007875z^{-8} \\
B2(z) &= -0.04001z^{-1} + 0.08869z^{-2} - 0.05428z^{-3} + 0.0132z^{-4} - 0.02556z^{-5} + \\
&\qquad 0.03411z^{-6} - 0.02769z^{-7} + 0.01149z^{-8} \\
B3(z) &= -0.007251z^{-1} + 0.02029z^{-2} - 0.02269z^{-3} + 0.005945z^{-4} - 0.01008z^{-5} + \\
&\qquad 0.0708z^{-6} - 0.09419z^{-7} + 0.03724z^{-8} \\
B4(z) &= 0.0002257z^{-1} + 0.005462z^{-5} - 0.01628z^{-7} + 0.0106z^{-8}
\end{aligned}\right\} \tag{4}$$

where $B1(z)$ is for solar radiation, $B2(z)$ is for indoor temperature, $B3(z)$ is for outdoor temperature and $B4(z)$ is for load.

After selecting the model orders and defining the structure of the ARX model, the estimations of the parameters were performed with a MATLAB using the Levenberg-Marquardt algorithms [22] to search for the parameters which minimizes the errors between the measured values ($y_m(t)$) and the simulated data ($y_s(t)$) for the developed model. Thus, this essentially required minimization of $e(t)$ as given by

$$\min[e(t)] = \min[y_m(t) - y_s(t)] \tag{5}$$

To measure adequacy of the model to capture the cooling effect of the vapour compression solar refrigeration system, root mean square difference (*RMSD*), mean bias difference (*MBD*) and coefficient of determination (R^2) were estimated. High value of R^2 and low values of *RMSD* and *MBD* are desirable to validate the model. Coefficient of determination is expressed as:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(T_{i,measure} - T_{i,model})^2}{\sum_{i=1}^{N}(T_{i,measure} - \bar{T}_{measure})^2} \tag{6}$$

The root mean square difference is given by

$$RMSD = \frac{\sqrt{\frac{\sum_{i=1}^{N}(T_{i,model} - T_{i,measure})^2}{N}}}{\frac{\sum_{i=1}^{N} T_{i,measure}}{N}} \times 100 \tag{7}$$

The mean bias difference is expressed as

$$MBD = \frac{\frac{\sum_{i=1}^{N}(T_{i,model} - T_{i,measure})}{N}}{\frac{\sum_{i=1}^{N} T_{i,measure}}{N}} \times 100 \tag{8}$$

where R^2 is coefficient of determination, *RMSD* is root mean square difference, *MBD* is mean bias difference, $T_{i,measure}$ is cooling temperature from the measurement, $T_{i,model}$ is cooling temperature from the model and N is amount of data.

3. Results and Discussions

Experimental studies on the cooling effect of a solar PV-powered vapor compression refrigeration system were conducted at the solar energy field laboratory of the Faculty of Science at Silpakorn University in Nakhon Pathom, Thailand to determine the performance of the system and to assess the capability of the ARX model to predict cooling effect of the system. The results are discussed in the following subsections:

3.1. Experimental performance

Fig. 4 shows the typical variations of the solar radiation and the outdoor and indoor temperatures during the study of the solar PV-powered vapor compression refrigeration system. The solar radiation increased with time from morning till noon and then decreases till sunset. There were fluctuations in solar radiation in both morning and afternoon since the skies were cloudy. The solar radiation increased sharply in the morning hours till noon, from 300 Wm^{-2} to 900 Wm^{-2} with fluctuations, and then decreased sharply to 0 Wm^{-2} at sunset. The outdoor air temperature varied from 25°C to 38°C while the indoor temperature varied from 27°C to 34°C. However, during night time, the outdoor temperature and indoor temperature remained almost constant at 27°C and 29°C, respectively.

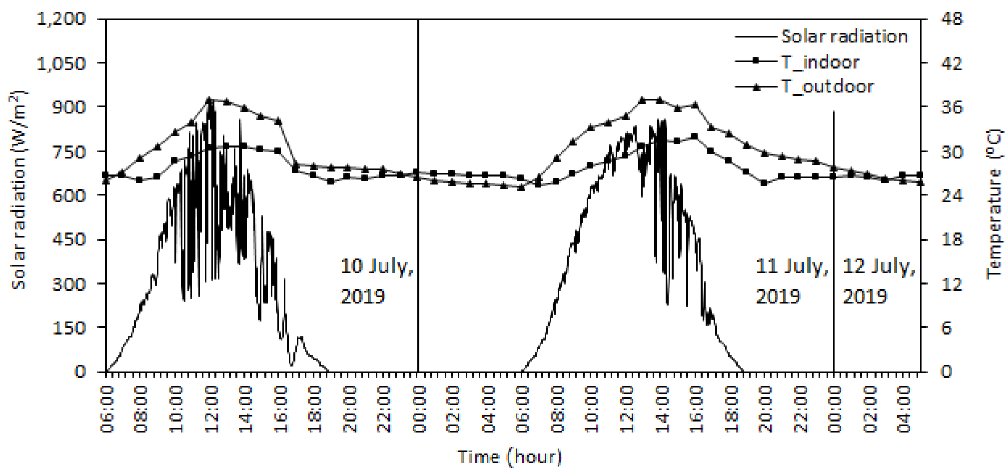

Fig. 4 The variations of the solar radiation, outdoor (T_outdoor) and indoor (T_indoor) air temperatures during operation of the vapour compression solar refrigeration system.

Fig. 5 shows the solar PV voltage and battery voltage. There were fluctuations in solar PV voltage during day time. Also, there was a time lag in in the start of the fluctuations in the solar PV voltage. Solar PV voltage was zero during night since there was no sunshine. However, the battery voltage remained almost constant during whole period of this study. This indicated that a 12 V battery was quite capable of providing a constant supply of 12 V supply of electricity to the 12 V DC motor of the compressor of the solar refrigeration system. This demonstrated that solar PV modules can provide the electrical energy needed to run the compressor of the refrigeration system.

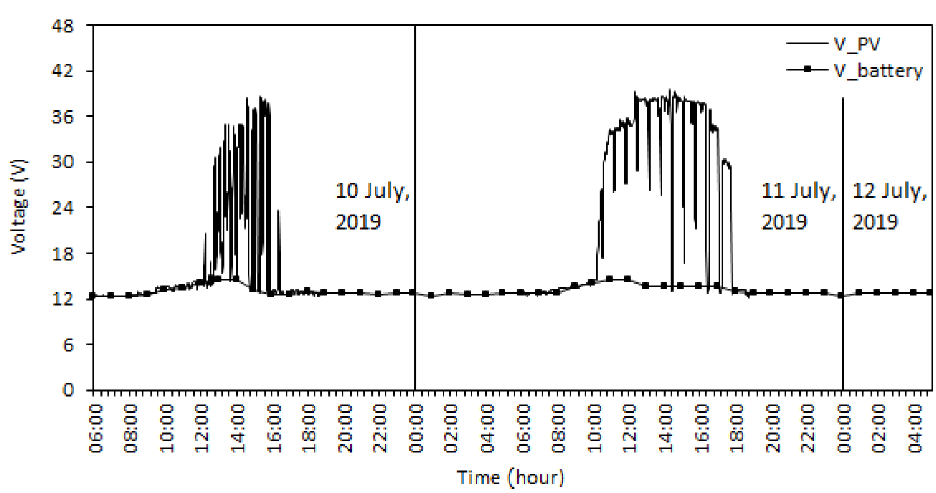

Fig. 5 The variations of solar PV voltage (V_PV) and battery voltage (V_battery) during operation of the vapour compression solar refrigeration system.

Fig. 6 shows the outdoor and indoor temperatures, and cooling water temperatures. The cooling water temperature was reduced smoothly to the set temperature because of the higher heat capacity of water and the cooling water quickly achieved the desired cooling temperature of 2°C and ultimately settles down to 2˚C, which was suitable for the cooling of food and agricultural products, typical of domestic refrigeration systems.

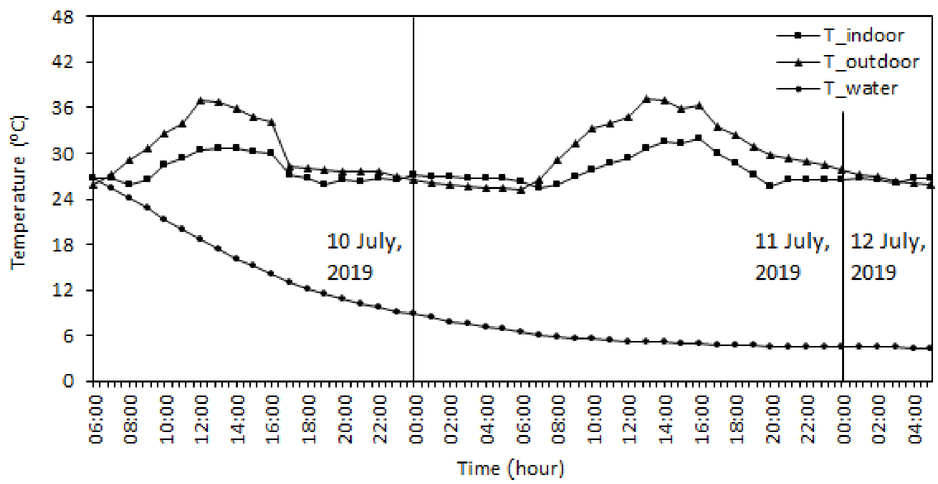

Fig. 6 The variations of the water temperature (T_water) and outdoor (T_outdoor) and indoor (T_indoor) air temperatures during operation of the vapour compression solar refrigeration system for the load of 60 liters of water.

Fig. 7 shows the cooling temperatures of water for different cooling loads of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 liters of water. The cooling time required to reach the equilibrium temperature depends on the initial temperature of the product, and the specific heat and the quantity of the product being cooled. As a result, even if under the same cooling condition, the equilibrium conditions reached were different for different loads. Although, the set up temperature was 2˚C, the load temperature to reach this set up temperature was only for low load. For higher loads, the equilibrium temperature was approximately 5˚C. However, the difference in the cooling temperature reached was very small and the temperature reached for different cooling conditions were within the well-defined optimal range of the temperatures for storage of food and agricultural products in a household or domestic refrigerators. Also, the initial temperature of the products was within the range of the normal temperatures usually found for storage of food and agricultural products in household or domestic refrigerators. These results suggested that the solar PV-powered vapor compression refrigeration system in this study can used for food and agricultural products, in areas where electricity is unreliable or the electrical grid system is non-existent.

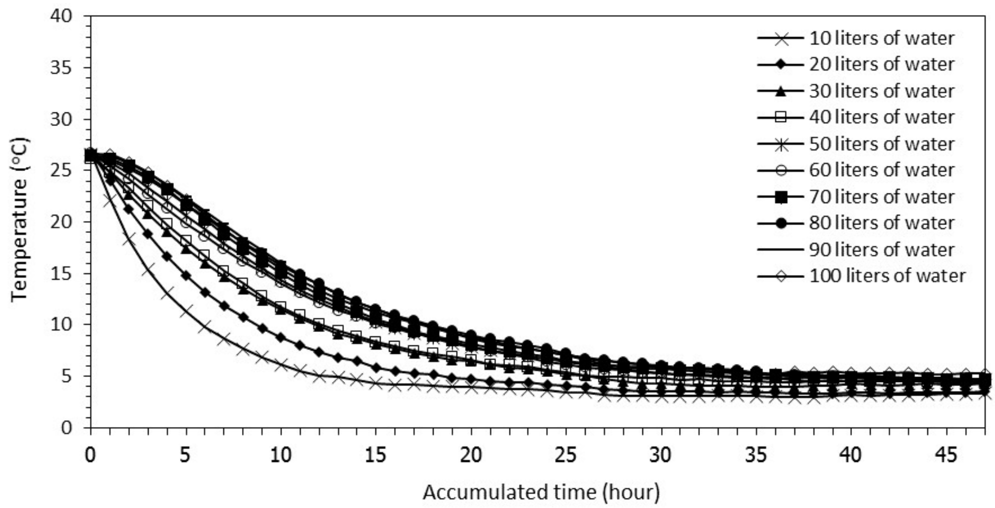

Fig. 7 Variations of the cooling water temperatures for a load of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 liters of water.

3.2. ARX simulated cooling performance

The ARX model simulation was used for the prediction of the water temperature inside the cooling chamber. The input data of the ARX model were: time series of solar radiation, indoor temperature, outdoor temperature and the volume of the water (i.e.; loads). The predicted output was the temperature of the water temperatures inside the cooling chamber.

To validate the use of the ARX model for predicting the cooling effect of the solar PV-powered vapor compression refrigeration system, the predicted water temperature inside the refrigeration system as determined by the ARX model, were compared with the actual experimental data of water temperature inside the refrigeration system. Fig. 8 shows a typical comparison between the ARX predicted cooling temperatures and the experimental data. The predictions of the model were evaluated based on the "Root Mean Square Difference (*RMSD*)", "Mean Bias Difference (*MBD*)" and "Coefficient of Determination (R^2)". The *RMSD* of the prediction values of the cooling temperatures inside the solar refrigeration system was 2.6 – 9.6%, the *MBD* was -0.9 – 3.5% and the R^2 was 0.99. These results demonstrated that the ARX model predictions of the cooling temperatures were good. It was within the acceptable limits of 10% [23].

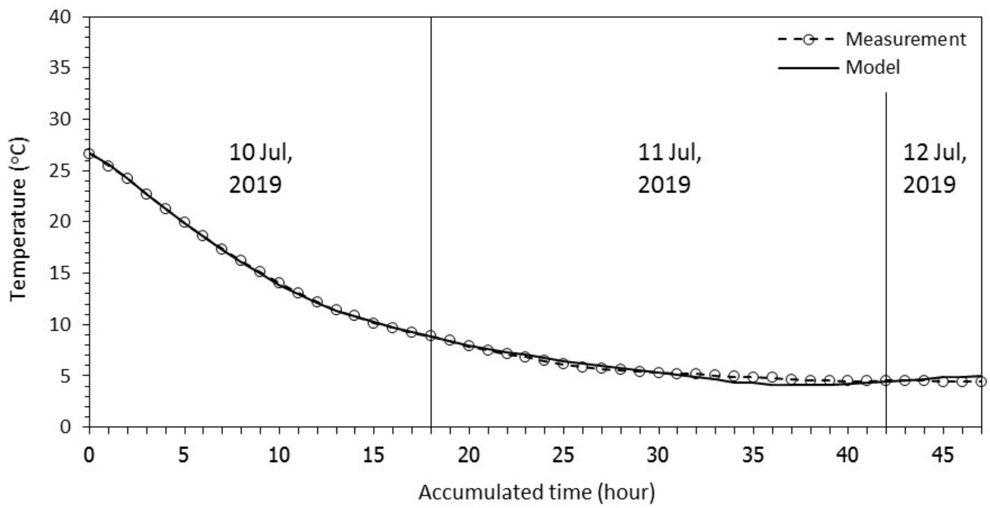

Fig. 8 Example of the comparison of the ARX simulated and experimental water temperatures during cooling for the load of 60 liters of water.

Fig. 9 shows the comparison of the results of the predictions of the ARX model and the actual observed data of the cooling effects of the refrigeration system for different cooling loads. The agreement between the predicted and observed values is good. This demonstrates that using the ARX model provides a simple and quick method for simulation studies to assess the performance of the solar PV-powered vapor compression refrigeration system. Table 1 shows the *RMSD*, *MBD* and R^2 for ARX modelling.

Table 1 *RMSD*, *MBD* and R^2 for ARX modelling.

Load (liter)	*RMSD* (%)	*MBD* (%)	R^2
20	9.6	3.5	0.9876
40	3.4	-0.9	0.9977
60	2.8	-0.2	0.9982
80	2.6	0.1	0.9983
90	3.4	1.0	0.9975
Combined data	4.3	0.6	0.9961

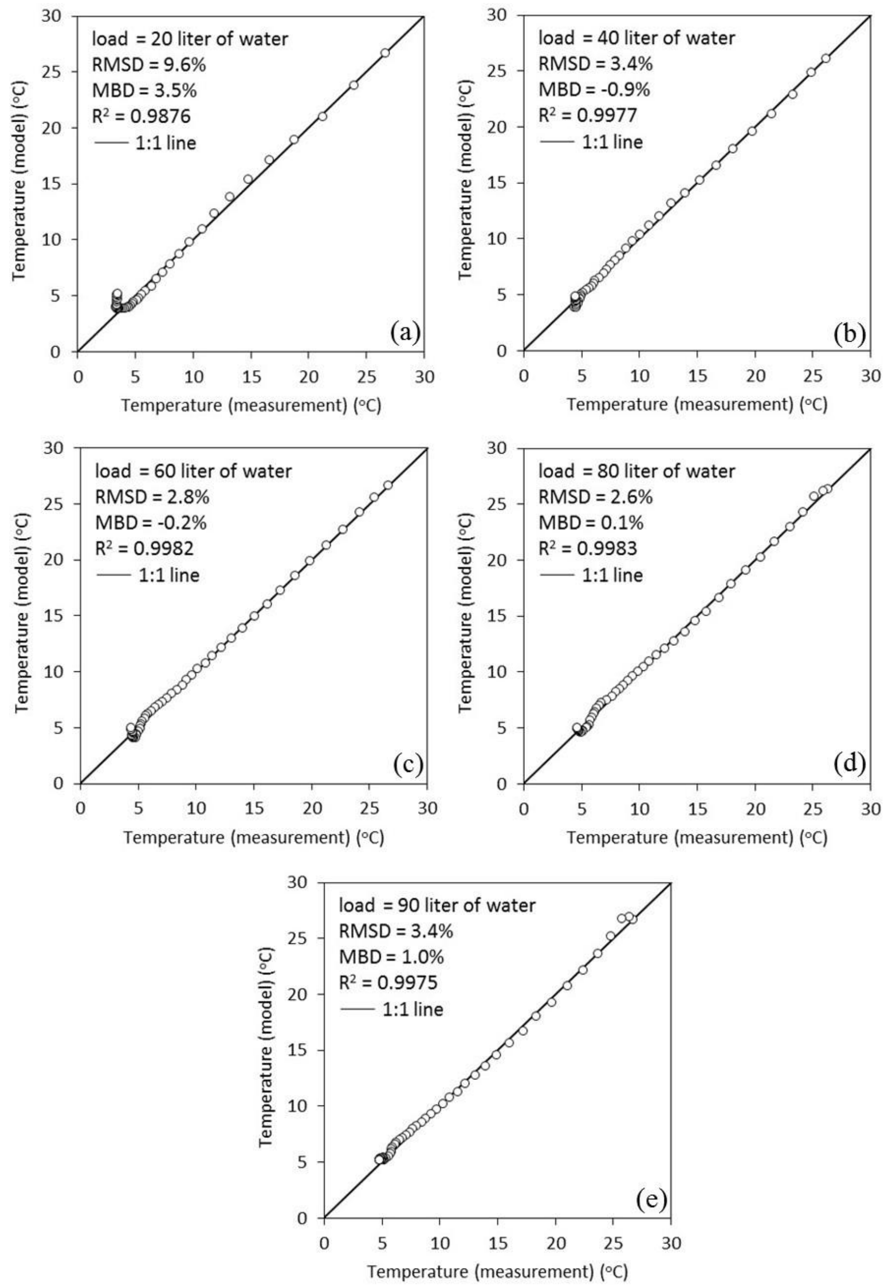

Fig. 9 The comparison of the ARX simulated temperature and experimental cooling water temperature for the loads of (a) 20 liters of water (b) 40 liters of water (c) 60 liters of water (d) 80 liters of water and (e) 90 liters of water.

From Table 1 and Fig. 9, we can see the value of *RMSD* and *MBD* are quite low (less than 10%) and the value of R^2 is very high (0.99), meaning that the ARX model performed well in predicting the cooling temperature [23].

In general, the performance of a solar PV system depends on three groups of parameters. These are 1) environmental parameters (e.g. solar radiation, ambient temperature) 2) design parameters (e.g. size of the system) and 3) operating parameters (e.g. flowrate). For a given set of environmental parameters, we can optimize design and operating parameters. To obtain the optimal parameters a simulation approach may be done. In this case, we need a model of the system and the ARX model can be used as the simulation model of the system.

4. Conclusion

The performance of a solar PV-powered vapor compression refrigeration system was evaluated. Simultaneous experimental field studies and simulated studies using the ARX model were conducted to assess the performance of a vapour compression solar refrigeration system. The refrigeration system reached a temperature of 5˚C with the average outdoor and indoor temperatures at 30˚C and 27˚C, respectively. During sunny days, the highest amount of solar energy received was between 11:45 AM and 13:05 PM. An ARX model of the solar PV-powered vapor compression refrigeration system was developed to simulate the cooling temperature inside the cooling chamber. The cooling temperatures obtained from the measurement in the cooling chamber and those predicted by the ARX model were in good agreement, with the discrepancy in terms of *RMSD* in the range of 2.6 – 9.6% and *MBD* of -0.9 – 3.5%.

The energy required for operating the solar PV-powered vapor compression refrigeration system is a clean source, an environment friendly renewable energy source. This study demonstrated that a solar PV-powered vapor compression refrigeration system is technically feasible, which can be proven using the ARX model, which can provide a simple and quick simulation method to assess the performance of solar PV-powered refrigeration systems for cooling household products in areas where electricity is unreliable or the electrical grid system is non-existent.

Nomenclature

$A(z)$ = coefficient of $y(t)$
$B(z)$ = coefficient of $u(t)$
dx_i = uncertainty in the measurement of variable x_i
$e(t)$ = model error (-)
I_{solar} = solar radiation (Wm^{-2})
i = order of data in Eq. 6-8 (-)
k = order of the input and output (-)
MBD = mean bias difference (%)
N = amount of data (-)
$RMSD$ = root mean square difference (%)
R^2 = coefficient of determination (-)
T_indoor = temperature of air inside the hut (˚C)
T_outdoor = temperature of air outside the hut (˚C)
T_water = temperature of water in the cooling chamber (˚C)
$T_{i,measure}$ = cooling temperature from the measurement for the i^{th} data (˚C)
$T_{i,model}$ = cooling temperature from the model for the i^{th} data (˚C)
t = time (minute)
$u(t)$ = input variable at time t
V_PV = voltage of output of solar cell module (V)
V_battery = voltage of battery (V)
x_i = actual value of variable x
x_{mean} = mean value of variable x from measurements
$y_m(t)$ = measured values of variable y at time t
$y_s(t)$ = the simulated values of variable y at time t

y(t) = output variable at time *t*
z = delay operator
Δ = interval of variable

Acknowledgment

Mr. Sattra Sirikeaw, the co-author of this paper, has received a scholarship from Science Achievement Scholarship of Thailand (SAST). We would like to thank SAST for this scholarship.

References

[1] Hundy, G. F., Trott, A. R., & Welch, T. C. (2016). *Refrigeration, air conditioning and heat pumps* (5th edition). Oxford, United Kingdom: Butterworth-Heinemann.
[2] Khurmi, R. S., & Gupta, J. K. (2008). *A Textbook of refrigeration and air conditioning*. New Delhi, India: S. Chand Publishing.
[3] Vaidya, V. N., & Shelke, R. S. (2017). A review on solar power air compression refrigeration system for rural application. *International Journal of Engineering Science and Computing, 7*(3), 4922-4925.
[4] Banjo, S. O., Ajayi, O. O., Bolaji, B. O., Emetere, M. E., Fayomi, O. S. I., Udoye, N. E., Olatunde, A. O., & Akinlabu, K. (2021). Evaluation analysis of a developed solar refrigerator using conventional refrigerant for rural and medical applications. *IOP Conference Series: Earth and Environmental Science*, *665*, 012028.
[5] Hammad, M., & Tarawneh, T. (2018). Performance study of a DC refrigerator powered by different solar PV modular sets: paper II. *Journal of Dynamics of Machines*, *1*(1), 1-11.
[6] Aktacir, M. A. (2011). Experimental study of a multi-purpose PV-refrigerator system. *International Journal of Physical Sciences*, *6*(4), 746-757.
[7] Ekren, O., Yilanci, A., Cetin, E., & Ozturk, H. K. (2011). Experimental performance evaluation of a PV-powered refrigeration system. *Elektronika ir Elektrotechnika*, *114*(8), 7-10.
[8] Sharma, N. K., Singh, H., Sharma, M. K., & Gupta, B. L. (2016). Performance analysis of vapour compression and vapour absorption refrigeration units working on photovoltaic power supply. *International Journal of Renewable Energy Research (IJRER)*, *6*(2), 455-464.
[9] Mba, E. F., Chukwuneke, J. L., Achebe, C. H., & Okolie, P. C. (2012). Modeling and simulation of a photo-voltaic powered vapor compression refrigeration system. *Journal of Information Engineering and Applications*, *2*(10), 1-15.
[10] Su, P., Ji, J., Cai, J., Gao, Y., & Han, K. (2020). Dynamic simulation and experimental study of a variable speed photovoltaic DC refrigerator. *Renewable Energy*, *152*, 155-164.
[11] Gao, Y., Ji, J., Han, K., & Zhang, F. (2021). Comparative analysis on performance of PV direct-driven refrigeration system under two control methods. *International Journal of Refrigeration*, *127*, 21-33.
[12] Kutlu, C., Erdinc, M. T., Li, J., Wang, Y., & Su, Y. (2019). A study on heat storage sizing and flow control for a domestic scale solar-powered organic Rankine cycle-vapour compression refrigeration system. *Renewable Energy*, *143*, 301-312.
[13] Achuthan, M., Venkataraman, A., & Rathnasamy, R. (2011). Experimental analysis on the performance and characteristics of compact solar refrigeration system. *Distributed Generation & Alternative Energy Journal*, *26*(3), 66-80.

[14] Furler, G. (1993). *Modelling of a photovoltaic powered refrigeration system* (Master's thesis). Madison, University of Wisconsin–Madison.

[15] Ljung, L. (1987). *System identification: Theory for the user.* New Jersy, USA: P T R Prentice Hall.

[16] Wasserman, P. D. (1989). *Neural computation: Theory and practice.* New York, USA: Van Nortrand Reinhold.

[17] Doiebelin, E. (1976). *Measurement systems*. New York, USA: The McGraw-Hill Companies.

[18] Holman, J. P. (2012). *Experimental methods for engineers* (8th edition). New York, USA: McGraw-Hill Companies.

[19] Schenck, H., & Richardson, P. (1979). *Theories of engineering experimentation*. New York, USA: McGraw-Hill Companies.

[20] Duffie, J. A. & Beckman, W. A. (2013). *Solar engineering of thermal processes* (4th edition). New York, USA: John Wiley and Sons.

[21] Ríos-Moreno, G. J., Trejo-Perea, M., Castañeda-Miranda, R., Hernández-Guzmán, V. M., & Herrera-Ruiz, G. (2007). Modelling temperature in intelligent buildings by means of autoregressive models. *Automation in Construction, 16*(5), 713-722.

[22] Blaifi, S. A., Moulahoum, S., Taghezouit, B., & Saim, A. (2019). An enhanced dynamic modeling of PV module using Levenberg-Marquardt algorithm. *Renewable Energy, 135*, 745-760.

[23] O'Callaghan, J. R., Menzies, D. J., & Bailey, P. H. (1971). Digital simulation of agricultural drier performance. *Journal of Agricultural Engineering Research*, *16*(3), 223-244.