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Thermal performance analysis of an inclined passive solar still using agricultural drainage water and artificial neural network in arid climate

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ABSTRACT

In this study, a model based on artificial neural network (ANN) was developed in order to predict the thermal performance of an inclined passive solar still in an arid climate, in which the thermal performance of the still was expressed as instantaneous thermal efficiency (ITE). Agricultural drainage water (AWD) was used as a feed for the desalination process, and this is considered a non-conventional water source. Appropriate meteorological variables, viz., ambient air temperature, relative humidity, wind speed, and solar radiation were used alongside the key operational variables, viz., flow rate, temperature, and total dissolved solids of feed water were used as input variables. The results revealed that an ANN with six neurons and a hyperbolic tangent transfer function was the most appropriate model for ITE prediction. Consequently, the optimal ANN model had a 7–6–1 architecture. The results also indicated that the optimal ANN model forecast the ITE accurately, with a mean root mean square error (RMSE) of just 1.933% and a mean coefficient of determination (CD) of 0.949. To create a sensible comparison, a multiple linear regression (MLR) model was also developed. It was found that the ANN model performed better than the MLR model, which displayed a mean RMSE of 4.345% and a mean CD of 0.739. The mean relative errors of forecasted ITE values within the ANN model were mostly in the region of +8% to −6%. One major output of this research is a comprehensive assessment of the ANN modeling technique for the ITE of a solar still, which adds a new perspective to system analysis, design and modeling of the potential productivity of solar stills in terms of the AWD desalination process.

1. Introduction

Globally, water consumption is dominated by agricultural activities, especially irrigation which account for 70% of consumption (WWAP, 2014), while approximately two-thirds of the water delivered to irrigated fields is lost as agricultural drainage or runoff (Gregory, 2012). However, the availability of plenty of agricultural drainage water (ADW) creates promising opportunities for desalinating significant quantities of water from this non-conventional source. The selection process of the appropriate method for desalinating this source is challenged by numerous technical, financial, and environmental issues to be taken into account (Sorour et al., 2003). Most published studies and research consider conventional desalination methods operated by fossil fuel energy or electrical energy for AWD desalination (Sorour et al., 1992; Abulnour et al., 2003; Talaat and Ahmed, 2007; McCool et al., 2010). Recently, some studies have proposed using solar energy for the AWD desalination process (Stuber et al., 2015; Mashaly et al., 2015a).

The solar still desalination system (SSDS) for AWD is a strategic option that can be used for producing fresh water suitable for agricultural, irrigation, and potable purposes (Mashaly et al., 2015b) and reducing the drainage water volume, which would minimize the environmental problems associated with it. Moreover, the SSDS exploits a sustainable and pollution-free source to yield high-quality water (Ayoub and Malaeb, 2012) and is one of the best solutions for facing water crises in remote arid and hyper-arid environments. It can be fabricated without difficulty with locally available materials and its operation is simple and easy, with no need for hard maintenance or skilled labor. This results in little operation and maintenance costs (Omara and Kabeel, 2014).

On the other hand, the SSDS is not popular because of its lower thermal performance and this is reflected in its efficiency. Of course, this will cause fear and hesitation for many people considering using it in the AWD desalination process. Thus, thermal performance analysis for the SSDS is very important. This enables us to know the thermal capacity of the SSDS and its potential productivity

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Nomenclature

ADW	agricultural drainage water
ANN	artificial neural network
AS	area of solar still
AVG	average value
B_j	biases in the hidden layer
B_k	biases in the output layer
BP	back propagation
CC	correlation coefficient
CD	coefficient of determination
CRM	coefficient of residual mass
CS	Chi-square
CV	coefficient of variation
F_h	activation function of the neuron in the output layer
F_o	activation function of the neurons in the hidden layer
ITE	instantaneous thermal efficiency
KPIs	key Performance Indicators
KUR	kurtosis value
LHV	latent heat of vaporization
MAE	mean absolute error
MAX	maximum value
ME	coefficient of model efficiency
M_F	feed flow rate
MIN	minimum value
MLP	multilayer perceptron
MLR	multiple linear regression
MXE	maximum error
OI	overall index of model performance
RH	relative humidity
RMSE	root mean square error
SD	standard deviation
SE	standard error
SIG	sigmoid transfer function
SKW	Skewness value
SR	solar radiation
SSDS	solar still desalination system
TANH	hyperbolic tangent transfer function
TDS_F	total dissolved solids of feed water
T_F	temperature of feed water
T_o	ambient temperature
W_{ji}	weights between input and hidden layers
W_{kj}	weights between hidden and output layers
WS	wind speed

and thermal efficiency. Actually, the precise and detailed thermal performance of the SSDS is quite complicated because of the many parameters involved, as its operation is governed by many heat transfer processes (Shukla, 2014). Consequently, efforts should be made to combine a number of the most vital parameters into an algebraic expression and formulate a mathematical model that can describe the thermal performance of the SSDS in a computationally efficient manner.

The question is how to model the thermal performance (i.e. the useful energy gain or the solar still thermal efficiency). Compared with classical modeling procedures, artificial neural networks (ANNs) show superiority as a modeling procedure for data sets presenting non-linear relationships and thus for both data-fitting and prediction capabilities (Bourquin et al., 1998). ANNs are non-linear models that mimic the learning process of the human brain, as the equations that can most efficiently diminish the gap between predicted data and observed data are chosen iteratively (Goh, 1995). They can be a powerful tool for predicting, optimizing and simulating complex nonlinear processes (Lek and Guégan, 1999; Basheer and Hajmeer, 2000; Fadare, 2009). Thermal solar energy systems can be precisely modeled using ANNs (Kalogirou et al., 1999a). Several studies have presented the applications of ANNs in the field of solar energy applications for various agricultural activities (Ferreira et al., 2002; Tripathy and Kumar, 2009; Çakmak and Yildiz, 2011; Arif et al., 2012; Dursun and Özden, 2014). Furthermore, ANNs have been widely employed in multiple ways to model, optimize, estimate, and forecast the performance of various desalination and solar desalination systems (Abbas and Al-Bastaki, 2005; Khayet et al., 2011; Porrazzo et al., 2013; Mashaly et al., 2015c; Aish et al., 2015; Mashaly and Alazba, 2016a, 2016b, 2016c; Cao et al., 2016; Mashaly and Alazba, 2017).

However, most of the existing/previous research on the SSDS has focused on modifying the solar still design configuration to enhance and improve the thermal efficiency, productivity, and performance of the still (Rai and Tiwari, 1983; Singh and Tiwari, 2004; Tripathi and Tiwari, 2005; Tiwari and Tiwari, 2006; Velmurugan et al., 2009; Monowe et al., 2011; Abderachid and Abdenacer, 2013; Refalo et al., 2016; Sharon et al., 2017). On the other hand, SSDS should be optimally designed and operated, and predictive modeling of thermal efficiency is one of the crucial parameters to be precisely estimated since it helps us to know the potential efficiency attainable by the SSDS and to ensure obtaining the best performance and optimal productivity and efficiency. To our knowledge, there has been no previous research directly examined and focused on determining the effectiveness of modeling thermal efficiency of SSDS desalinated AWD using ANNs. In the current study, we are planning to take a step towards this objective by implementing, developing and analyzing an ANN model for estimating thermal efficiency, which was expressed here as instantaneous thermal efficiency (ITE). The aims of this study are to (1) develop a mathematical model to estimate the ITE using ANNs; (2) assess and analyzes the performance of the developed ANN model by comparing the ITE results obtained from the ANN and the experimental results statistically; (3) compare the ANN model with multiple linear regression (MLR) model in terms of their appropriateness and accuracy for predicting ITE; and (4) determine the importance or contribution of each variable in modeling process.

2. Materials and methods

2.1. Experimental set-up

The experiments were conducted at the Agricultural Research and Experiment Station at the Department of Agricultural Engineering, King Saud University, Riyadh, Saudi Arabia (24°44′10.90″ N, 46°37′13.77″E) between October and November 2013. The weather data were obtained from a weather station (model: Vantage Pro2; manufacturer: Davis, USA) close by the experimental site (24°44′12.15″N, 46°37′14.97″E). The solar still system used in the experiments was constructed from a 6 m^2 single stage C6000 panel (F Cubed. Ltd., Carocell Solar Panel, Australia). The solar still panel was manufactured using modern, cost-effective materials such as coated polycarbonate plastic. When heated, the panel distilled a film of water that flowed over the absorber mat of the panel. The panel was fixed at angle of 29° from the horizontal plane. The basic construction materials were galvanized steel legs, an aluminum frame and polycarbonate covers. The transparent polycarbonate was coated on the inside with a special material