International Journal of Engineering & Technology, 7 (3.16) (2018) 90-93

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Simulation Models of the Seawater Greenhouse

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Abstract

In arid climates, extremely high temperatures in the summer and the chronic water scarcity put a firm barrier against agricultural development and sustainability. The SWGH technology is an engineering phenomenon that came to overcome both the constraints particularly in areas where seawater is accessible and/or brackish groundwater is available. It is a greenhouse used to cultivate crops and at the same time produce its own freshwater need. This study aimed to highlight the models that were carried out to simulate the SWGH as a whole or only the dehumidification rate of the SWGH condenser. Four types of simulation models were identified, namely, analytical, numerical, empirical and artificial neural network simulations. The factors affecting the dehumidification rate were also discussed taking into consideration the results from the simulation models.

Keywords: *Analytical; numerical; empirical; ANN; Simulation models*

1. Introduction

In arid and semi-arid climates, agricultural development is curbed with two major obstacles, namely, extremely hot weather which not conducive for most vegetable crops and water unavailability. The seawater greenhouse (SWGH) offers a solution for both the obstacles. It is an evaporatively-cooled greenhouse that provides suitable microclimate for plant growth and at the same time, it produces its own irrigation water. Figure 1 illustrates the working protocol of the SWGH.

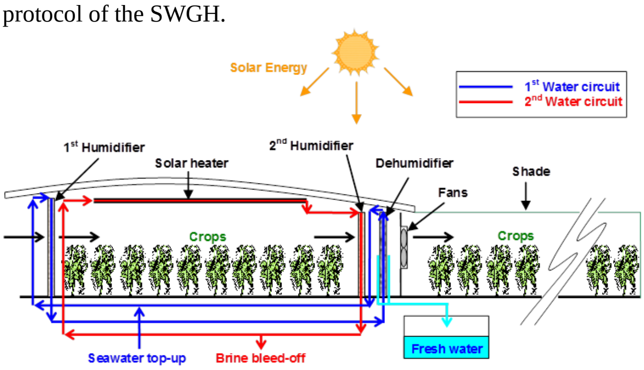

Fig. 1. Schematic of the SWGH (Al-Ismaili, 2009).

Seawater, saline groundwater or water byproduct from oil industry can be used to moisten the two humidifiers of the SWGH (Bailey and Raoueche, 1998; Bourouni et al., 2011; Davies et al., 2004a). The first humidifier produces cooler air with more moisture as a result of the evaporative cooling process. In addition to cooling the ambient air, the first humidifier reduces the temperature of the saline water used to moisten the humidifier itself (Al-Ismaili and Jayasuriya, 2016). By the end of the cropping area, the air becomes warmer due to the solar heat load and carries more moisture from the evapotranspiration process. However, in terms of relative humidity, the air becomes drier due to the simultaneous increase in temperature (Al-Ismaili, 2003). Solar preheated saline water is used in the second humidifier to increase air temperature due to convection and to saturate it due to evaporation (Al-Ismaili and Jayasuriya, 2016). In the dehumidifier, cold saline water from the first humidifier is used as a coolant in order to produce a temperature gap between the moist air and the surface of the condenser which is very crucial in the condensation process (Al-Ismaili and Jayasuriya, 2016; Alkhalidi et al., 2013; Mahmoudi et al., 2010). To date, some SWGH modules managed to generate more freshwater than their own need and others failed to do so. For instance, the SWGH in Oman managed to produce an average amount of about 300 L/day which is less than the daily irrigation requirement (Mahmoudi et al., 2008). Attempts to improve the effectiveness of the SWGH are still on-going. This study aims to highlight the simulation work that was carried on the SWGH technology since its advent.

2. Simulation Models

The SWGH received a substantial attention from a large number of researchers aiming to understand the thermodynamic process taking place in the greenhouse and as a result, to enhance these processes for better effectiveness. Some of these models simulated all components of the SWGH while the majority simulated only the dehumidification rate of the condenser. The discussion in this section will be divided according to the four types of simulation models found in literature, namely, analytical, numerical, analytical and artificial neural network (ANN) models.

2.1. Analytical Modelling

Raoueche (1997) was credited with the first attempt to simulate the SWGH technology by simulating all components and processes of the SWGH module in Tenerife, Spain (Fig. 2). The simulated components included the first evaporative cooler, greenhouse microclimate, humidifier and condensation between the two layers of the roof, second humidifier and the condenser (Bailey and Raoueche, 1998; Raoueche et al., 1996). Results from this simulation were used to improve the performance of the forthcoming modules of the SWGH.

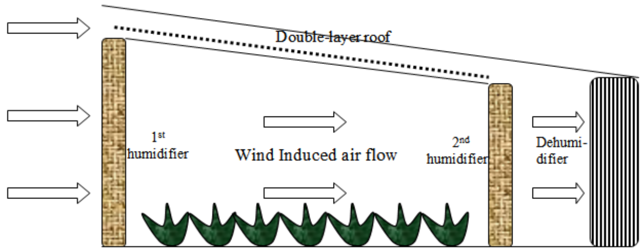

Fig. 2: Illustration of the Tenerife SWGH [re-sketched from: Raoueche and Bailey (1997)]

Heat and mass transfer balances were used as the bases for the analytical modeling by many researchers. For instance, the effectiveness of the SWGH condenser was studied by Davies and Paton (2006). This simulation included the two humidifiers, cropping area and condenser and emphasized on the importance of reducing the solar heat load to the greenhouse because otherwise it would necessity higher freshwater production. Considering the same components and processes, another simulation model was developed and executed in Matlab software to optimize the effectiveness of the SWGH taking into account the Tenerife SWGH module. The accuracy of the predicted results was matching well with the measured values.

Paton et al. (2001) conducted a very thorough simulation to study the feasibility and adaptability of the SWGH technology in Oman. This study predicted a maximum freshwater production of 125 m3/ha.day under the local weather conditions of Oman (Goosen et al., 2001; Sablani et al., 2003). The results from this study encouraged the construction of the SWGH module in Oman (Fig. 3). However, the actual freshwater production from the Oman SWGH was far less than the predicted amount (Al-Ismaili and Jayasuriya, 2016). Another simulation focused on the condensation unit of the SWGH and concluded that the most appropriate cooling technique for the condenser is to use the outflow water from the first evaporative cooler as a coolant (Dawoud et al., 2006). This study also proposed to split the water circulation inside the greenhouse in two water circuits such that one circuit connects the first evaporator with the condenser and the other one connects the second evaporator with the solar heater. Both suggestions from this study are currently implemented in the Oman SWGH.

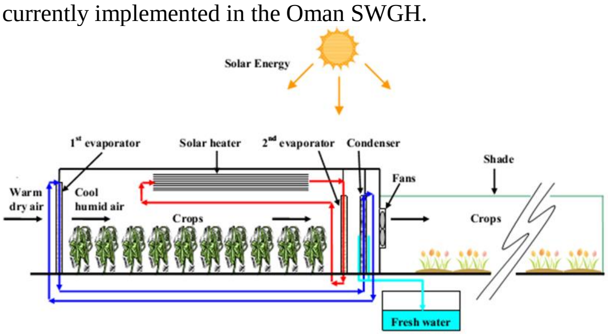

Fig. 3: Schematic of the Oman SWGH (Al-Ismaili and Jayasuriya, 2016).

A very detailed analytical simulation for all components and processes of the SWGH was conducted by Zurigat et al. (2008). However, the accuracy of this simulation is still unknown because there was no validation experiments conducted as part of this study. A heat-balance simulation was developed to predict the dehumidification rate of the condenser in the Oman SWGH (Fig. 4) as influenced by inlet moist air temperature, humidity and solar radiation (Tahri et al., 2009a; Tahri et al., 2009c). When the predicted and measured values were compared against each other, it was found that the model was deviating from the measured values by 8-15%. A similar simulation model was developed by Douani et al. (2011) to predict the dehumidification rate but still some inaccuracy between predicted and measured values was noticed. To reduce this inaccuracy, Tahri et al. (2013b) developed a mass-balance model to predict the dehumidification rate. Results showed a good agreement between predicted and measured values.

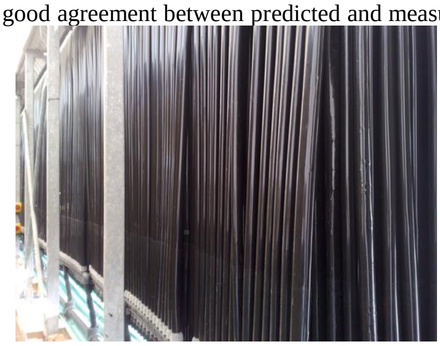

Fig. 4: The cross-flow plastic condenser of the Oman SWGH.

Another analytical model aiming to predict the dehumidification rate of the condenser in the Oman SWGH was conducted by Hajiamiri and Salehi (2013). In another study, Zamen et al. (2013) proposed, designed and simulated a new type of condensers for the Oman SWGH. This condenser is a direct-contact condenser where the moist air and the coolant are in direct-contact to enhance the condensation rate. Results showed that the new condenser will produce significantly more freshwater using a cheaper technology than the existing indirect cross-flow plastic condenser.

2.2. Numerical Modelling

The numerical simulation technique has not received proper attention by researchers. In one study, CFD approach was used to simulate the wind flow surrounding the Tenerife SWGH and to find the effect of wind direction on freshwater production (Davies et al., 2004b). From this study, the best orientation for the SWGH was identified. Using the UAE SWGH module (Fig. 5), another CFD model was used to simulate the air flow effect on freshwater production and the greenhouse microclimate temperature. Figure 6 illustrates the air velocity field inside the UAE SWGH as simulated by the CFD model.

Fig. 5: The UAE SWGH (Davies and Paton, 2005).

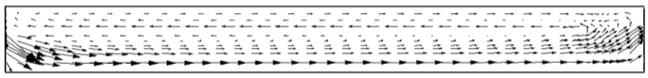

Fig. 6: Air velocity inside the UAE SWGH as simulated by the CFD Model (Davies and Paton, 2005).

2.3. Empirical Modelling

To date, three empirical models simulating the freshwater production of the SWGH condenser are available. Equation (1) represents the first empirical model used to predict the freshwater production rate (R_c, m^3/day) as a influenced by the width (W, m) and length (L, m) of the greenhouse. However, when comparing the actual measurements of the production rate with predicted values, Al-Ismaili and Jayasuriya (2016) noticed a significant overestimation of the freshwater production rate using this model.

$$R_c = 81.861\ (W/L)^{0.1571} \quad (1)$$

The second empirical model (Eq. 2) was developed by Yetilmezsoy and Abdul-Wahab (2014) to predict the freshwater production (Rc, kg/hr) of the SWGH as a function of five input variables, viz., moist air dry bulb temperature ($T_{a,in}$, °C), relative humidity ($RH_{a,in}$, fraction), mass flowrate ($m_{a,in}$, kg/s), and coolant temperature ($T_{w,in}$, °C) and mass flowrate ($m_{w,in}$, kg/s).

$$R_c=[0.001883\ (T_{a,in})^{2.915}\ (RH_{a,in})^{3.382}\ (m_{a,in})^{0.222}] \div [(T_{w,in})^{0.147}\ (m_{w,in})^{0.073}] \quad (2)$$

The third model (Eq. 3) was recently developed to predict the dehumidification rate of the SWGH condenser using four input variables, namely, ambient solar radiation (S, W/m^2), moist air dry bulb temperature (T_{ai}, °C), humidity ratio (H_{ai}, kg/kg) and mass flowrate (m_a, kg/s) (Al-Ismaili et al., 2018). It was found the third model was more accurate than the second model as verified using five performance indicators, i.e. R^2, root mean square error, mean predictive error, mean absolute predictive error and fractional variance.

$$R_c=-10.782 + 0.0413\ S - 0.471\ T_{ai} + 650.300\ H_{ai} + 0.973\ m_a \quad (3)$$

2.4. ANN Modelling

The ANN simulation approach received the least attention among the SWGH researchers. Zarei et al. (2017) conducted the only study implementing the ANN approach to simulate the dehumidification rate of the SWGH condenser. In this study, the dehumidification rate and energy consumption were predicted using the Support Vector Regression method within the ANN simulation. The input variables of the simulation included the width and length dimensions of the greenhouse, transparency of the covering material, the height of the first humidifier, second humidifier, condenser and cultivation chamber, wall thickness, seawater pipe diameter, air and water volumetric flowrates and greenhouse orientations. The ANN model provided that optimal greenhouse design and operating conditions that gives the highest dehumidification rate (161.6 m^3/day) at the lowest energy consumption (1.558 kWh/m^3.day).

3. General Remarks

The effectiveness of the SWGH technology solely relies on the effectiveness of the condenser (Alkhalidi et al., 2010; Ghaffour et al., 2015). From the above simulation models, it was found that the dehumidification rate of the SWGH condenser is directly proportional to the air velocity through the condenser (Tahri et al., 2013a; Tahri et al., 2012), solar radiation intensity (Tahri et al., 2010), moist air dry bulb temperature (Tahri et al., 2009b), moist air humidity (Alkhalidi et al., 2010) and water flowrate in the first humidifier (Salehi et al., 2011) and inversely proportional to air flowrate through the first humidifier (Salehi et al., 2011) and coolant temperature (Eslamimanesh and Hatamipour, 2009). The solar radiation intensity was deemed the most important climatic factor influencing the dehumidification rate (Bourouni et al., 2011; Kabeel and Almagar, 2013).

4. Conclusion

In this study, four types of models were used to simulate the SWGH components and processes. These types were the analytical, numerical, empirical and artificial neural network (ANN) simulations. The analytical simulation received the largest attention among researchers and the ANN simulation received the least. Some of these models were dedicated to simulate all components and processes of the SWGH while the majority was only focusing on the simulation of the dehumidification rate of the condensation unit. Through simulation, the factors positively and negatively affecting the dehumidification rate were identified.

Acknowledgement

We would like to express our sincere thanks to Sultan Qaboos University for the research grant provided through His Majesty Research Fund (Project # SR/AGR/SWAE/17/01).

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