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SIMULATION OF THE CONDENSER OF THE SEAWATER GREENHOUSE
Part II: Application of the developed theoretical model

T. Tahri[1], *S. A. Abdul-Wahab*[2*], *A. Bettahar*[1], *M. Douani*[1], *H. Al-Hinai*[2] *and Y. Al-Mulla*[3]

[1]Faculty of Sciences and Engineering Sciences, Hassiba Ben Bouali University, P.O. Box 151, Chlef 02000, Algeria
[2]College of Engineering, P.O. Box 33, Sultan Qaboos University, Al-khod 123, Sultanate of Oman
[3]College of Agricultural and Marine Sciences, P.O. Box 34, Sultan Qaboos University, Al-Khod 123, Muscat, Sultanate of Oman

A theoretical model is developed in Part I of this study to simulate the physical process of condensation of the humid air in the condenser of an existing seawater greenhouse that is located in Muscat, Oman. Application is conducted in this part to validate the theoretical developments. Comparisons are made between the predictions and the existing experimental results. The results indicate that the comparison is well consistent. The effect of the relative humidity, the dry bulb temperature and the solar radiation are also discussed to see their effects on the condensate values.

Keywords: *condensation,condenser, heat and mass model, seawater greenhouse, simulation, Sultanate of Oman*

Introduction

Irrigation demand puts considerable pressure on renewable water resources which often leads to groundwater deficit. The economical and social consequences are apparent in many coastal regions of arid countries such Oman where the overuse of groundwater has caused saline intrusion, which in turn has reduced the ability to grow crops and resulted in agricultural land being discarded [1, 2]. Arid countries may suffer from of lack fresh water but they generally can benefit from great solar energy potential. Thus, solar desalination may provide a sustainable solution to supply dry regions with fresh water [3]. Indeed, solar distillation projects have been demonstrated in several locations around the world [4, 5].

The seawater greenhouse is a new development that produces fresh water from sea water, and cools and humidifies the growing environment, creating optimum conditions for the cultivation of temperate crops [6]. The use of greenhouses in arid regions decreases crop water requirements by reducing evapotranspiration. The plastic cover utilized on these structures changes locally the radiation balance by entrapping long-wave radiation and creates barrier to moisture losses. As a result, evapotranspiration is reduced by 60 to 85% compared to outside the greenhouse [7]. The concept of the seawater greenhouse has been developed in collaboration with a number of distinguished research organizations and tested with a prototype on the Canary Island of Tenerife [8]. The solution lies in augmentation of fresh water resources [2]. The high cost of fuel-powered desalination (multi-stage flash and reverse osmosis) does not render these techniques feasible for arid land agriculture [9]. Thermodynamic modelling has shown that the dimensions of the greenhouse have the greatest overall effect on the water production and on the energy consumption. Low power consumption went hand-in-hand with high efficiency. A wide shallow greenhouse, 200 m wide by 50 m deep gave 125 m^3 per day of fresh water. This was greater than a factor of two compared to the worst-case scenario with the same overall area (50 m wide by 200 m deep), which gave 58 m^3 per day. The wide shallow greenhouse consumed 1.16 KWh m^{-3}, while the narrow deep structure consumed 5.02 KWh m^{-3} [10]. The system consists of a salt gradient solar pond, which was used to load the air with humidity. Fresh water was collected by cooling the air in a dehumidifying column [11]. In a similar study, a closed-air cycle humidification-dehumidification process was used by Al-Hallaj *et al.* [12] for water desalination. The humidification-dehumidification method was used in a greenhouse-type structure for desalination and for crop growth as a pilot plant at Al-Hail [6], Muscat, in the Sultanate of Oman. Their seawater greenhouse produced fresh water and crop cultivation in one unit. It was suitable for arid regions that have seawater nearby. The temperature differences between the solid surfaces heated by the sun and cold water drawn from below the sea surface was the driving force in the system. The greenhouse acted as a solar still providing

* Author for correspondence: sabah1@squ.edu.om

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Akadémiai Kiadó, Budapest, Hungary
Springer, Dordrecht, The Netherlands

a controlled environment inside the greenhouse. A thermodynamic model was employed in analysis of water production and energy consumption [13]. The greenhouse is equipped with humidification-dehumidification devices which create the proper climate to grow valuable crops and at the same time produce freshwater from saline water. The need to employ the greenhouse in coastal and isolated regions has driven the search for energy from renewable sources such as wind and solar power [14].

An overview on the possible cooling technologies of the condenser of a seawater greenhouse desalination technique was described by Dawoud *et al.* [15]. The possibilities to cool water of such condenser are to apply evaporative cooling for surface seawater, to make use of a cooling machine, or to utilize deep seawater as a condenser coolant [15]. After the work of Merkel [16], who developed the basic theory of evaporative cooling, Berliner [17] has described the basics of calculating and constructing different types of cooling towers. Poppe and Rögener [18] developed design algorithms for evaporative cooling systems.

In this present study, the performance of the condenser of the seawater greenhouse was simulated to determine the amount of water condensate. The simulated condensate values were compared with that of the actual measured values. The relationships between the amount of condensate and other variables such as the relative humidity, the solar radiation and the dry bulb temperature were also investigated.

Condenser process description

The real picture of the existing seawater greenhouse in the Sultanate of Oman is shown in Fig. 1. Details about the idea of its operation and the principal parameters of its design are given in Tahri *et al.* [19]. The condenser of the seawater greenhouse is a heat exchanger where the seawater is the coolant and the humid air is the hot fluid. The condenser consists of a set of 302 rows of parallel tubes arranged vertically and with an angle of 30 degrees with the direction of flow of humid air. Each row has 14 identical vertical tubes with diameter of 33 mm (D) and a height of 1.8 m (L).

Fig. 1 Seawater greenhouse at Al-Hail, Muscat, Oman

Results and discussion

Variation of the average heat transfer coefficient for film condensation (h_{ave})

The weekly variation of the average heat transfer coefficient for film condensation (h_{ave}) according to the location of the tubes of the condenser during the period of 20 December 2005 to 6 February 2006 is shown in Fig. 2a. It can be seen that the average heat transfer coefficient for film condensation increased along the length of the condenser. Larger value of h_{ave} was seen in the last tube of condenser whereas the lower value of h_{ave} was seen in the first tube. This behavior is attributed to the lower difference between the saturation and the outer wall temperatures (T_{sat}–T_{wout}) along the length of the condenser which results in increasing the values of h_{ave} as shown in Eq. (16) in the first part of this article. The reduction in the difference (T_{sat}–T_{wout}) along the length of the condenser may be explained to the decrease of the dry bulb temperature (T_{db}) which results in the decrease of

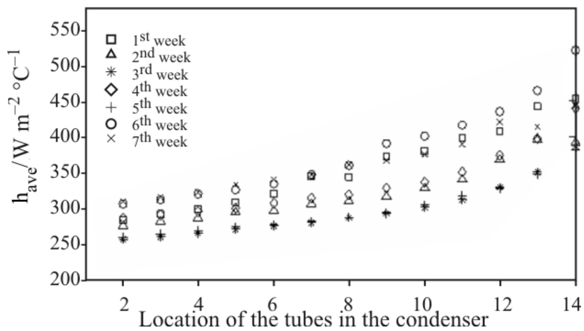

Fig. 2a Variation of the calculated weekly average of heat transfer coefficient for film condensation h_{ave}

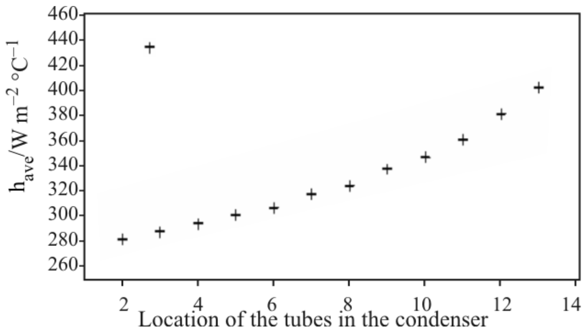

Fig. 2b The average overall heat transfer coefficient for film condensation

the saturation temperature (T_{sat}) as well. On the other hand, the seawater temperature (T_{sw}) is expected to increase which results in the increasing of the outer wall temperature (T_{wout}) of the tubes along the length of the condenser. Accordingly, this results in decreasing the difference between the saturation and the outer wall temperatures (T_{sat}–T_{wout}) along the length of the condenser. The average overall heat transfer coefficient for film condensation during the total period of study (20 December 2005 to 6 February 2006) is illustrated in Fig. 2b. It can be seen that the values of h_{ave} was varied with the week, although they showed a similar trend.

Comparison between the measured and predicted mass condensate rate

The daily measured and calculated values of the mass condensate rates resulting from the condenser of the seawater greenhouse during the period from 30 December 2005 until 9 January 2006 are shown in Fig. 3a. It should be noted that the measured mass condensate were taken from the freshwater tank by the tipping bucket gauge whereas the predicted mass condensate were calculated directly as they formed at the outer surface of the tubes of the condenser. Although, it is noted that the trend of the predicted and the measured mass condensate rates were close, a gap was clearly seen between them. This gap is attributed to the tipping bucket gauge which did not register outflow from the condenser due to low production rate of condensate. Formation of water droplets on the fins and tubes of the condensers were observed but only a small fraction of the droplets made their way to the gutter collecting the condensate [2]. Hence, the predicted mass condensate rates were calculated instantaneously as they condense at the outer surface of the tubes of the condenser whereas the measured mass condensate was taken from the fresh water tank.

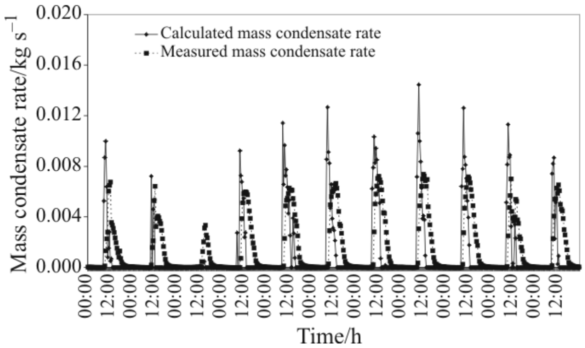

Fig. 3a Comparison of the measured and calculated mass condensate rate of the condenser in the seawater greenhouse Muscat (30 December 2005 to 9 January 2006)

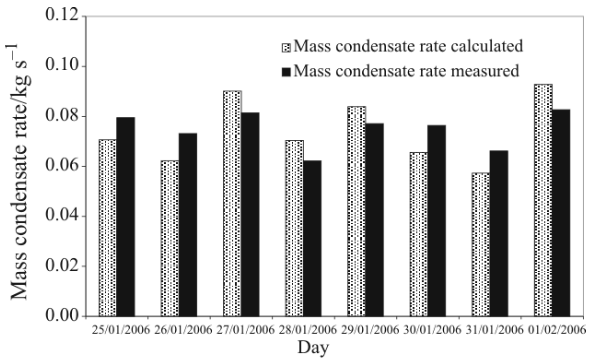

Fig. 3b Comparison of the measured and the calculated average mass condensate rate of the condenser in the seawater greenhouse Muscat (25 January 2006 to 1 February 2006)

Table 1 Diurnal mass condensate rate of the condenser

Day	Mass condensate rate/kg s^{-1}		Rel. error/%
	Calculated	Measured	
25/01/2006	0.0706	0.0795	11.2
26/01/2006	0.0623	0.0731	14.7
27/01/2006	0.0901	0.0814	10.6
28/01/2006	0.0704	0.0622	13.2
29/01/2006	0.0839	0.0771	8.8
31/01/2006	0.0656	0.0764	14.1
31/01/2006	0.0573	0.0662	13.4
01/02/2006	0.0928	0.0827	12.2

Figure 3b and Table 1 compare the measured and the calculated total mass condensate rates with the day during the period from 25 January 2006 to 1 February 2006. It can be seen clearly that the measured mass condensate rates were close to calculated mass condensate rates predicted by the model. Table 1 indicates that the relative errors between the measured and the calculated mass condensate rates were in the range of 8–15%.

Figure 3c shows the calculated and measured mass condensate rates according to the hours of the day of 20 January 2006. Looking at Fig. 3c, it can be seen that there was a time gap between the calculated and the measured condensate rates as mentioned before (Fig. 3a). For example, the predicted mass condensate rate formed in the outer surface of the tubes of the condenser was calculated at 08:00 whereas the measured mass condensate rate collected in the freshwater tank was taken after 1 h (at 09:00).

Impact of the meteorological variables on the mass condensate rates

In solar system design it is essential to know the amount of sunlight available at a particular location at

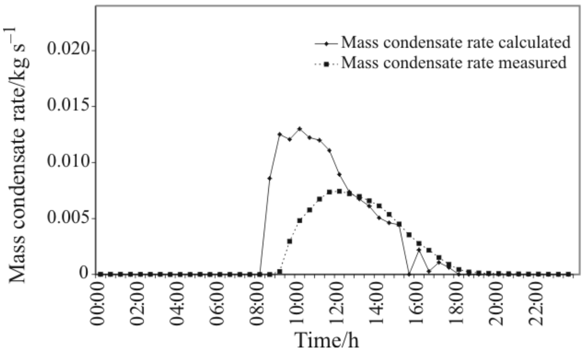

Fig. 3c Comparison of the diurnal measured and calculated mass condensate rate of the condenser in the seawater greenhouse Muscat (20 January 2006)

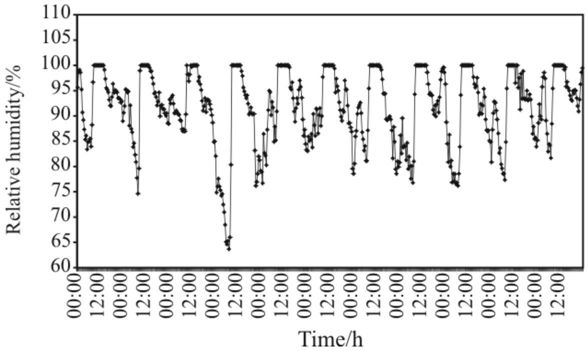

Fig. 4c Variation of the inlet relative humidity in the condenser (30 December 2005 to 9 January 2006)

a given time. The common method which characterizes the amount of sunlight is the solar radiance [14]. The solar radiance is an instantaneous power density in units of kW m^{-2}. Figure 4a shows solar radiation values inside the seawater greenhouse which are taken every half an hour during the period from 30 December 2005 to 9 January 2006. Figure 4b shows the distribution of the dry bulb temperatures taken every half hour at the entrance of the condenser during the period from 30 December 2005 to 9 January 2006, whereas Fig. 4c describes the distribution of the relative humidity values taken every half hour at the entrance of the condenser during the same period. Figure 5a shows the variation of the measured and the predicted mass condensate rates together with the solar radiation. The data were depicted every half an hour for the day of 20 January 2006. It can be seen that the solar radiation values were observed only during the interval from 08:00 to 18:00. and it was almost null during the night time. In general, it can be noted that the amount of the calculated and measured mass condensate rates went hand-in-hand with solar radiation.

Figure 5b shows the variation of the measured and the predicted mass condensate rates together with the dry bulb temperature. The data were depicted

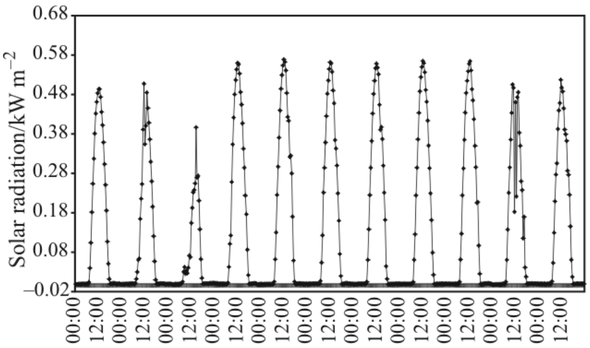

Fig. 4a Variation of the solar radiation inside the SWGH (30 December 2005 to 9 January 2006)

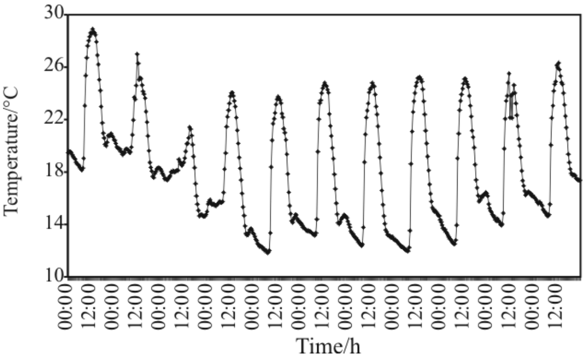

Fig. 4b Variation of the inlet dry bulb temperature in the condenser (30 December 2005 to 9 January 2006)

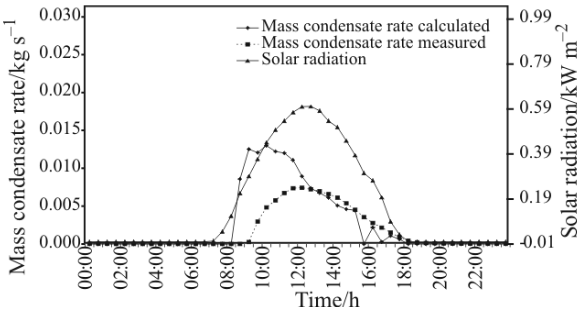

Fig. 5a Comparison of the diurnal mass condensate rate and the solar radiation inside SWGH (20 January 2006)

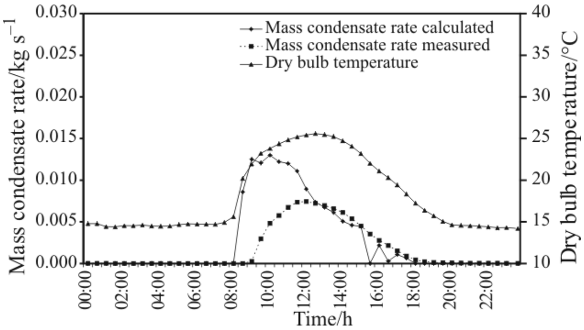

Fig. 5b Comparison of the diurnal mass condensate rate and the inlet dry bulb temperature (20 January 2006)

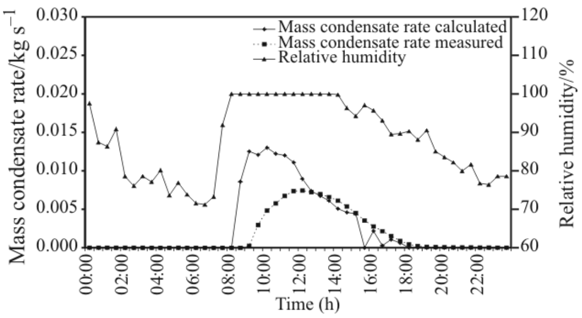

Fig. 5c Comparison of the diurnal mass condensate rate and inlet relative humidity (20 January 2006)

every half an hour for the day of 20 January 2006. It can be noted that the two plots of the measured and the predicted mass condensate rates were seen to follow the same trend of the dry bulb temperature (i.e., condensate went hand-in-hand with dry bulb temperature).

Figure 5c depicts the variation of the measured and the predicted mass condensate rates together with the relative humidity which drawn every half an hour for the day of 20 January 2006. It can be seen that the relative humidity values were high (100%) between 08:00 and 14:00 while lower values ($RH \geq 65\%$) were seen during the rest of the day. It should be noted that in the interval extended from 09:00 to 18:00, the seawater greenhouse produced 98% of the total daily freshwater. This is consistent with the interval when the relative humidity values were high (100%).

Conclusions

This paper discussed the simulation of the condenser of the seawater greenhouse at Al Hail in Muscat, Oman. For this purpose, a theoretical model was developed to describe the process of the condensation by using the heat and mass transfer equations. A comparison was made between the mass condensate rate values calculated by the model with that of the corresponding measured values. The results of the comparison were consistent with calculated error in the range of 8.0–15.0%.

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