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Sensitive analysis on an integrated system of brackish water greenhouse desalination for freshwater production and crop growth

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ABSTRACT

In order to provide favourable conditions for the crop growth and freshwater for irrigation, a novel integrated system of brackish water greenhouse desalination (BWGD) with return air is proposed. A one-dimensional steady-state model of the proposed BWGD has been developed to investigate sensitive analysis of factors based on orthogonal test method. The thermal stratification phenomena caused by the return air divides the internal space of the greenhouse into the crop layer and internal air layer. Both the favourable temperature of the crop layer and optimal freshwater production can be satisfied by merely regulating the most significant factors of inlet brackish water temperature and flow rate of condenser while the air temperature and relative humidity at the conditions of the optimal freshwater production does not favor the crop growth in the classical BWGD. The maximum freshwater production does not occur at 11 am when the solar radiation is the greatest due to the thermal stratification phenomena. The freshwater production of 1,118 L/d outweighs the total irrigation demand of 1,082 L/d. The proposed BWGD, which is an important step forward towards improving the performance of BWGD, provides innovative solutions to the problems of water for agriculture and the crop growth.

Keywords: Greenhouse; Brackish water desalination; Sensitive analysis; Orthogonal test method; Thermal stratification; Return air

1. Introduction

The population boom and industry and agriculture developments have overthrown the whole world to a freshwater crisis in recent years [1,2]. The United Nations predicts a severe shortage of water for 48 countries by 2025 [3]. The agriculture section, which is the largest consumer of water resources, is facing severe water stress [4]. It becomes necessary to find alternative methods instead of merely consuming available water resources to efficiently solve the issue between the agricultural development and the scarcity of freshwater in arid and semi-arid areas [5,6]. The brackish water greenhouse desalination (BWGD), which is developed based on the principle of air humidification–dehumidification, can produce freshwater from brackish water for irrigation purposes [7]. The complex heat and mass transfer phenomena in the BWGD, which results from the intrinsically coupled nature between heat transfer process and dynamic interaction in the multi-phase flows of air, vapor, water and soil, have received substantial attention to obtain reliable knowledge for developing an efficient brackish water desalination [8,9].

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The relationships between the performance of the BWGD and parameters were experimentally investigated. The effects of ambient conditions of solar radiation, air temperature and relative humidity on the freshwater production indicated that the freshwater production with the solar radiation were in perfect agreement [10]. Al-Ismaili [11] proved that the humidifier allowed a maximum decrease of 10°C in the ambient air temperature. It was found in the experiment that the air temperature of 30°C~38°C exceeded the favourable conditions for the crop growth [12]. The experiment conducted by the response surface method suggested that the temperatures of both ambient air and humidifier water determined the freshwater production [14]. There seemed to exist the following two issues in the above experimental research: (a) the variation rules of the measured freshwater production with ambient conditions were inconsistent or even contradictory due to the fact that the ambient conditions, which depended on the geographical environment, were interlinked with each other; (b) most of the experiments mainly focused on optimizing the freshwater production with little attention paid to favourable conditions for the crop growth, which resulted in a low efficiency of greenhouse planting.

Significant calculating efforts have been made to study the freshwater production of the BWGD. The first attempt to develop a mathematical model of the Tenerife's BWGD failed to take into account the parameters of the humidifier [16]. The model regarding the BWGD in Oman assumed the long narrow greenhouse as one unit and ignored the effect of the crop transpiration [15]. Zurigat et al. [16] divided the greenhouse unit into three subsystems of soil, crop and air merely in the vertical direction of the greenhouse. Owing to the obvious increase of air temperature and relative humidity along the length of the greenhouse, the air temperature and relative humidity inside the greenhouse were out of the favourable range for the crop growth. The effect of a single variable of the running parameters on the freshwater production was analyzed [17,18]. Zamen et al. [19] found that the freshwater production increased, then decreased with an increasing air flow rate while Hajiamiri and Salehi [17] revealed the freshwater production was negatively correlated with the air flow rate. The conclusion on the significance analysis of parameters on the freshwater production agreed poorly with each other due to the fact that other parameters except the given single variable differed from each other. The optimized greenhouse structure dimensions for the maximum freshwater production were suggested based on the artificial neural network model [20,21]. Based on calculations on the dehumidification in the condenser, empirical correlations of the freshwater production have been developed [22,23] and the improved condensers of the plate channel condenser [24], passive condenser [25] and direct contact condenser [13,19,26] were proposed. The present calculation primarily focused on the freshwater production while the calculated temperature of 30°C and relative humidity of 80% was unfavourable for the crop growth. It resulted in a kind of cooling energy waste that the dehumidified air with a temperature of 24°C was directly discharged to the ambient.

Although a large number of studies on the BWGD in both the calculation and experiment have been done, there is a demand to further develop a novel BWGD to solve the key deficiencies. The conflicting conclusions on the freshwater production are due to the lack of the significance ranking of interactional parameters. The unfavourable conditions of air temperature and relative humidity in the greenhouse result from the isolation of the brackish water desalination and crop growth. Herein, a proposed BWGD, where the crop layer and internal air layer occur owing to the thermal stratification phenomena, serves to couple the crop growth with the freshwater production. On the condition of the favourable air temperature and relative humidity for the crop growth in the crop layer, the significance ranking of factors and parameters of the optimal freshwater production are obtained based on orthogonal test method.

2. System description

A proposed BWGD, which consists of three subsystems of humidification, dehumidification and ventilation, is illustrated in Fig. 1. The fresh brackish water from the brackish water pool is directly pumped to the tubes of the condenser where it absorbs the latent heat and sensible heat released by the vapor of the humid air condensing outside the tubes. The preheated brackish water flows partly through the two humidifiers where the remaining feed brackish water returns to the brackish water pool, and partly to the brackish water pool. The brackish water temperature in the brackish water pool is regulated by flow rates of both low-temperature underground brackish water and drained brackish water. The ambient air successively flows through the first humidifier to be initially cooled and humidified, internal air layer to absorb the solar radiation, second humidifier to be further humidified and condenser to produce freshwater by the dehumidification. Compared with the classical BWGD shown in Fig. 2, the proposed BWGD differs in the ventilation subsystem which serves to venting and cooling the crops. The cool air of 24°C exiting from the condenser, which was discharged to the ambient in the classical BWGD, is introduced to cool the crop layer from the south of the greenhouse along its length after it is further dehumidified to a relative humidity of 50% in the dry pad. The thermal stratification, which is formed by the cross flow between the cool transverse air through the crops and the hot longitudinal air above the crops, divides the internal space of the greenhouse into the crop layer and internal air layer. The cool air jets to the crop canopy, then discharges to the ambient at the exits of the north side of the greenhouse. The crop canopy naturally disturbs the cross mixing of the cool air and hot air in our experiment shown in Fig. 1c, which is proven by existing stagnant air boundary layer near the crop canopy [27]. The new ventilation subsystem provides the favourable temperature and relative humidity required for the crop growth.

3. Mathematical model and validations

3.1. Mathematical model

A one-dimensional steady-state BWGD with return air is modeled with the following assumptions:

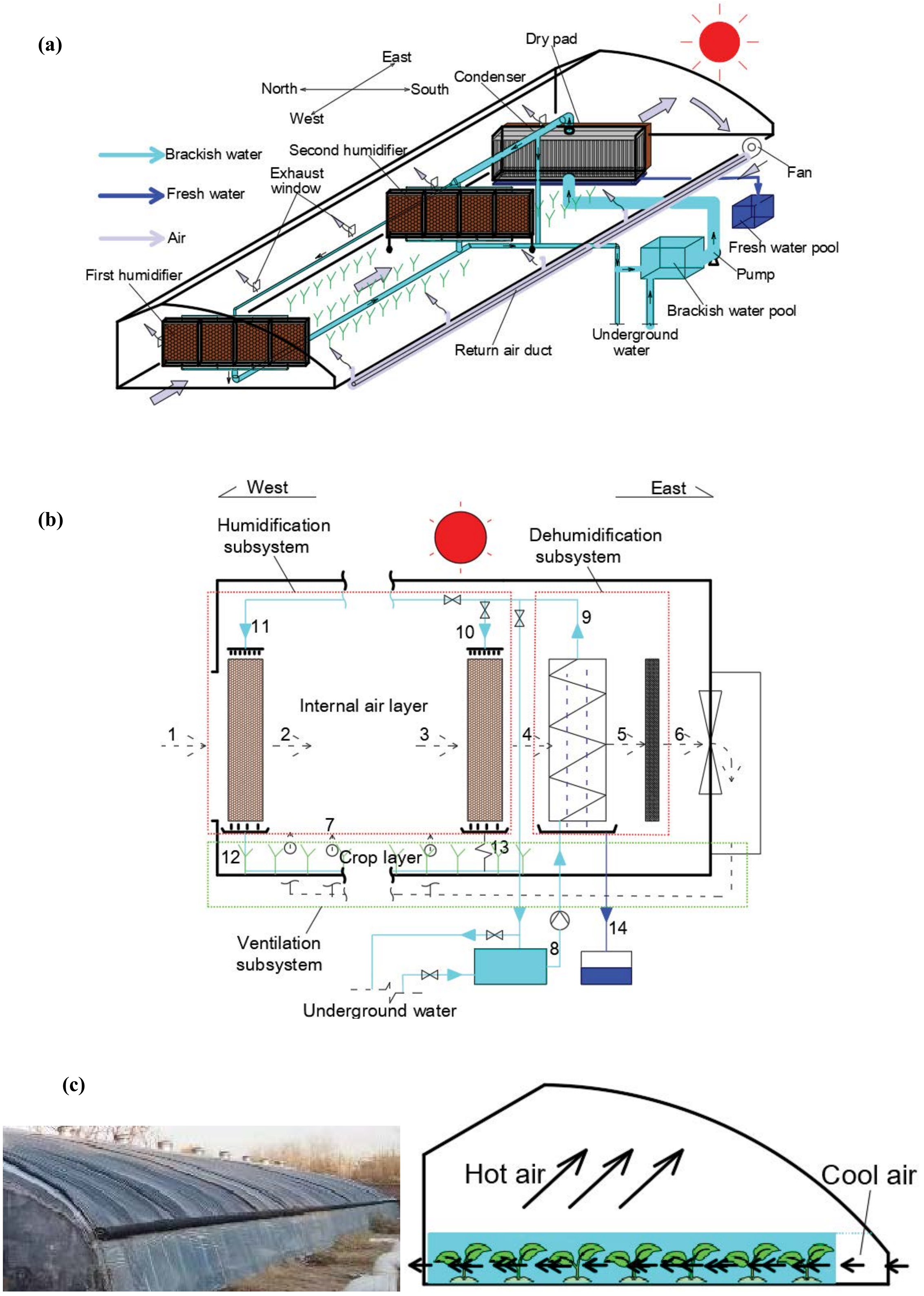

Fig. 1. Diagram of a proposed brackish water greenhouse desalination (a) side view, (b) plan view and (c) experiment of thermal stratification in Jinan. 1-Ambient air; 2-First humidifier outlet air; 3-Second humidifier inlet air; 4-Second humidifier outlet air; 5-Condenser outlet air; 6-Dry pad outlet air; 7-Crop layer outlet air; 8-Condenser inlet brackish water; 9-Condenser outlet brackish water; 10-Second humidifier inlet brackish water; 11-First humidifier inlet brackish water; 12-First humidifier outlet brackish water; 13-Second humidifier outlet brackish water; 14-Freshwater.

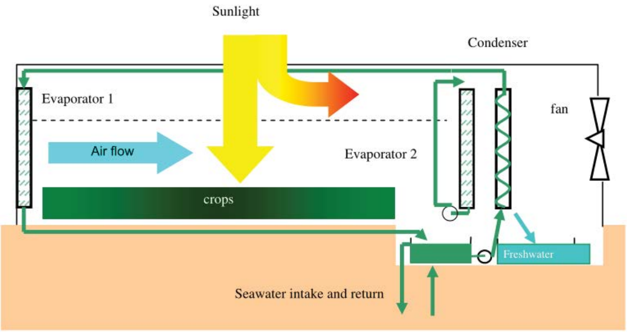

Fig. 2. Diagram of the classical brackish water greenhouse desalination [30].

- Heat loss is negligible [28];
- Air is homogeneous in its thermal and moisture properties [28];
- Water-air interface temperature in the humidifier equals to the average temperature of its inlet and outlet brackish water [28];
- A small part of solar radiation absorbed by the crops for photo synthesis and soil is ignored [28];
- A relative humidity of the air exiting from the condenser is 95%.

Equations of the energy and mass conservation in the first and second humidifier are given by [29]:

$$m_a h_1 + m_{11} h_{11} = m_a h_2 + m_{12} h_{12} \tag{1}$$

$$m_a w_1 + m_{11} = m_a w_2 + m_{12} \tag{2}$$

$$m_a h_3 + m_{10} h_{10} = m_a h_4 + m_{13} h_{13} \tag{3}$$

$$m_a w_3 + m_{10} = m_a w_4 + m_{13} \tag{4}$$

Equations of the cooling efficiency in the first and second humidifier are given by [28]:

$$\eta_{a1} = \frac{t_1 - t_2}{t_1 - t_{1,\text{wb}}} \times 100\% \tag{5}$$

$$\eta_{a2} = \frac{t_3 - t_4}{t_3 - t_{3,\text{wb}}} \times 100\% \tag{6}$$

Equations of the energy and mass conservation in the classical BWGD are given by [28]:

$$m_a h_2 + \left(1 - \phi_p\right) Q_s \tau A = m_a h_3 + K_c A_c \left(\frac{t_2 + t_3}{2} - t_1\right) + Q_T + f_v A\sigma \left(\varepsilon_s \left(\frac{t_{2,k} + t_{3,k}}{2}\right)^4 - t_{\text{sky},k}^4\right) \tag{7}$$

$$m_a w_2 + \frac{Q_T}{L_v} = m_a w_3 \tag{8}$$

Equations of the energy and mass conservation of the internal air layer and crop layer in the proposed BWGD are given by [31]:

$$m_a h_2 + \left(1 - \phi_p\right) \tau Q_s A a_1 = K A_c \left(\frac{t_2 + t_3}{2} - t_1\right) + m_a h_3 \tag{9}$$

$$m_a h_6 + \left(1 - \phi_p\right) \tau Q_s A a_2 = m_a h_7 + f_v A\sigma \left(\varepsilon_s \left(\frac{t_{6,k} + t_{7,k}}{2}\right)^4 - t_{\text{sky},k}^4\right) + Q_T \tag{10}$$

$$m_a w_6 + \frac{Q_T}{L_v} = m_a w_7 \tag{11}$$

The constants in the above equations are as follows [31]: $a_1 = 0.7$, $a_2 = 0.3$

Equations of the energy and mass conservation in the condenser are given by [29]:

$$m_a h_4 + m_8 h_8 = m_a h_5 + m_9 h_9 + m_{14} h_{14} \tag{12}$$

$$m_a w_4 = m_a w_5 + m_{14} \tag{13}$$

The relative humidity of the dehumidified cool air through the dry pad is calculated by [32]:

$$3.62 \times 2 \times 1.16 \times \left(\text{RH}_5 - \text{RH}_6\right) \times W_{5,\text{wb}} = \left(1 + 41.3\%\right) \times 500 \times 50\% \times L_d \tag{14}$$

The relative deviation is given by:

$$\text{RD} = \frac{X_{\text{sim}} - X_{\text{exp}}}{X_{\text{exp}}} \times 100\% \tag{15}$$

The range R_t and R_m are calculated by [33]:

$$R_t = \max\left\{K_{t1}, K_{t2}, K_{t3}, K_{t4}, K_{t5}\right\} \tag{16}$$

$$R_m = \max\left\{K_{m1}, K_{m2}, K_{m3}, K_{m4}, K_{m5}\right\} \tag{17}$$

A simplified flowchart of the computation program is shown in Fig. 3. Based on the input data, the program starts to assume the brackish water temperature at the outlet of condenser. The parameters of air exiting from the first humidifier, internal air layer, second humidifier, condenser and crop layer are calculated according to Eqs. (1)–(6) and Eqs. (9)–(14). The brackish water temperature at the condenser outlet and freshwater production are calculated by Eqs. (12) and (13).

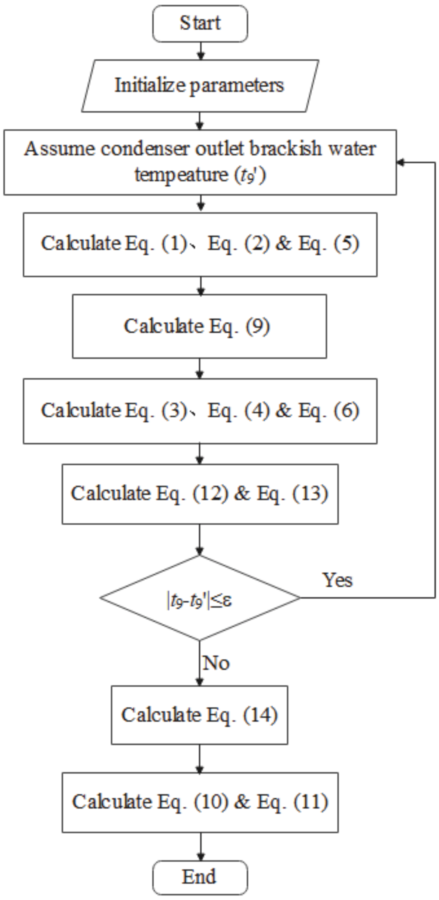

Fig. 3. Flowchart of the computation program.

3.2. Model validations

Comparisons of the calculated air temperature and humidity ratio at the outlets of the humidifier, greenhouse and condenser with the experimental data in the classical BWGD [28] are presented in Fig. 4.

The comparisons show that the predictions are in a good agreement with the experimental data. It is shown in Fig. 4a that the relative deviations of the calculated air temperature and humidity ratio at the outlet of the humidifier are 0%~7% and 0%~–4%, respectively. The overestimation of the calculated air temperature is due to the fact that the measured air temperature at the middle height of the humidifier is lower than the averaged one of the inlet and outlet air in the humidifier as a vertical decrease in the brackish water temperature results in a non-linear decrease in the air temperature. It can be seen in Fig. 4b that the deviations of the air temperature and humidity ratio are less than 5% before 12 am and slightly increase after 12 am. This is attributed to the ignored heat storage of the soil in the assumption which becomes more pronounced on the air temperature in the greenhouse after 12 am. The marginal deviations of the air temperature and humidity ratio at the outlet of the condenser shown in Fig. 4c, which are –2%~2% and –3%~2%, respectively, prove the accuracy of the assumed relative humidity of air exiting from the condenser.

4. Results and discussion

The ambient conditions on July 22 2020 in Jinan are shown in Fig. 5. The details of the geometric sizes and physical parameters of the proposed BWGD are listed in Tables 1 and 2. The subsequent calculations are performed on the given parameters in Fig. 5 and Tables 1 and 2.

4.1. Range analysis of the orthogonal test

Orthogonal test method, which is a kind of designing method to study multiple factors and levels, is used to obtain the significance ranking of factors. The thickness of the first humidifier, position of the second humidifier, air flow rate of the crop layer and inlet brackish water temperature and flow rate of the condenser are symbolized by A, B, C, D and E, respectively. These factors are chosen as the controllable factors as the ambient conditions and geometric sizes are fixed among all the factors affecting the performance of the proposed BWGD. According to the favourable temperature, relative humidity and flow rate of air for the crop growth, underground brackish water temperature and minimum brackish water flux of the humidifier, levels of the chosen factors are given in Appendix A1. On the favourable condition of the air temperature of 24°C and relative humidity of 55% [34,35], the orthogonal test results at 8 am, 11 am and 5 pm are presented in Appendix A2. The temperature of the crop layer (t_{crop}) and the freshwater production (m_c) are taken into account as the air relative humidity is dehumidified to 50% by the dry pad.

The range analysis results of t_{crop} and m_c at 11 am are shown in Tables 3 and 4 according to the orthogonal test results in Appendix A2. The reason for the range analysis at 11 am is that the greatest solar radiation at 11 am is the most unfavourable for the crop growth. The statistics of the range R_t and R_m as well as the significance ranking of factors at 8 am, 11 am and 5 pm are shown in Tables 5 and 6, respectively.

It is found in Table 5 that the range R_t and R_m of factor D and E are far greater than that of factor A, B and C. This proves that factors of both factor D and E are the most significant ones on t_{crop} and m_c regardless of the time. The reasons can be attributed to the following: (a) the outlet air temperature and dehumidification rate in the condenser, which are determined by the inlet temperature and flow rate of the brackish water, directly affect t_{crop} and m_c; (b) the temperature of the brackish water preheated by the condenser has a great effect on humidifying and cooling air through the two humidifiers. The increasing thickness of the first humidifier causes little impact on humidifying air as the decreasing vapor partial pressure difference between the brackish water interface of the humidifier and the air with increasing thickness results in a decreasing gradient of the evaporation rate along the thickness of the first humidifier. The cooling efficiency of the second humidifier is not obviously affected by the position of the second humidifier due to the small air temperature rise of 1°C~4°C in the internal air layer. A slight range of air flow rate in the crop layer between 0.5 to 0.7 m/s accounts for its inconsequential effect on t_{crop} and m_c. Therefore, factors A, B and C are the non-significant ones.

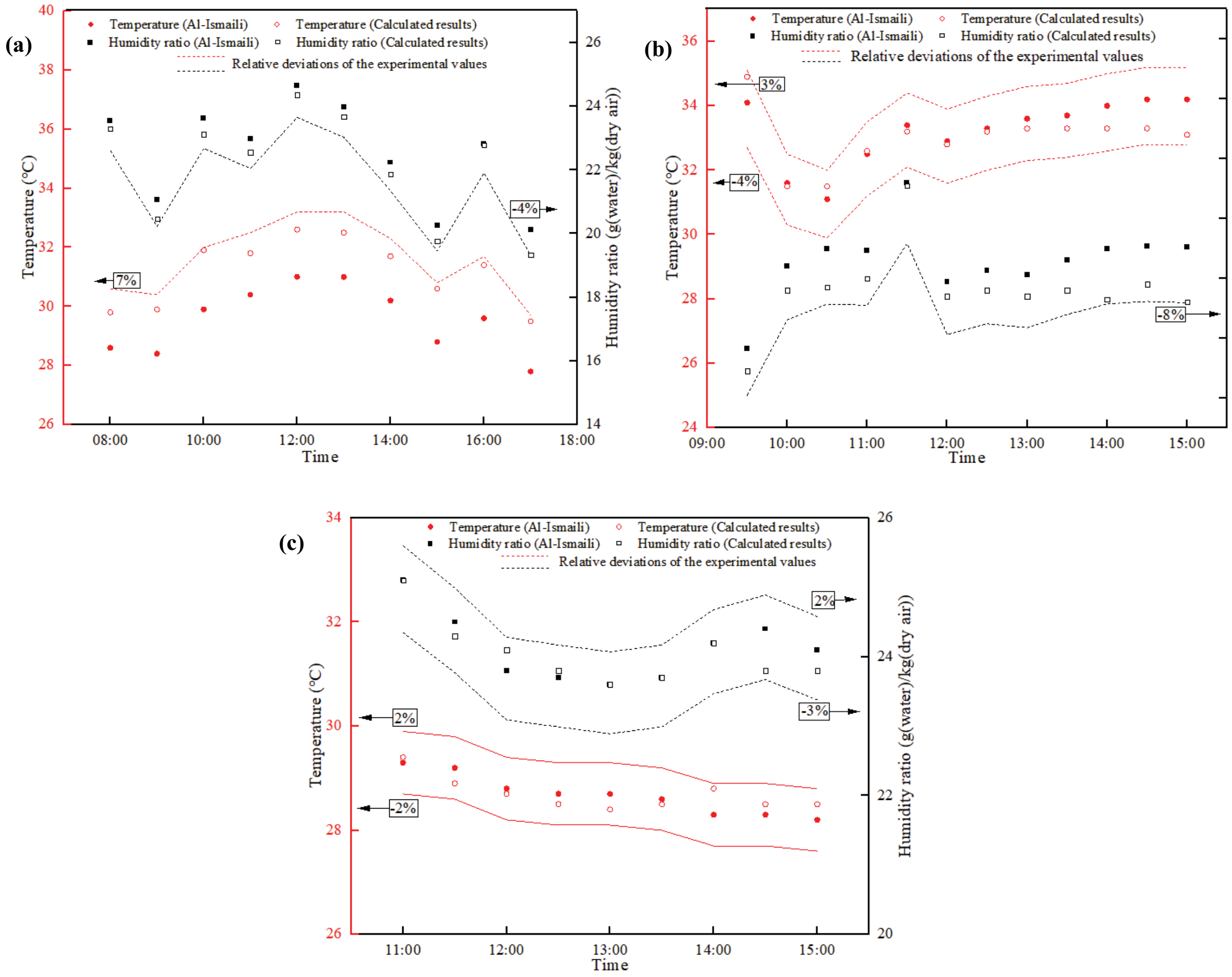

Fig. 4. Comparisons of outlet air temperature and humidity ratio (a) humidifier, (b) greenhouse and (c) condenser.

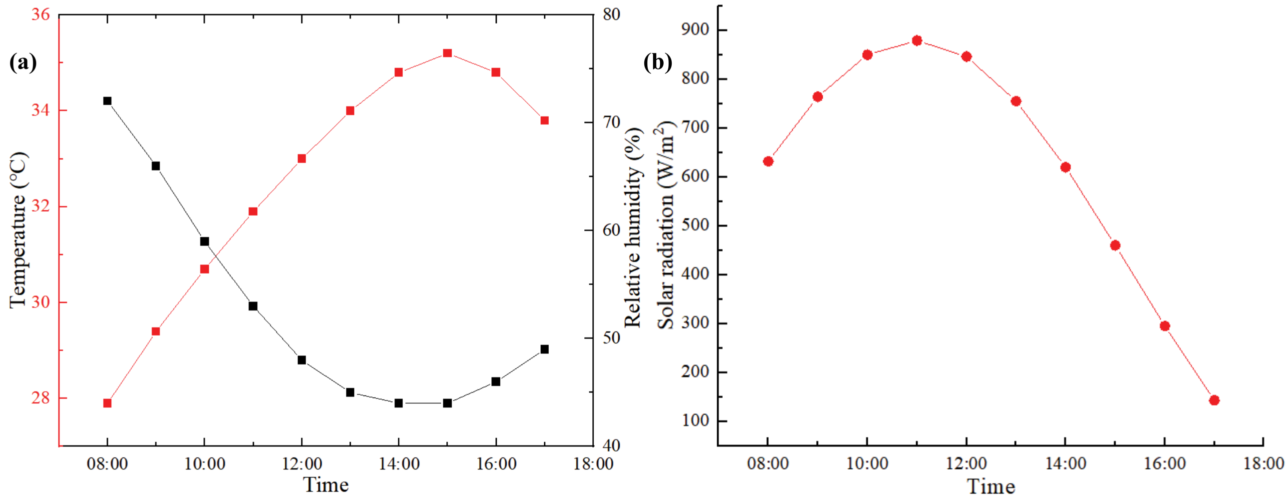

Fig. 5. Ambient conditions on July 22 2020 in Jinan (a) ambient air temperature and relative humidity and (b) solar radiation.

It can be seen from Table 6 that the significance ranking of factors on t_{crop} at 8 am is the same as that at 5 pm, and that there exists the difference between the significance ranking of factors on t_{crop} at 11 am and that at 8 am and 5 pm. The difference is due to the fact that the greater solar radiation at 11 am results in a greater air temperature rise of 4°C through the internal air layer than that of 1°C~2°C at 8 am and 5 pm. As a result, the effect of factor *B* on t_{crop} outweighs that of factors *A* and *C* at 11 am. It is also shown in Table 8 that the significance ranking of factors on m_c at 8 am is the same as that at 11 am, and that factor *C* is more important than factor *B* on m_c at 5 pm. The reason for the difference at 5 pm is due to the fact that the brackish water evaporation rate of the first and second humidifiers linearly increases with the increasing air flow rate while the small air temperature rise of 1°C~2°C in the internal air layer caused by the low solar radiation restrains the effect of the position of the second humidifier on its evaporation rate.

4.2. Comparisons of the significance ranking of factors

For the same geometric and physical parameters of Tables 1 and 2 in the proposed BWGD, the orthogonal test in the classical BWGD shown in Fig. 2 is performed to compare the significance ranking of factors between the two BWGD systems. The significance ranking of factors on t_{crop} and m_c in the classical BWGD is shown in Table 7. It can be seen that there exist the significant factors of factor *A* and *B* on t_{crop} and the ones of factor *D* and *E* on m_c. The reason for

Table 1
Geometric parameters of the proposed brackish water greenhouse desalination

Geometric parameters	Values
Dimensions of the greenhouse (m)	30 × 9 × 3
Dimensions of the humidifier (m)	7 × 1.75 × (0.10~0.20)
Height of the crop (m)	0.50
Total area of the cover (m^2)	216

Table 2
Physical parameters of the proposed brackish water greenhouse desalination

Physical parameters	Values
Spray density (m^3/m^3·s)	0.0008
Solar transmittance of the cover	0.82
Overheat transfer coefficient of the cover (W/m^2°C)	7
Shape factor from canopy to sky	0.81
Leaf area index	1.27
Coefficient of photosynthetically active radiation	0.50
Emissivity of the crop canopy	0.98
Short-wave reflectance of the crop canopy	0.25

Table 3
Range analysis results of t_{crop} at 11 am

Factors	t_{crop} (°C)				
	A	*B*	*C*	*D*	*E*
K_{t1}	24.0	24.0	24.0	23.6	24.4
K_{t2}	24.1	24.1	24.0	23.9	24.2
K_{t3}	24.1	24.0	24.1	24.1	24.1
K_{t4}	24.1	24.1	24.1	24.3	24.0
K_{t5}	24.1	24.2	24.2	24.6	23.9
R_t	0.1	0.2	0.2	1.0	0.5

Table 4
Range analysis results of m_c at 11 am

Factors	m_c (L/h)				
	A	*B*	*C*	*D*	*E*
K_{m1}	86.4	82.0	85.0	115.4	77.0
K_{m2}	89.4	84.0	89.2	103.8	85.8
K_{m3}	91.8	91.2	90.2	89.2	95.4
K_{m4}	92.0	94.8	93.2	81.8	97.0
K_{m5}	95.0	102.6	97.0	64.4	99.4
R_m	8.6	20.6	12.0	51.0	22.4

Table 5
Statistics of the range R_t and R_m at 8 am, 11 am and 5 pm

Time	Factors	Range				
		A	*B*	*C*	*D*	*E*
8:00	R_t	0.1	0.1	0.2	1.1	0.4
	R_m	4.8	16.2	10.0	50.0	19.6
11:00	R_t	0.1	0.2	0.2	1.0	0.5
	R_m	8.6	20.6	12.0	51.0	22.4
17:00	R_t	0.1	0.1	0.3	1.0	0.5
	R_m	6.0	8.0	11.8	50.8	21.2

Table 6
Significance ranking of factors at 8 am, 11 am and 5 pm

Time	Ambient conditions	Significance ranking of factors	
		t_{crop}	m_c
8:00	t_1 = 27.9°C, RH$_1$ = 72%, Q_s = 632 W/m^2	$D > E > C > A = B$	$D > E > B > C > A$
11:00	t_1 = 31.9°C, RH$_1$ = 53%, Q_s = 879 W/m^2	$D > E > B = C > A$	$D > E > B > C > A$
17:00	t_1 = 33.8°C, RH$_1$ = 49%, Q_s = 143 W/m^2	$D > E > C > A = B$	$D > E > C > B > A$

the difference in the significance ranking of factors between the proposed BWGD and classical one lies in the thermal stratification phenomena in the proposed BWGD. The air humidified by the first humidifier directly flows through the greenhouse in the classical BWGD, while the air flowing in the greenhouse is divided into the internal air layer and crop layer under the action of the thermal stratification phenomena in the proposed BWGD. The difference in the significance ranking of factors results in different regulating methods. In the proposed BWGD, both the favourable t_{crop} and optimal m_c can be satisfied by merely regulating the inlet brackish water temperature of factor *D* and flow rate of condenser of factor *E*. In contrast, the favourable t_{crop} is obtained by regulating the thickness of the first humidifier of factor *A*, position of the second humidifier of factor *B* and m_c is optimized by regulating the inlet brackish water temperature of factor *D* and flow rate of condenser of factor *E* in the classical BWGD. Therefore, the temperature and relative humidity at the conditions of the optimal m_c does not favor the crop layer. The conflicting result between the favourable t_{crop} and optimal m_c is proved by the previous experimental and calculated research where both the favourable t_{crop} and optimal m_c could not be achieved, simultaneously.

Table 7
Significance ranking of factors in the classical brackish water greenhouse desalination

Time	Significance ranking of factors	
	t_{crop}	m_c
8:00	$B > A = D > E > C$	$D > E > C > B > A$
11:00	$B > A > D > E = C$	$D > E > C > A > B$
17:00	$B > A > D > E = C$	$D > E > C > B > A$

Table 8
Optimal parameters at 8 am, 11 am and 5 pm

Time	*A* (m)	*B* (m)	*C* (m/s)	*D* (°C)	*E* (kg/s)	m_c (L/h)
8:00	0.16	30	0.70	19	4.8	85
11:00	0.20	24	0.65	16	4.4	114
17:00	0.18	30	0.70	18	6.0	115

4.3. Optimization of parameters in the proposed BWGD

It is seen that all the levels of factor *A* and former four levels of factors *B* and *C* meet the favourable t_{crop} in Table 5, and that m_c increases with an increase in these levels in Table 6. The non-significant factors for the favourable t_{crop} at 11 am is $A_5B_4C_4$. Similarly, the non-significant factors are $A_3B_5C_5$ at 8 am and $A_4B_5C_5$ at 5 pm.

The profiles of t_{crop} and m_c with respect to two significant factors of factor *D* and *E* are presented in Figs. 6–8. It can be found that t_{crop} decreases and m_c increases with increasing inlet brackish water flow rate of condenser and decreasing inlet brackish water temperature of condenser at 8 am, 11 am and 5 pm. Take Fig. 7 at 11 am as an example, when factor *D* increases by 1°C, the temperature of preheated brackish water for the humidifiers increases by 0.5°C. The decreasing temperature difference between the air and brackish water in the humidifiers results in a decrease in the cooling and humidifying efficiencies. Subsequently, the air temperature increases by 0.1°C and the air relative humidity decreases by 0.5% at the inlet of the condenser. The decreasing heat transfer temperature and humidity ratio cause a decreasing heat transfer in the condenser. As a result, t_{crop} increases by 0.3°C and m_c decreases by 14 L/h. It is show in Figs. 6–8 that t_{crop} decreases and m_c increases with increasing factor *D* at a decreasing rate, and that both the decreasing rate of t_{crop} and increasing rate of m_c with increasing factor *E* hardly change.

It can be also observed that t_{crop} is no more than 24°C for $D \leq 18$°C at 8 am in Fig. 6a and $D \leq 17$°C at 5 pm in Fig. 8a, and that t_{crop} is greater than 24°C for $D \geq 18$°C at 11 am in Fig. 7a. This means that the favourable t_{crop} is guaranteed by the condenser inlet brackish water temperature which can be lowered by mixing underground brackish water in the

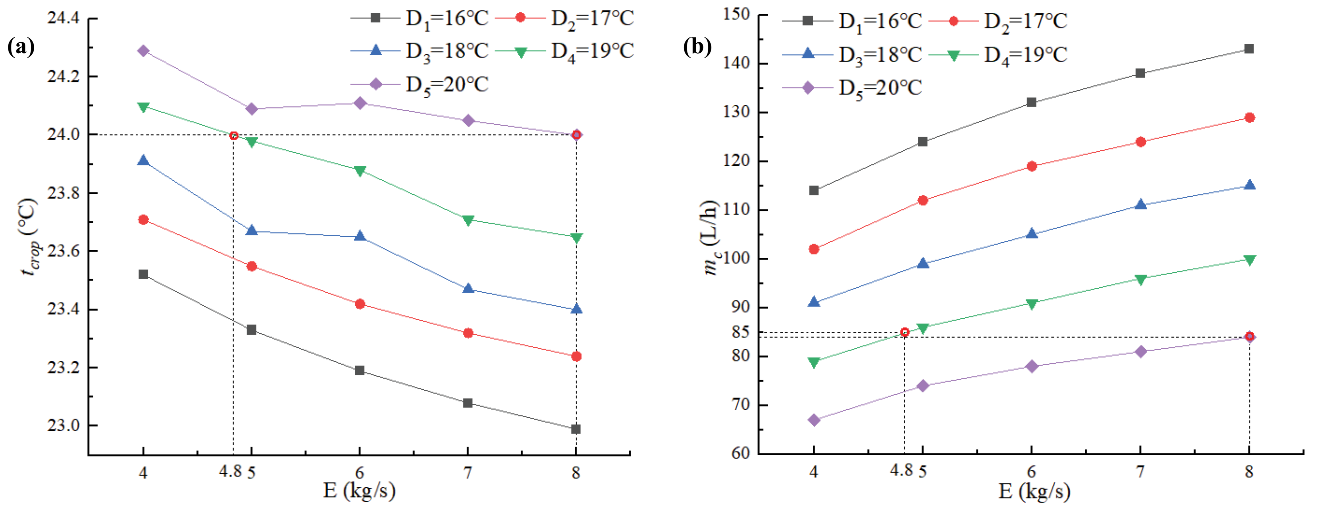

Fig. 6. Profiles of (a) t_{crop} and (b) m_c for different *D* and *E* at 8 am. ($A_3 = 0.16$ m, $B_5 = 30$ m, $C_5 = 0.7$ m/s).

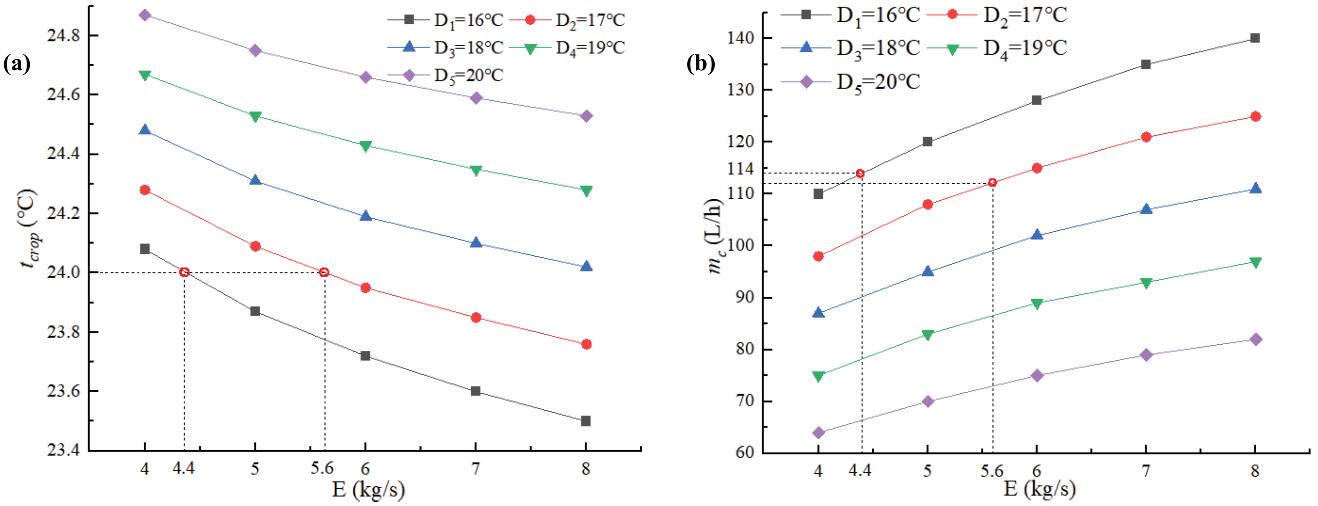

Fig. 7. Profiles of (a) t_{crop} and (b) m_c for different D and E at 11 am. $A_5 = 0.2$ m, $B_5 = 30$ m, $C_4 = 0.65$ m/s).

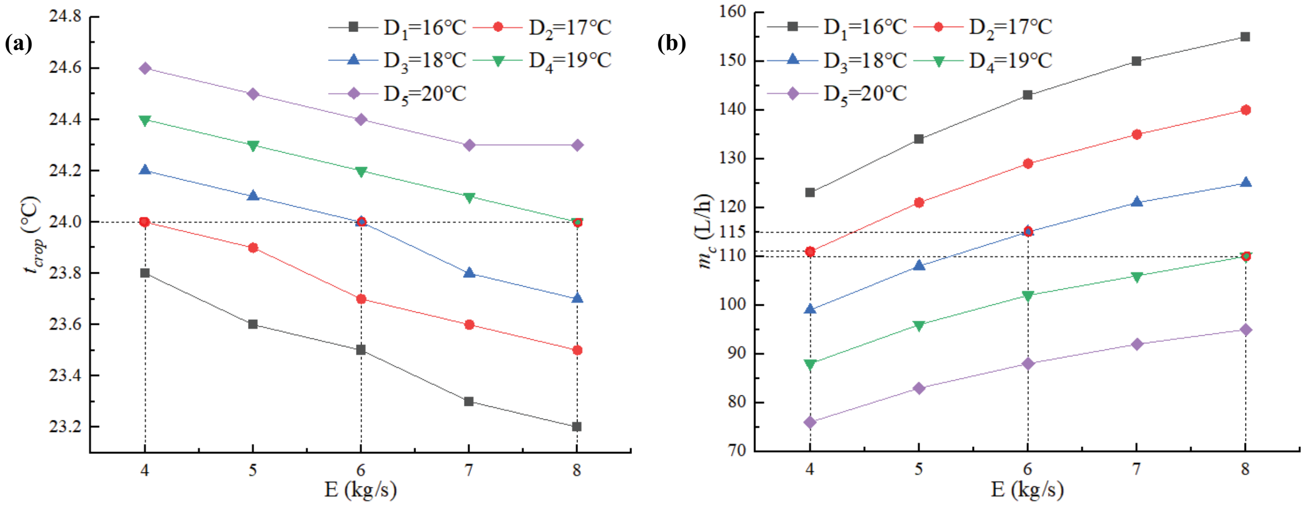

Fig. 8. Profiles of (a) t_{crop} and (b) m_c for different D and E at 5 pm. ($A_4 = 0.18$ m, $B_5 = 30$ m, $C_5 = 0.7$ m/s).

brackish water pool. At 11 am when the solar radiation is the greatest, the favourable t_{crop} can be approached by lowering the condenser inlet brackish water temperature from the brackish water pool and increasing the condenser inlet brackish water flow rate.

The optimal parameters for the favourable t_{crop} and optimal m_c are listed in Table 8. It is interestingly found that m_c at 11 am is not the maximum or even less than that at 5 pm. This result is contradictory to the one in the classical BWGD that m_c increases with increasing the solar radiation. The reason for the contradictory result is that the maximum m_c is achieved at the expense of favourable t_{crop}. Owing to the thermal stratification phenomena, the solar radiation directly affects the air temperature in the internal air layer in the proposed BWGD rather than in the crops in the classical BWGD and the air flowing to the crop layer is cooled by the brackish water in the condenser.

Based on the above analysis of three typical moments, it is inferred that the favourable conditions for the crop growth and optimal freshwater production can be approached in the daytime by regulating the brackish water temperature in the brackish water pool and condenser inlet brackish water flow rate according to the solar radiation.

4.4. Comparisons of the optimal results

According to the above optimization analysis at 8 am, 11 am and 17 pm, the optimal results of the proposed BWGD and classical one are shown in Fig. 9 from 8 am to 17 pm, similarly. The optimal results of the two BWGD for the ambient conditions in Fig. 5 are compared in Fig. 9. It is indicated in Fig. 9a that the temperature of 26°C~30°C and relative humidity of 80%~95% in the crop layer of the classical BWGD are beyond the favourable conditions for the crop growth from 8 am to 5 pm, while the favourable temperature of 24°C and relative humidity of 55% in the crop layer of the proposed BWGD do not vary. It is seen in Fig. 9b that the optimal m_c in the proposed BWGD is less than that

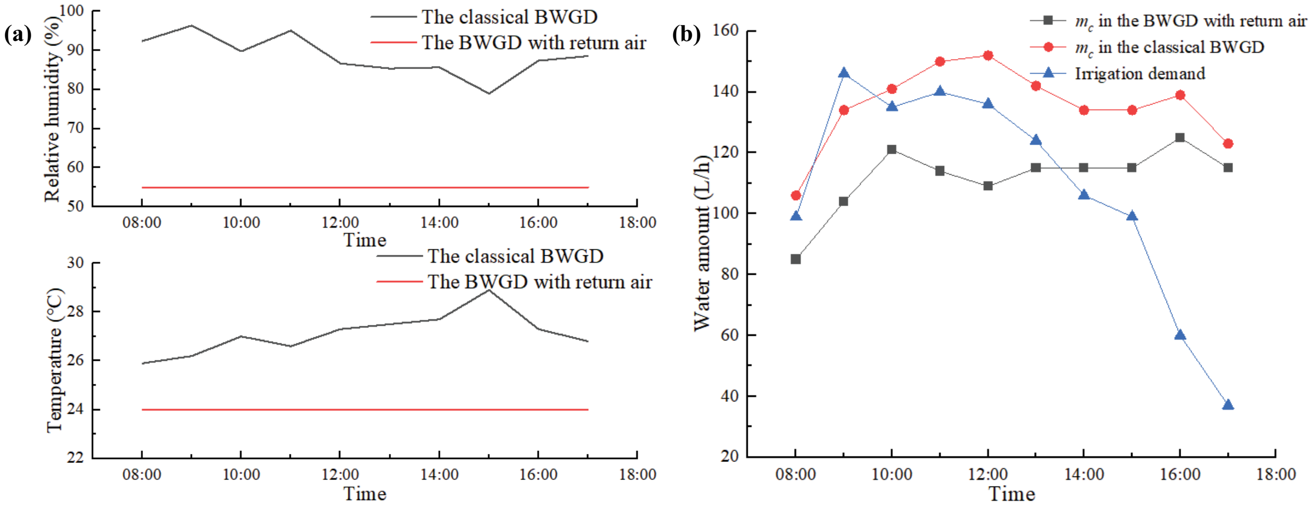

Fig. 9. Comparisons of the optimal results between the proposed brackish water greenhouse desalination and classical one.

in the classical BWGD. Meanwhile, the freshwater production of 1,118 L/d in the proposed BWGD outweighs the total irrigation demand for the crops of 1,082 L/d. Although the concept of the greenhouse desalination was proposed to integrate the crop growth with the humidification–dehumidification desalination technology, the maximum freshwater production is the preferred goal with little attention to the favourable conditions for the crop growth in the classical BWGD. The thermal stratification phenomena contribute to satisfy the favourable conditions for the crop growth and self-sufficiency in freshwater in the proposed BWGD.

5. Conclusions

A novel integrated system of BWGD is proposed to satisfy the favourable conditions for the crop growth and freshwater for irrigation, simultaneously. A one-dimensional steady-state model of the proposed BWGD has been developed to investigate sensitive analysis of factors based on orthogonal test method. The good agreement between the calculated and experimental results validates the accuracy of the developed model.

- The inlet brackish water temperature and flow rate of the condenser are the most significant factors on the crop layer temperature and freshwater production regardless of the time, while the difference in the significant ranking of non-significant factors at 8 am, 11 am and 5 pm is caused by the solar radiation.
- Both the favourable temperature of the crop layer and optimal freshwater production can be satisfied by merely regulating the inlet brackish water temperature and flow rate of the condenser in the proposed BWGD while the air temperature and relative humidity at the condition of the optimal freshwater production does not favor the crop layer in the classical BWGD.
- The temperature of the crop layer decreases and the freshwater production increases with increasing inlet brackish water flow rate of condenser and decreasing inlet brackish water temperature of condenser at 8 am, 11 am and 5 pm in the proposed BWGD. The freshwater production at 11 am is not the maximum or even less than that at 5 pm due to the thermal stratification phenomena, which is contradictory to the one in the classical BWGD that the freshwater production increases with the increasing solar radiation.
- The freshwater production of 1,118 L/d in the proposed BWGD outweighs the irrigation demand of 1,082 L/d in the greenhouse. Therefore, the proposed BWGD, which is an important step forward towards improving the performance of BWGD, provides innovative solutions to the problems of water for agriculture and the crop growth, and the developed model would be a useful tool to investigate the feasibility of the BWGD based on the weather conditions of the location and the operating conditions.

Declarations

Conflict of interest

The authors emphasize that there are no conflicts of interest about the publication of this article.

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Symbols

A — Total area of crop planting, m^2
A_c — Total area of the cover, m^2
a_1 — Absorbance coefficient of the crop layer
a_2 — Sensible heating ratio of the internal air layer
f_v — Shape factor from canopy to sky
h — Specific enthalpy, kJ/kg

K_c — Overheat transfer coefficient of the cover, W/m²°C
K_{mi} — Average of m_c corresponding to each factor at the i level, i = 1~5
K_{ti} — Average of t_{crop} corresponding to each factor at the i level, i = 1~5
LAI — Leaf area index
L_d — Thickness of dry pad, m
L_v — Latent heat of vaporization of water, J/kg
m — Mass flow rate, kg/s
m_a — Mass flow rate of dry air, kg/s
m_c — Freshwater production, L/h
Q_0 — Solar radiation, kW/m²
Q_T — Heat transfer rate of crops' transpiration, W
RD — Relative deviation, %
RH — Relative humidity, %
R_m — Range of m_c
R_t — Range of t_{crop}
X_{exp} — Experimental values
X_{sim} — Calculated values
t — Temperature, °C
t_{crop} — Temperature of the crop layer, °C
$t_{\text{sky},k}$ — Sky effective temperature, K
w — Humidity ratio, g(water)/kg(dry·air)

Greek

ε_s — Emissivity of the crop canopy
η_{a1} — Efficiency of the first humidifier, %
η_{a2} — Efficiency of the second humidifier, %
σ — Stephan–Boltzmann constant
τ — Solar transmittance of the cover
φ_{p} — Short-wave reflectance of the crop canopy

Subscripts

wb — Wet bulb
k — Thermodynamic temperature
1 — Ambient air
2 — First humidifier outlet air
3 — Second humidifier inlet air
4 — Second humidifier outlet air
5 — Condenser outlet air
6 — Dry pad outlet air
7 — Crop layer outlet air
8 — Condenser inlet brackish water
9 — Condenser outlet brackish water
10 — Second humidifier inlet brackish water
11 — First humidifier inlet brackish water
12 — First humidifier outlet brackish water
13 — Second humidifier outlet brackish water
14 — Freshwater

Acronyms

BWGD — Brackish water greenhouse desalination

References

[1] S. Al-Mutawa, S. Al-Jazeeri, M. Kamil, W. Zubari, A. El-Sadek, Development of benchmarking system for the wastewater sector in the Kingdom of Bahrain, Desal. Water Treat., 176 (2019) 345–354.

[2] I.H. Alhajria, B.M. Goortanib, Concentrated solar thermal cogeneration for zero liquid discharge seawater desalination in the Middle East: case study on Kuwait, Desal. Water Treat., 226 (2021) 1–8.

[3] M.A. Siddiqui, M.A. Azam, M.M. Khan, S. Iqbal, M.U. Khan, Y. Raffat, Current trends on extraction of water from air: an alternative solution to water supply, Int. J. Environ. Sci. Technol., 20 (2023) 1053–1080.

[4] A. Al-Busaidi, A. Al-Busaidi, S. Dobretsov, M. Ahmed, Risks associated with treated wastewater in greenhouse cooling system, Desal. Water Treat., 263 (2021) 98–107.

[5] A. Al-Busaidi, M. Ahmed, H. Al-Maskari, S. Al-Maamari, Improving water use efficiency of crops for sustainable agriculture in dry lands, Desal. Water Treat., 176 (2020) 182–189.

[6] A. Amiri, C.E. Brewer, Biomass as a renewable energy source for water desalination: a review, Desal. Water Treat., 181 (2020) 113–122.

[7] Z.B.M. Elamine, D.E. Moudjeber, M. Djennad, H. Mahmoudi, M.F. Goosen, Coupling a brackish water greenhouse desalination system with membrane distillation for Southern Algeria, Desal. Water Treat., 255 (2022) 229–235.

[8] L. Huang, L. Deng, A. Li, R. Gao, L. Zhang, W. Lei, A novel approach for solar greenhouse air temperature and heating load prediction based on Laplace transform, J. Build. Eng., 44 (2021) 102682, doi: 10.1016/j.jobe.2021.102682.

[9] O. Choukai, D. Zejli, Modeling of Seawater Greenhouse by a block diagram environment program and an equations solver program and simulations on different Moroccan locations, Desal. Water Treat., 240 (2021) 203–209.

[10] T. Tahri, S.A. Abdul-Wahab, A. Bettahar, M. Douani, H. Al-Hinai, Y. Al-Mulla, Desalination of seawater using a humidification–dehumidification seawater greenhouse, Desal. Water Treat., 12 (2009) 382–388.

[11] A. Al-Ismaili, Seawater Greenhouses in Oman: Experimental Results, In International Agriculture Congress, Putrajaya, Malaysia, 2014.

[12] J.S. Perret, A.M. Al-Ismaili, S.S. Sablani, Development of a humidification–dehumidification system in a Quonset greenhouse for sustainable crop production in arid regions, Biosyst. Eng., 91 (2005) 349–359.

[13] T.K. Bait Suwailam, A.M. Al-Ismaili, N.A. Al-Azri, L.J. Jeewantha, H. Kotagama, Enhancement of freshwater production of the seawater greenhouse condenser, J. Arid Land, 13 (2021) 397–412.

[14] A. Raoueche, Seawater Greenhouse for Arid Lands, Thesis, Cranfield University, England, 1997.

[15] O. Choukai, D. Zejli, Seawater Greenhouse Modeling Simulation and Analysis of Inputs Impact, 2016 International Renewable and Sustainable Energy Conference (IRSEC), IEEE, Marrakech, Morocco, 2016, pp. 741–744.

[16] Y.H. Zurigat, T. Aldoss, B. Dawoud, G. Theodordis, Greenhouse State of the Art Review and Performance Evaluation of Dehumidifier, MEDRC Project 03-AS-003, 2008. Available at: www.medrc.org

[17] M. Hajiamiri, G.R. Salehi, Modeling of the seawater greenhouse systems, Life Sci. J., 10 (2013) 353–359.

[18] O. Choukai, D. Zejli, Solar pond driven seawater greenhouse–simulations on different Moroccan locations, Desal. Water Treat., 179 (2020) 28–37.

[19] M. Zamen, M. Amidpour, M.R. Firoozjaei, A novel integrated system for freshwater production in greenhouse: dynamic simulation, Desalination, 322 (2013) 52–59.

[20] A.M. Al-Ismaili, N.M. Ramli, M.A. Hussain, M.S. Rahman, Artificial neural network simulation of the condenser of seawater greenhouse in Oman, Chem. Eng. Commun., 206 (2019) 967–985.

[21] T. Zarei, R. Behyad, Predicting the water production of a solar seawater greenhouse desalination unit using multi-layer perceptron mode, Sol. Energy, 177 (2019) 595–603.

[22] T. Tahri, M. Douani, M. Amoura, A. Bettahar, Study of influence of operational parameters on the mass condensate flux in the

condenser of seawater greenhouse at Muscat, Oman, Desal. Water Treat., 57 (2016) 13930–13937.

[23] A.M. Al-Ismaili, H. Jayasuriya, Y. Al-Mulla, H. Kotagama, Empirical model for the condenser of the seawater greenhouse, Chem. Eng. Commun., 205 (2018) 1252–1260.

[24] A.A.T. Al-Khalidi, Y.H. Zurigat, B. Dawoud, T. Aldoss, G. Theodoridis, Performance of a Greenhouse Desalination Condenser: An Experimental Study, 2010 1st International Nuclear & Renewable Energy Conference (INREC), IEEE, Amman, Jordan, 2010, pp. 1–7.

[25] H. Mahmoudi, N. Spahis, S.A. Abdul-Wahab, S.S. Sablani, M.F.A. Goosen, Improving the performance of a seawater greenhouse desalination system by assessment of simulation models for different condensers, Renewable Sustainable Energy Rev., 14 (2010) 2182–2188.

[26] A. Eslamimanesh, M.S. Hatamipour, Mathematical modeling of a direct contact humidification–dehumidification desalination process, Desalination, 237 (2009) 296–304.

[27] H. Fang, K. Li, G. Wu, R. Cheng, Y. Zhang, Q. Yang, A CFD analysis on improving lettuce canopy airflow distribution in a plant factory considering the crop resistance and LEDs heat dissipation, Biosyst. Eng., 200 (2020) 1–12.

[28] A.M. Al-Ismaili, Modeling of a Humidification–Dehumidification Greenhouse in Oman, Thesis, Cranfield University, England, 2009.

[29] F. Mahmood, T.A. Al-Ansari, Design and thermodynamic analysis of a solar powered greenhouse for arid climates, Desalination, 497 (2021) 114769, doi: 10.1016/j.desal.2020.114769.

[30] C. Paton, P. Davies, The Seawater Greenhouse Cooling, Fresh Water and Fresh Produce from Seawater, The 2nd International Conference on Water Resources in Arid Environments, Riyadh, 2006.

[31] P.A. Davies, A solar cooling system for greenhouse food production in hot climates, Sol. Energy, 79 (2005) 661–668.

[32] J.T. Guo, The Research on Greenhouse Environment Control-A Dry & Cooling Pad System, Thesis, Hunan University, China, 2019.

[33] G. Shi, H. Li, X. Liu, Z. Liu, B. Wang, Transport performance improvement of a multiphase pump for gas–liquid mixture based on the orthogonal test method, Processes, 9 (2021) 1402, doi: 10.3390/pr9081402.

[34] NY/T 1451-2007, Code for Ventilation Design of Greenhouse.

[35] A. Li, L. Huang, T.F. Zhang, Field test and analysis of microclimate in naturally ventilated single-sloped greenhouses, Energy Build., 138 (2017) 479–489.

Appendix A

Appendix A1
Factors and corresponding levels

Factors Levels	*A*: thickness of the first humidifier (m)	*B*: position of the second humidifier (m)	*C*: air flow rate of the crop layer (m/s)	*D*: condenser inlet brackish water temperature (°C)	*E*: condenser inlet brackish water flow rate (kg/s)
Level 1	0.12	6	0.50	16	4
Level 2	0.14	12	0.55	17	5
Level 3	0.16	18	0.60	18	6
Level 4	0.18	24	0.65	19	7
Level 5	0.20	30	0.70	20	8

Appendix A2
Results of orthogonal test

Test number	Factor levels					t_{crop} (°C)			m_c (L/h)		
	A (m)	*B* (m)	*C* (m/s)	*D* (kg/s)	*E* (°C)	8:00	11:00	17:00	8:00	11:00	17:00
1	0.12	6	0.50	4	16	23.0	23.7	23.3	86	82	100
2	0.12	12	0.55	5	17	23.2	23.9	23.5	90	89	103
3	0.12	18	0.60	6	18	23.3	23.9	23.6	88	88	99
4	0.12	24	0.65	7	19	23.6	24.2	23.8	85	88	95
5	0.12	30	0.70	8	20	23.9	24.5	24.1	81	85	89
6	0.14	6	0.55	7	18	23.2	23.8	23.5	84	82	100
7	0.14	12	0.60	8	19	23.6	24.1	23.8	81	81	96
8	0.14	18	0.65	4	20	24.2	24.8	24.5	57	55	68
9	0.14	24	0.70	5	16	23.1	23.8	23.4	116	118	126
10	0.14	30	0.50	6	17	23.1	23.8	23.3	105	111	112
11	0.16	6	0.60	5	20	24.0	24.6	24.3	53	49	69
12	0.16	12	0.65	6	16	23.0	23.6	23.3	116	115	131
13	0.16	18	0.70	7	17	23.3	23.9	23.6	116	117	130
14	0.16	24	0.50	8	18	23.2	23.8	23.4	95	100	105
15	0.16	30	0.55	4	19	24.0	24.6	24.2	74	78	81
16	0.18	6	0.65	8	17	23.0	23.6	23.4	108	106	126
17	0.18	12	0.70	4	18	23.8	24.5	24.2	77	74	92
18	0.18	18	0.50	5	19	23.7	24.3	24	69	71	80
19	0.18	24	0.55	6	20	24.0	24.6	24.2	68	72	78
20	0.18	30	0.60	7	16	22.9	23.6	23.2	130	137	140
21	0.20	6	0.70	6	19	23.8	24.5	24.1	75	91	93
22	0.20	12	0.50	7	20	23.8	24.4	24.0	60	61	74
23	0.20	18	0.55	8	16	22.6	23.3	22.9	121	125	135
24	0.20	24	0.60	4	17	23.6	24.2	23.8	94	96	104
25	0.20	30	0.65	5	18	23.7	24.3	24.0	97	102	106