The optimum air-conditioning system design of water-saving greenhouse and its effects on growth in plants

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Abstract: The climate change will make the scarcity of water resources more serious. Especially, in the region where people can't use clean water and cultivate crops, one of the solutions of the problems is the introduction of greenhouse. The authors designed the optimal air-conditioning system of the water-saving greenhouse and investigated the effects on growth in plants under these conditions. In this design, heat balance model and water balance model in the greenhouse were constructed. Moreover, the objective function unified with electric power in a moisture loss and the electric power used and these constrained conditions were defined. In the examination of plants, in order to evaluate the influence of the plant on this condition, the effect of higher relative humidity levels on the growth chambers of cucumber seedlings were investigated. Three higher relative humidity conditions, RH74.5%, 86% and 97.8%, were taken into consideration in the experiment. Consequently, the air-conditioning system of the water-saving greenhouse that the energy becomes smallest where could be designed. It was useful to introduce the fog cooling system, thermal storage mediums, and the gas absorption refrigerator with dehumidification ability. Furthermore, it was found that the level that cropper's growth becomes biggest exists under the high humidity condition from a cultivation experiment, it was suggested that this design in this water-saving greenhouse is effective.

Keywords: high-efficient water, energy-saving, optimal design, temperature and humidity adjustment, environmental control, photosynthesis

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1 Introduction

Recently, the global warming has caused the severe climate change all over the world. This climate change makes and will make the scarcity of water resources more serious (Okazaki et al., 2012). The food storage is highly related to the water resources; therefore we have to take some steps about the water shortage. In the region where people can't use clean water and cultivate crops, one of the solutions of the problems is the introduction of the plant factory. The plant factory let the people maintain the staple food supply by recycling used water. In addition to that, the plant factory saving energy by using solar power will be better for them (Kawashiro et al., 2009). Therefore, the authors have already proposed a new type greenhouse system (Matsuo et. al, 2011). In this system, water saving and energy reduction could be achieved by using various equipment and solar heat energy (Figure 1). The proposed system is composed of the following three sections, Desalting system, Recovered water system and Greenhouse air conditioning system. In first section, irrigation water is separated from salt water by freezing method with absorption refrigerator using high solar energy under arid climate (Fujioka et. al., 2013). Simultaneously, the cold energy generated from the desalting system by making ice is supplied to the greenhouse. In second section, the water in which crops transpired is collected and it is reused by cultivation. In

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third section, some apparatus are equipped in green house, water saving and energy reduction could be achieved. In addition, it's expected that the humidity in the house always becomes high because a house maintains the closed position in this design. The humidity of greenhouse is an important thing of environmental control. However, the effect of the humidity on growth and the yield of plants is insufficiently understood because high humidity is considered to increase disease damage. It is suggested that the photosynthetic rate increased with an increase in relative air humidity because higher relative air humidity lowers water stress in the leaf and increases stomatal conductance (Yabuki and Miyagawa,1970). To maintain relative humidity in the greenhouse in a suitable range for photosynthesis is one of the main factors that cause the yield difference between the Netherlands and Japan (Heuvelink and Dorais, 2005).

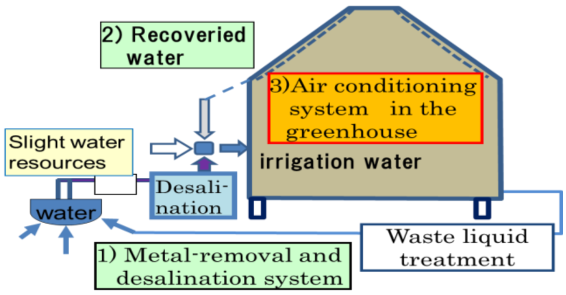


Figure 1 A plant factory with a high-efficient water use in arid area

The purpose of the study is to design the optimal air-conditioning system of the water-saving greenhouse and to investigate the effects on growth in plants under these conditions. In this design, the authors proposed new system which consists of the ammonia gas absorption refrigerator equipped with the dehumidification capability to use solar heat and the thermal storage of the cold energy becomes possible in the temperature field of nighttime without other electric power (Matsuo et al., 2011). Moreover, Dynamical heat balance and water balance model in the greenhouse were constructed (Kozai, T, 2013), and the optimal combination of each air conditioner was calculated with the optimization technique. In calculation, an objective function and constraints are selected. To determine the objective function, the quantity of the lost water and the consumption energy of air-conditioning equipment in a greenhouse were constructed. In the examination of plants, in order to evaluate the water-saving culture environment at increased humidity levels, the effect of increased relative humidity levels, level 1: RH74.5%: level 2: 86%, level 3: 97.8%, in growth chambers with cucumber seedlings was investigated. Four assimilation boxes made by a clear acrylic board were used for an experiment. An assimilation box was installed in the homeothermal room set as 295K of temperature. Relative humidity and the temperature in assimilation box were controlled by combining two dehumidification pumps and silica gel and using a control computer.

2 A greenhouse with a high-efficient water use

Figure 2 shows the proposed greenhouse system (Matsuo et al., 2011). In this greenhouse, the cold temperature of the air conditioner, the fog cooling system, a single roof ventilator, evaporation from plant and the latent heat of thermal storage material are equipped for air cooling. The green-house was naturally ventilated with a single roof ventilator and a fogging system is the most effective and economical greenhouse cooling systems. Irrigated water can be recycled by collecting evapotranspirated water from plants because of water saving. It is expected that the thermal storage of the cold energy becomes possible in the temperature field of nighttime without other electric power and the temperature rise in greenhouse can be controlled. Furthermore, the authors designed the ammonia gas absorption refrigerator equipped with the dehumidification capability to use solar heat.

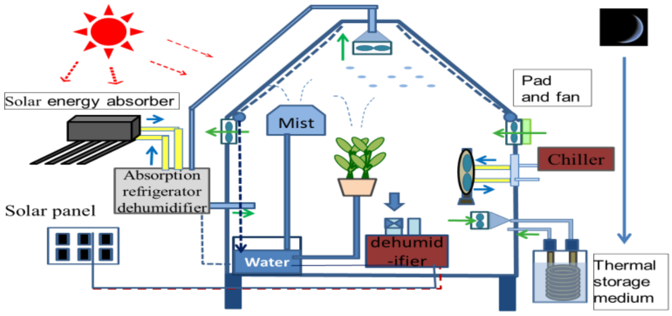


Figure 2 Air-conditioning system of the energy-efficient and water-saving greenhouse

3 Mathematical model in greenhouse

3.1 Heat balance and water balance equation

In the air-conditioning system in greenhouse, heat balance and water balance of this system are given by the following equation.

1) Heat balance equation

Dynamical heat balance in greenhouse is derived from Equation (1).

$$\rho V_v C_p \frac{dT_V}{dt} = C_p pU_o T_o - C_p pU_v T_v + q_{sun} + q_w + q_g - q_{acn} - q_{hsm} - q_{mst} - q_{plt} - q_{ref} \quad (1)$$

Where, T_v and T_o are the air temperature of inside and outside of a house, K, ρ is the density of the atmosphere, kg/m^3, V_v is the house volume, m^3, C_p is the specific heat of air, J/kgK. U_v is ventilation rate of the greenhouse, m^3/s, and U_o is ventilation rate from the outside air, m^3/s, q_{acn} and q_{ref} are the heat of air conditioner and the absorption refrigeration machine, W. Moreover, q_{sun}, q_w, q_g, q_{plt}, q_{mst} and q_{hsm} are the heat of sun flux, the surface of a wall, a floor, transpiration heat of plant, the evaporation heat by fog cooling system and latent heat storage material, W. These are calculated from the following formula.

$$q_{sun} = C_{sf} \cdot \Phi_{sun} \cdot S_{rf} \quad (2)$$

$$q_w = a_w S_w (T_o - T_v) \quad (3)$$

$$q_g = a_g \cdot S_g (T_o - T_v) \quad (4)$$

$$q_{plt} = w_{plt} \cdot r \cdot S_{plt} \quad (5)$$

$$q_{mst} = w_{mst} \cdot r \quad (6)$$

$$q_{hsm} = m_{hsm} \cdot r_{hsm} \cdot R_{hsm} \quad (7)$$

Where Φ_{sun} is the heat flux of the sun, W/m^2, C_{sf} is the damping coefficient of greenhouse, -, a_w and a_g are coefficient of heat transfer of the wall-outside air and floor-outside air, W/m^{2}K. S_{rf} , S_w ,S_g and S_{plt} are the surface area of the roof, wall and floor, m^2, r and r_{hsm} are vaporization heat of water and latent heat storage material, J/kg. w_{plt} is the transpiration rate of plant per unit time per surface area, kg/s/m^2, w_{mst} is the flow rate of fog cooling system, kg/s, and m_{hsm} is the flow rate of latent heat storage material converted per time, kg/s. R_{hsm} is the dehumidification efficiency of an absorption refrigeration machine, -.

2) Water balance equation

Next, dynamical water balance in greenhouse is derived from Equation (8).

$$\rho V_v \frac{dX_V}{dt} = pU_o X_o - pU_v X_v + w_{plt} + w_{mst} - w_{def} - w_{ref} \quad (8)$$

Where, X_v and X_o show are the absolute humidity of the air in a house and the outside air, kg/kg, w_{def} is the moisture rate of the dehumidifier, kg/s, and w_{ref} is the moisture rate dehumidified with an absorption refrigeration machine, kg/s, it is expressed with Equation (9),

$$w_{ref} = \rho \cdot U_{ref} (X_v - X_{ref}) R_{ref} \quad (9)$$

where, X_{ref} is the absolute humidity in an absorption refrigeration machine, kg/kg, U_{ref} is the feeding rate of it, m^3/s, and R_{ref} is the dehumidification efficiency of an absorption refrigeration machine, -.

3.2 Derivation of temperature and humidity from stationary model

Temperature T_V in the house drawn from the balanced conditions of Equation (1) is described by the following Equation (10)..

$$T_v = \frac{(C_p pU_o + a_w S_w)T_o + a_g S_g T_g - \rho C_p U_{ref} T_{ref} + C_{cnst}}{C_p pU_v + a_w S_w + a_g S_g + \rho C_p U_{ref}} \quad (10)$$

$$(C_{cnst} = q_{sun} - q_{acn} - w_{mst} r + w_{plt} r S_{plt} - m_{hsm} r_{hsm} R_{hsm})$$

On the other hand, the amount W_h of moisture which exists per unit time within a house is calculated by substituting for the following equation pX_v drawn from the stationary model of the water balance of Equation (8).

$$W_h = (pX_v)V = \frac{w_{mst} + w_{plt} + pX_0 U_o + pU_{ref} X_{ref} - w_{def}}{U_v + U_{ref}} V \quad (11)$$

where, X_{ref} and X_o are the absolute humidity in an absorption refrigeration machine and besides a house, and these are drawn from Equation (12) and (13).

$$\begin{cases} X_o = 0.622 \cdot e_o^s \cdot \frac{H_o}{100} / (P - e_o^s \cdot \frac{H_o}{100}) \\ e_o^s = 6.1078 \cdot \exp(\frac{17.269 \cdot T_o}{T_o + 237.3}) \end{cases} \quad (12)$$

$$\begin{cases} X_{ref} = 0.622 \cdot e_{ref}^s \cdot \frac{H_{ref}}{100} / (P - e_{ref}^s \cdot \frac{H_{ref}}{100}) \\ e_{ref}^s = 6.1078 \cdot \exp(\frac{17.269 \cdot T_{ref}}{T_{ref} + 237.3}) \end{cases} \quad (13)$$

Where, P is atmospheric pressure, P_a, H_o and H_{ref} are the relative humidity in a house and a freezer, %. Moreover, es_o and es_{ref} are the saturation vapor pressure in the house exterior and a freezer, hPa.

Finally the relative humidity H_v in a house is denoted by Equation (15) from the water vapor pressure e_v in Equation (14).

$$e_v = PX_v / (X_v + 0.622) = \frac{P \cdot W_h}{W_h + 0.622 \rho V} \quad (14)$$

$$H_v = 100 \cdot \frac{e_v}{e_v^s} = \frac{100 \cdot P \cdot W_h}{(W_h + 0.622 pV) \cdot 6.1078 \cdot \exp(17.269 T_v / (T_v + 273.3))} \quad (15)$$

4 The optimal design of air conditioner in a house by an optimization technique

4.1 Optimization method

Based on the expression of relations drawn for the previous chapter, the optimal combination of each air conditioner was calculated with the optimization technique. In calculation, an objective function and constraints are selected. To determine the objective function, the quantity of the lost water and the consumption energy of air-conditioning equipment in a greenhouse were constructed.

1) The loss of moisture and the consumption energy of air-conditioner

The loss W_{los} of moisture in the house per time h_s is denoted by the following formula from moisture and exhaust moisture.

$$W_{los} = (pU_v H_v - pU_o H_o) \cdot h_s = (\frac{U_v \cdot W_h}{V} - pU_o X_o) \cdot h_s \quad (16)$$

Next, the consumption energy of the air conditioner was calculated in the time h_s, s. E_{acn} is the amount of electric power in the time h_s of the equipment which supplies cold energy, J, it is calculated by the following formula from coefficient-of-performance COP_{acn} of equipment, kW/kW.

$$E_{acn} = (\frac{1}{COP_{acn}}) q_{acn} \cdot h_s = (\frac{1}{q_{acn} / E_{acn}}) q_{acn} \cdot h_s \quad (17)$$

Similarly, E_{def} is the electric power of the dehumidifier in the time h_s, J, it is calculated by the following formula. Where P_{def} is the power consumption of it, kW, a_{def} is the moisture withdrawal of it, kg/s..

$$E_{def} = (\frac{P_{def}}{a_{def}}) \cdot w_{def} \cdot h_s \quad (18)$$

Furthermore, E_{ref} is the electric power of the absorption refrigeration machine by solar heat utilization in the time h_s, J, it is calculated from Equation (19). Where P_{ref} is the power consumption of it, kW, a_{ref} is the moisture withdrawal of it , kg/s, and U_{ref} is the air content of unit time of it , m^3/s, COP_{ref} is the coefficient-of-performance of it, kW/kW.

$$E_{ref} = \{(\frac{P_{ref}}{a_{ref}}) U_{ref} + \frac{r}{COP_{ref}} w_{ref}\} R_{Eref} \cdot h_s \quad (19)$$

2) Constraints

The instrumental variable and environment variable which are shown in Equation (20) were selected as the environmental element x in the house for the optimal design. Inequality restrictions of constraints were drawn from the maximum and minimum value of quantity of state and an instrumental variable based on a cultivation condition.

$$\mathbf{X} = [x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6 \ x_7 \ x_8]^T = [q_{acn} \ U_o \ U_{\mathrm{ref}} \ w_{mst} \ w_{def} \ m_{hsm} \ T_v \ H_v]^T \quad (20)$$

$$\mathbf{x}_{\min} < \mathbf{x} \le \mathbf{x}_{\max} \quad (21)$$

In the equation restrictions, the stationary model of the previous of the heart balance and water balance of Equation was used for the equation restrictions type. These equation restrictions are expressed by the following formula by arranging the relation shown in Equations (10)-(15).

$$\mathbf{A} \cdot \mathbf{X} = \mathbf{C} \quad (22)$$

$$\mathbf{A} = \begin{bmatrix} -1 & -C_{\mathrm{p}} p T_{\mathrm{o}} & -r & 0 & -r_{hms} R_{\mathrm{hms}} & A_{16} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_v^s \\ 0 & -p\mathrm{X}_o & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & W_v & W_v + V & -V & V & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (A_{16} = a_{\mathrm{w}} S_{\mathrm{w}} + a_{\mathrm{g}} S_{\mathrm{g}} + C_{\mathrm{p}} p U_0 + m_{ice} C_w + \rho C_p U_{ref}) \quad (23)$$

$$\mathbf{C} = \begin{bmatrix} -a_{\mathrm{w}} S_{\mathrm{w}} T_{\mathrm{o}} - a_{\mathrm{g}} S_{\mathrm{g}} T_{\mathrm{g}} - q_{\mathrm{sun}} + w_{\mathrm{plt}} r + m_{\mathrm{ice}} r_{\mathrm{ice}} \\ 100 \\ w_{\mathrm{pl}} \mathrm{V} + p \mathrm{X}_{\mathrm{ref}} \\ 0 \\ -273.3 \ln(e_v^s) / (\ln(e_v^s) - 6.108 \cdot 17.27) \end{bmatrix} \quad (24)$$

3) Objective function

In a setup of an objective function, it becomes important how energy saving of an air conditioner and the loss of moisture in a water-saving house are minimized. In this case, if power consumption is chosen as an objective function, the heat in a house will bring about the increase in the loss of moisture by an exhaust gas positively. Conversely, if a moisture loss is chosen as an objective function, in order to maintain a closed state in a house, the power consumption of a cold energy unit will increase. Here, objective functions were all unified with electric power by transposing the moisture lost in outdoor to the electric power of the absorption refrigeration machine collected by dew condensation. As a result, an objective function is finally described as follows.

objective function

$$\begin{cases} \min f(x_i) = E_{\mathrm{acn}} + E_{\mathrm{ref}} + E_{los}(W_{\mathrm{los}}) \\ = \{ \dfrac{q_{acn}}{\mathrm{COP}_{acn}} + \dfrac{P_{\mathrm{def}} \cdot w_{\mathrm{def}}}{a_{\mathrm{def}}} + \dfrac{P_{\mathrm{ref}} \cdot U_{\mathrm{o}}}{a_{\mathrm{ref}}} + \dfrac{\mathrm{r} \cdot W_{\mathrm{los}}}{\mathrm{COP}_{\mathrm{ref}}} \} h_{\mathrm{s}} \end{cases} \quad (25)$$

4.2 Simulation conditions

The optimal combination of the air conditioner was searched for based on assumption to the preceding chapter. First, the cultivation condition of the crops in the assumed water-saving house is as follows. The conditions used for the simulation and the inequality constraints of an optimization technique are shown in Table1,2 and Figure 3.

- Cultivation method: cultivation (hydroponics), water-saving culture.

- Crop items: a leaf vegetable, fruit vegetable.

- House quality of the material: lath house.

- House size: 10 m^2 (50 m^2, 100m^2 in future).

- Outside environment: a semiarid land belt, dry land farming.

Table 1 Simulation conditions

Parameters	Values	Parameters	Values
A_f / W/(m^2K)	5.8	Φ_{sun} / W/m^2	1,370
A_{w} / W/(m^2K)	5.8	W_{def} / g/s	0.31
A_{g} / W/(m^2K)	5.8	W_{plt} / kg/s/m^2	0.035
C_{p} / J/(kgK)	1.006	W_{def} / kg/s	0.40
C_{w} / J/(kgK)	4.217	h_{s} / hour	8
ρ/ J/(kgK)	1.29	$\mathrm{COP}_{\mathrm{ref}}$ / %	1.2
r / J/g	2257	COP_{acn} / %	5.0
r_{hsm} / J/g	230	P_{def} / W	200
C_{plt} / %	3	P_{ref} / W	100
R_{ref} / %	1	C_{spnl} / %	0.5
$RE_{\mathrm{\_ref}}$ / %	0.3	P / hPa	1,013

Table 2 Simulation conditions of inequality constraint

Parameters	Values	Parameters	Values
$U_{\mathrm{out\_min}}$ / m^3/s	0.01	$w_{\mathrm{mist\_max}}$ / kg/s	1
$U_{\mathrm{ref\_min}}$ / m^3/s	0.01	$w_{\mathrm{def\_max}}$ / kg/s	1
$w_{\mathrm{mist\_min}}$ / kg/s	0	$q_{\mathrm{acn\_max}}$ / W	2,000
$w_{\mathrm{def\_min}}$ / kg/s	0	$U_{\mathrm{out\_max}}$ / m^3/s	0.1
$M_{\mathrm{hsm\_min}}$ / kg	80	$U_{\mathrm{ref\_max}}$ / m^3/s	0.05
$M_{\mathrm{hsm\_max}}$ / kg	120	$q_{\mathrm{acn\_min}}$ / W	100
T_{min} / K	293	T_{min} / K	308
H_{min} / %	70	H_{min} / %	90

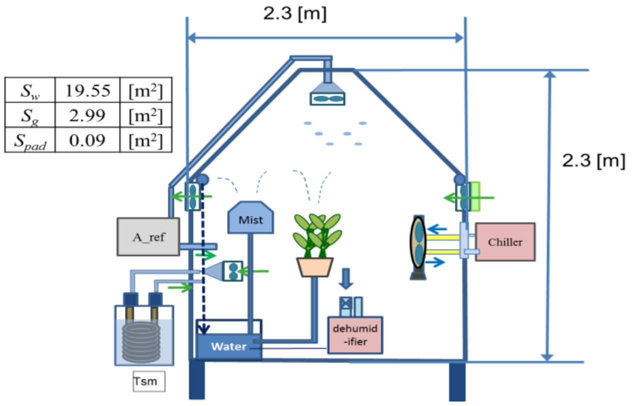
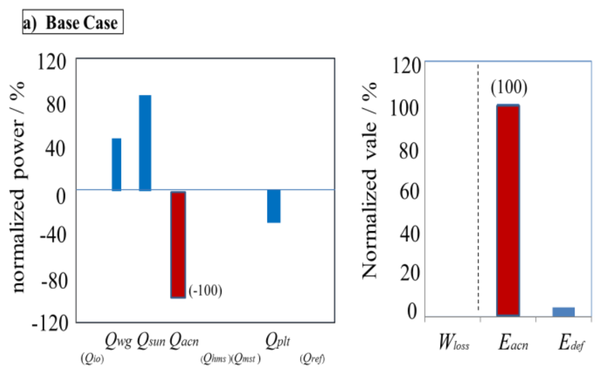


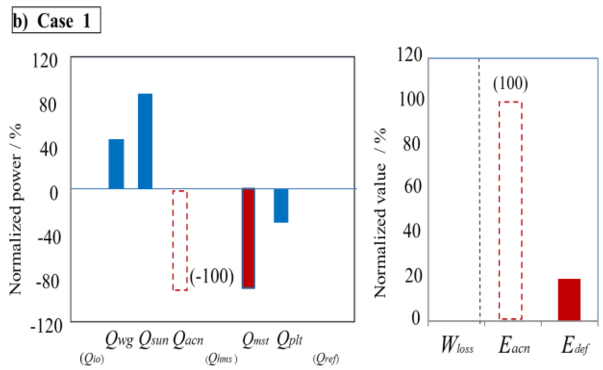
Figure 3 The size in water-saving greenhouse

5 Simulation results and discussion

When the outdoor exhaust gas of the air in a house is set to 0 and only a cooling device with the highest power consumption is used, an example of the results of a water loss and power consumption are shown in Figure 4 (a). Here, Q_{io}, Q_{wg}, Q_{sun}, Q_{acn}, Q_{hsm}, Q_{mst}, Q_{plt}, Q_{ice}, and Q_{ref} are cold energy by a house air intake exhaust gas, the surface of a wall and the ground, solar heat, air conditioner, latent heat storage material, fog cooling, vegetable transpiration, and salt removal system, and the quantity of heat by an absorption refrigeration machine, respectively. The amount of moisture losses in the house per unit time and the operating electric energy of a cooling device and a dehumidifier are shown in the figure. Figure 4 (b) shows the results of electric power and water loss when the fog cooling system and house ventilation which are performed by the usual cultivation are used together. From this figure, moisture in a house can be reduced without using a dehumidifier, but the loss of moisture by the ventilation in a house will increase. So, although this method is effective only for reduction of electric power, it is not suitable for water saving.



a) base case



b) case1

Figure 4 Simulation results of energy balance & water loss, energy

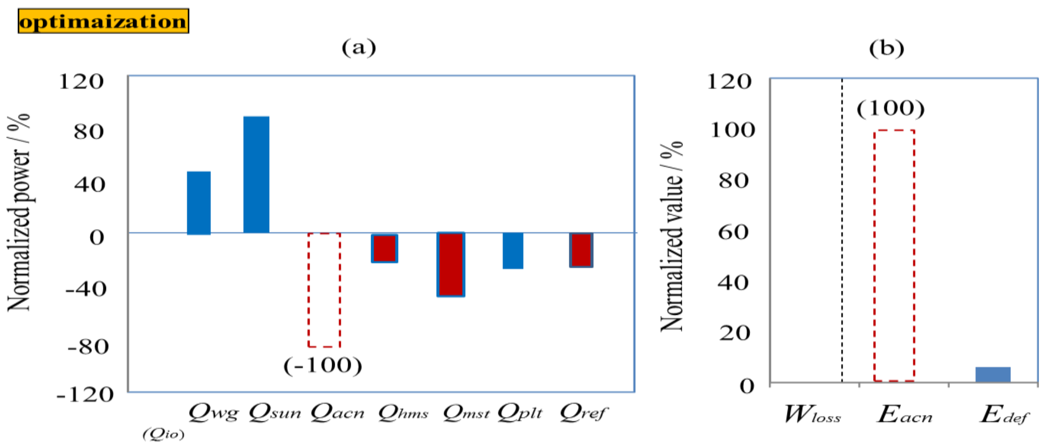


Figure 5 Simulation results by optimization method

(a) energy balance (b) water loss, energy

Finally, Figure 5 shows the optimum coordination result of the air-conditioning system obtained by the optimization technique using the unified objective function. According to this, it turns out that it has attained in the combination of the air-conditioner considered to reduce power consumption where the loss of moisture of a house is made into the minimum and the validity of the proposed technique was suggested.

6 Cultivation experiments and results

In order to evaluate the water-saving culture environment at increased humidity levels, the effect of increased relative humidity levels, level 1: RH74.5%: level 2: 86%, level 3: 97.8%, in growth chambers with cucumber seedlings was investigated.

6.1 Material and methods

Cucumber was used in an experiment. Figure 6 shows a scheme of an assimilation box under increased humidity conditions. Four assimilation boxes made by a clear acrylic board (width 50 cm x depth 50 cm x height 80 cm) were used for an experiment. An assimilation box was installed in the homeothermal room set as 22℃ of temperature. Relative humidity in the assimilation box was controlled by combining two dehumidification pumps and silica gel (about 2 kg). The fan to stir air, a temperature sensor and a moisture sensor were installed in the assimilation box. Five light sources were installed in an assimilation box. The distance from a light source to the stand in which a stump was installed was 57 cm, and light quantity on the stand was 136 μ mol, 1/m^2 and 1/s. The temperature in assimilation box, relative humidity and CO_2 density were controlled using a control computer (made of KV3000 and Keyence) during the session length, and these data were recorded every one minute.

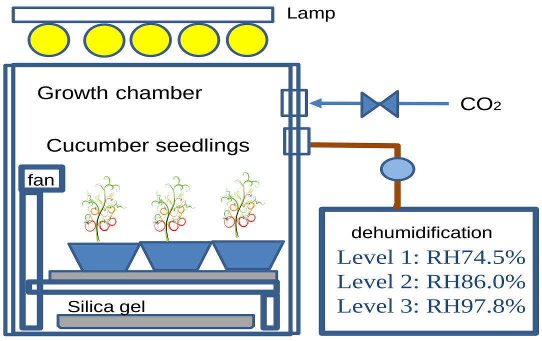


Figure 6 A schematic diagram of assimilation box under increased humidity conditions

6.2 Experimental results

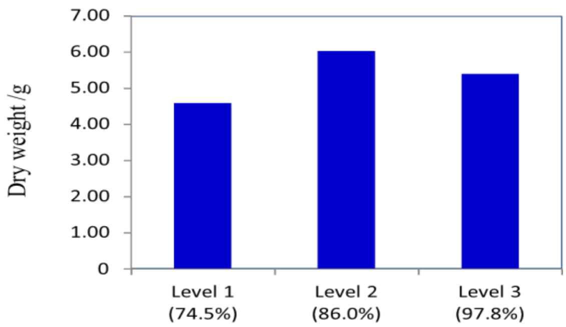


Figure 7 Results of mean values of total dry weight at three levels

Figure 7 shows the results of mean values of total dry weight at three levels. As can be seen in this figure, dry matter production and relative growth rate (RGR) were largest when seedlings were grown in the level 2 chamber. The leaf area of seedlings became larger under level 2 than under level 1. These results indicated that dry matter production increased because of the maximum photosynthetic rate and expansion of leaf areas due to higher humidity. In contrast, dry matter production decreased under level 3. The reduction of the transpiration rate was probably induced by the decreased nutrient uptake by seedlings under level 3. These results indicate that good cultivation is possible at high humidity conditions and there is an optimal humidity level.

7 Conclusions

The authors designed the optimal air-conditioning system of the water-saving greenhouse and to investigate the effects on growth in plants under these conditions. In this design, the authors proposed the ammonia gas absorption refrigerator equipped with the dehumidification capability to use solar heat and the thermal storage of the cold energy becomes possible in the temperature field of nighttime without other electric power. And the optimal combination of each air conditioner was calculated with the optimization technique. In the examination of plants, in order to evaluate the water-saving culture environment at increased humidity levels, the effect of increased three relative humidity levels in growth chambers with cucumber seedlings was investigated. Relative humidity and the temperature in assimilation box were controlled by combining two dehumidification pumps and silica gel and using a control computer. Consequently, it turns out that it has attained in the combination of the air-conditioner considered to reduce power consumption where the loss of moisture of a house is made into the minimum and the validity of the proposed technique was suggested. It was also useful to introduce the fog cooling system, thermal storage mediums, and the gas absorption refrigerator with dehumidification ability. Furthermore, it was found that dry matter production and relative growth rate were largest when seedlings were grown in the 86% level chamber. The leaf area of seedlings became larger under level 86% than under level 74.5%, in contrast, the reduction of the transpiration rate was probably induced by the decreased nutrient uptake by seedlings under 97.8% level. These results indicate that good cultivation is possible at high humidity conditions and there is an optimal humidity level.

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