Developing a new energy-saving, photosynthesis-promoting environmental control system for greenhouse production based on a heat pump with a heat storage system

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Abstract

We installed an experimental environmental control system, consisting of a heat pump, a fan coil unit, a soil-water heat exchanger, and a heat storage tank, in a greenhouse and investigated its thermal characteristics. The system reduced ventilation time, and the CO₂ concentration and humidity in the greenhouse thus remained high. Therefore, promotion of photosynthesis is expected. Its energy consumption was only 45% of that of a conventional oil-fired air heater.

Key words: CO₂ enrichment, Coefficient of performance, Energy saving, Environmental control system, Greenhouse, Thermal storage.

1. Introduction

To reduce emissions of greenhouse gases and to cope with rapid fluctuations in fuel prices, Japanese greenhouse growers need to reduce their energy consumption. In addition, their income has dropped on account of downturns in the market price of their produce. Thus, new technologies to reduce energy consumption while increasing yield per unit area are needed.

In coastal areas on the Pacific Ocean side of Japan, heated greenhouses must be ventilated during the day, which causes heat loss, even in winter. If the heat could be stored and used for heating at night, energy use and cost could be greatly reduced. Heat storage techniques were investigated extensively when fuel prices soared in the 1980s, and some were introduced into commercial greenhouses (Oguni, 1982; Shoji *et al.*, 1982; Hayashi *et al.*, 1983; Kozai *et al.*, 1983).

However, they fell out of use when fuel prices fell again.

CO₂ enrichment in greenhouses promotes photosynthesis by crops (Kawashima, 1991; Kawashiro *et al.*, 2009), yet only 2.7% of the total greenhouse area in Japan uses it (MAFF, 2009). Ventilation defeats the purpose of CO₂ enrichment, so the effect on yield is often unclear. Any technique that avoids the need for ventilation would improve the effect of CO₂ enrichment.

We have developed a new environmental control system that uses a heat pump to store heat, thus reducing energy consumption, avoiding the need for ventilation and so promoting photosynthesis. To improve efficiency of energy use in the heat storage/release process, we designed the system using a fan coil unit and a soil heat exchanger in combination with a heat pump. Here, we evaluated the system's thermal and energy-saving properties, and investigated the effects on the environment in a greenhouse, especially on CO₂ concentration and relative humidity, which greatly affect photosynthesis.

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2. Materials and Methods

2.1 Greenhouses and experimental setup

In two north-south-oriented greenhouses, a conventional oil-fired air heater installed at the northern end supplied hot air via two plastic ducts laid on the ground along both side walls (Fig. 1). In one greenhouse, designated the experimental greenhouse (G_{ex}), we installed our environmental control system. The other was designated the control greenhouse (G_{ct}).

Both were single-span, saddle-roof greenhouses of 12 m long, 6.3 m wide, and 3.3 m high, made of steel pipes covered with polyolefin film. The internal thermal screens were made of polyethylene film. The thermal screens of the roofs and side walls were opened during the daytime (0800h-1700h) and closed during the night (1700h-0800h). The side windows of the greenhouses were opened and closed for ventilation depending on the room air temperature.

The experiment ran from March 10 to April 9, 2009 in Natori City, Japan (38.17°N).

2.2 Environmental control system

The environmental control system consists of a heat storage tank, a heat pump, a fan coil unit, a soil-water heat-exchange unit, and three circulation pumps (Fig. 2). We also installed an auxiliary oil air heater, a CO₂ generator, and various sensors.

The heat storage tank was made of 10-mm plywood insulated with 100-mm polystyrene foam, and waterproofed with 2-mm-thick plastic sheeting. It formed a rectangular parallelepiped of 2.7 m long, 0.9 m wide, and 1.2 m deep, with a capacity of 2916 L. It was installed underground inside the northern end of the greenhouse and filled with water.

An air-water heat pump (YWYP125A, Daikin, Osaka, Japan; 3.75 kW rated electric power consumption, 13.5 kW heating capacity, 11.2 kW cooling capacity) and a fan coil unit (UAHM90B water-air heat exchanger, Daikin; 0.4 kW rated electric power consumption) were equipped with three water circulation pumps (WUP3-325-0.15S, Kawamoto Pump, Aichi, Japan; 0.15 kW rated power output). Each circulation pump ran simultaneously with the heat pump or the fan

Fig. 1. Schematic diagram of the experimental greenhouses. G_{ex} : greenhouse with experimental environmental control system; G_{ct} : greenhouse with conventional oil heater.

Fig. 2. Schematic diagram of the experimental environmental control system.

coil unit. Polyethylene pipes (27 mm wide, 1 mm thick) were buried 0.3 m deep, 0.3 m apart, in the soil in the greenhouse as a soil-water heat exchanger (with a surface area of 8.0 m² and a water capacity of 56 L). A programmable logic controller (KV-3000 series, Keyence, Osaka, Japan) controlled the system.

An oil-fired air heater (KA-205, Nepon Inc., Tokyo, Japan; 23.3 kW) was installed in each greenhouse, and kerosene consumption was measured with an oil meter (RE10LF, Nitto Seiko, Kyoto, Japan). A CO₂ generator (0.3 L h⁻¹ kerosene) ran continuously from 0830h to 1200h every day in each greenhouse.

When the daytime air temperature exceeded 25°C, the environmental control system removed heat from inside the greenhouse and stored it in the heat storage tank and the soil of the greenhouse floor. When the air temperature fell below 23°C, it stopped. When the air temperature exceeded 30°C, the system opened the side windows for ventilation. When the nighttime air temperature fell below 15°C, the stored heat was piped in, and when it exceeded 17°C, the system stopped.

During cooling, the system selected the fan coil unit when the water temperature in the heat storage tank was < 15°C and selected the heat pump when the water temperature was ≥ 15°C. When the water temperature reached 45°C, it stopped. When the temperature

difference between the water in the tank and the soil at a depth of 20 cm (between the heat-exchange pipes) was > 10°C, the system started circulating the hot water into the soil-water heat exchanger, and when the difference was ≤ 5°C, it stopped. During heating, when the water temperature in the tank was ≥ 20°C, the system used the fan coil to release heat, and when the water temperature was < 20°C, it used the heat pump. Some of the heat stored in the soil radiated directly from the soil surface into the greenhouse at night. When the outlet water temperature of the heat pump decreased to ≤ 5°C, the system stopped the heat pump to prevent damage by freezing, and the auxiliary air heater supplied heat.

2.3 Measurements

The air temperature inside and outside the greenhouses was measured by platinum resistance thermometers (RD-10M, Shimaden Co., Ltd., Tokyo, Japan; Pt100) with an aspirated tube radiation shield. The inside sensors were set at 0.5 and 1.0 m above the ground in the center of the greenhouse. The inside relative humidity (RH) was measured by a humidity sensor (ES2-HB, Omron, Kyoto, Japan). The CO₂ concentration inside was measured by a CO₂ sensor (MA-10, Chino, Yamagata, Japan). The mass flow rate of the water in the pipes was measured by flow

meters (VWK30RC pulse transmitter, Kimmon Co., Tokyo, Japan). The temperature of the water entering and leaving the heat pump, fan coil unit, and soil-water heat exchanger was measured by platinum resistance thermometers (RD-10M) mounted on the inlet and outlet lines. The electrical power input into the heat pump, fan coil unit, and circulating pumps was measured by wattmeters (Clamp On Power HiTESTER 3168, Hioki E. E. Corp., Nagano, Japan). The ground temperatures at depths of 0.1 and 0.2 m were measured by platinum resistance thermometers (RD-10M). The solar radiation inside and outside the greenhouse was measured by a pyranometer (MS-601, EKO Instruments Co. Ltd., Tokyo, Japan). All data from the sensors were automatically recorded in the programmable logic controller every 60 s.

2.4 Plants

Paprika (*Capsicum annuum* cv. Fiesta) plants were grown hydroponically during the experiment. Seedlings at the flowering stage were transplanted at a planting density of 2.7 plants m^{-2} in both greenhouses on January 17, 2008. The soil surfaces of the greenhouses were covered with black non-woven cloth.

3. Results

3.1 Environmental measurements

Environmental measurement data are summarized from 0600h of one day to 0559h of the next day (Table 1). Average minimum and maximum air temperatures were 14.9 and 31.5°C inside and 1.4 and 14.3°C outside, respectively. Average minimum and maximum water temperatures in the heat storage tank were 12.5 and 41.1°C, respectively. Average minimum and maximum soil temperatures were 20.4 and 26.5°C at 0.1 m and 21.7 and 26.8°C at 0.2 m, respectively. Average minimum and maximum inside relative humidities were 34.8 and 75.5%, respectively.

3.2 Thermal performance

The daily solar radiation during the experiment averaged 2,382 Wh m^{-2} . Only on one day (March 24) was the solar radiation insufficiently high to warrant cooling. The average heat energy removed was 879 Wh m^{-2} : 823 Wh m^{-2} (93.6%) by the heat pump and 57 Wh m^{-2} (6.5%) by the fan coil unit. The heat pump, which was more effective, dominated the cooling because the primary purpose of cooling was to reduce the ventilation time. Of the heat energy removed, 445 Wh m^{-2} was transferred into the soil by the soil-water heat-

exchange unit. The electricity consumption during cooling averaged 309 Wh m^{-2} per day (Table 2).

At night, the average heat energy released was 444 Wh m^{-2} : 251 Wh m^{-2} (56.5%) by the heat pump and 193 Wh m^{-2} (43.5%) by the fan coil unit. The electricity consumption during heating averaged 97 Wh m^{-2} (Table 3).

The outlet water temperature of the heat pump at midnight was $<5^{\circ}\text{C}$ (and the heat pump stopped) on 15 days during the experiment. At these times, the air heater cut in. The average heat energy supplied by the heater was 111 Wh m^{-2} per day (Table 3).

3.3 Supply of heat from the soil surface to the air inside the greenhouse

The average heat load, $Q_{\text{load,h}}$, was 1,139 Wh m^{-2} per day, calculated from the consumption of kerosene by the air heater in G_{ct} and the average heating degree hour of $182^{\circ}\text{C}\cdot\text{h day}^{-1}$ during the experiment (Table 3). In G_{ex} , the total amount of heat released from the fan coil unit, the heat pump, and the air heater, $Q_{\text{total,h}}$, averaged 556 Wh m^{-2} . We presume that the difference between $Q_{\text{total,h}}$ and $Q_{\text{load,h}}$ is the amount of heat radiated from the soil surface to the air inside the greenhouse ($Q_{\text{soil,h}}$), which was 583 Wh m^{-2} per day. The amount of heat transferred from the heat storage tank to the soil during the daytime, $Q_{\text{soil,c}}$, averaged 445 Wh m^{-2} per day. The difference between $Q_{\text{soil,h}}$ and $Q_{\text{soil,c}}$, 138 Wh m^{-2} per day, was therefore the heat transferred directly from the air to the soil surface or from solar radiation to the soil surface.

3.4 Coefficient of performance of the system

The coefficient of performance (COP) during cooling, ϵ_{c} , ranged from 2.1 to 14.5 (mean, 3.3; Table 4). COP during heating, ϵ_{h} , ranged from 2.7 to 6.4 (mean, 4.6). If the purpose of the cooling is to store the heat for release at nighttime, calculation of the COP for heating should include the electricity consumed during cooling. In this case, overall COP, ϵ_{tl} , ranged from 0.3 to 5.7 (mean, 1.4). COP ϵ_{tl} increased when there was less daytime cooling and it decreased when there was less nighttime heating, since cooling consumed more energy than heating.

For the COP of the heat pump, during cooling, the water temperature at the inlet of the heat pump influenced the COP: a higher inlet water temperature reduced the COP (Fig. 3). During heating, the COP decreased with decreasing temperature of the inlet water to the heat pump (operated at $<20^{\circ}\text{C}$) (Fig. 4).

Table 1. Daily maximum and minimum air temperatures inside and outside the greenhouse, and of the heat storage tank.

Date 0600h-0559h next day	Inside air temp. (°C)		Outside air temp. (°C)		Water temp. in heat storage tank (°C)		Soil temp. at 0.1 m depth (°C)		Soil temp. at 0.2 m depth (°C)		Inside relative humidity (%)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
March												
10-11	14.5	31.8	0.5	16.0	11.5	44.6	18.6	24.9	19.4	25.3	31.6	74.0
11-12	13.8	29.9	-0.7	6.8	11.7	40.4	18.7	24.0	19.9	24.2	27.9	68.1
12-13	14.5	32.7	-1.7	10.3	10.8	44.4	18.4	25.2	19.6	25.6	29.8	72.3
13-14	14.1	29.0	-0.2	13.7	10.8	37.5	19.4	23.6	20.5	24.0	35.2	82.7
14-15	14.4	28.8	2.7	12.5	11.2	33.6	18.4	21.5	20.0	22.3	34.0	84.0
15-16	14.3	35.8	0.6	13.9	11.6	44.4	18.0	25.8	19.2	25.9	26.7	81.5
16-17	15.9	30.8	0.8	17.8	15.6	44.6	20.5	25.1	21.4	25.9	38.9	83.3
17-18	15.2	27.5	0.5	14.8	14.2	44.6	20.3	24.4	21.3	25.7	42.7	78.0
18-19	15.9	40.4	1.1	17.0	11.7	44.3	20.0	27.8	21.2	27.6	38.4	83.0
19-20	16.1	40.2	8.2	22.5	25.9	44.3	22.4	30.1	23.6	29.5	32.8	86.4
20-21	15.2	32.7	2.2	13.8	11.8	44.5	21.9	27.2	23.9	28.1	30.3	85.2
21-22	14.3	23.8	3.2	12.8	9.9	13.0	19.1	21.4	20.3	21.6	57.7	84.8
22-23	15.0	29.2	-0.9	12.6	10.0	44.7	18.8	25.6	19.9	26.2	36.7	69.8
23-24	15.9	32.0	1.2	10.5	11.1	44.4	20.2	27.4	21.5	27.2	34.8	77.6
24-25	13.9	17.8	0.4	5.2	9.8	17.8	17.9	21.8	19.8	23.4	54.0	69.3
25-26	13.8	29.4	-2.9	10.0	9.9	44.8	17.7	24.6	19.3	25.5	40.7	69.0
26-27	14.1	32.7	-1.5	10.9	11.7	44.3	19.1	26.5	20.7	26.5	36.6	64.2
27-28	14.6	30.6	-1.4	11.0	11.5	44.2	19.9	26.1	21.3	26.5	35.5	70.9
28-29	15.9	31.6	-0.5	10.6	11.3	44.5	20.3	27.1	21.7	27.4	38.0	72.0
29-30	14.8	31.0	-1.4	14.3	13.3	44.6	21.3	26.8	22.4	27.4	36.0	74.1
30-31	16.1	31.1	0.6	14.1	11.6	44.3	21.0	27.6	22.3	27.9	38.7	76.7
April												
31-1	14.4	21.1	3.3	5.7	9.9	23.3	18.6	22.2	20.4	23.9	58.7	72.6
1-2	15.2	31.4	1.7	13.6	10.0	44.5	18.5	26.8	20.1	26.8	32.8	70.7
2-3	15.9	33.3	2.2	19.4	12.8	44.6	20.9	28.6	22.1	28.4	21.6	80.1
3-4	15.6	31.3	6.5	15.3	21.7	44.5	22.2	27.3	23.6	28.2	40.6	83.0
4-5	13.8	34.9	2.0	20.4	12.7	44.4	22.3	29.9	23.9	29.6	18.9	71.6
5-6	14.1	35.2	3.1	17.7	12.5	44.5	22.9	31.2	24.3	30.3	22.9	66.7
6-7	14.5	35.1	4.2	22.5	12.7	44.4	24.0	31.1	25.0	30.5	23.2	74.1
7-8	16.6	34.8	3.9	18.9	13.0	44.5	24.7	31.6	25.5	30.9	22.6	66.7
8-9	15.8	39.1	5.0	25.3	12.9	44.3	24.6	32.2	25.6	31.3	26.6	72.7
Average	14.9	31.5	1.4	14.3	12.5	41.1	20.4	26.5	21.7	26.8	34.8	75.5

Table 2. Heat and electric energy flux measurements during daytime.

Date 0600h-1759h	Solar radiation inside	Heat removed by HP	Heat removed by FC	Heat removed by FC + HP (Wh m ⁻²)	Heat stored in soil	Electricity consumption
	H	Q _{hp,c}	Q _{fc,c}	Q _{hp+fc,c}	Q _{soil,c}	Q _{e,c}
March						
10	1,985	1,063	0	1,063	606	329
11	2,065	763	64	827	443	289
12	2,423	1,065	57	1,122	595	393
13	1,889	589	101	691	380	240
14	1,005	187	0	187	260	46
15	2,706	1,101	73	1,174	591	349
16	1,608	805	0	805	558	297
17	1,595	833	0	833	518	310
18	2,594	1,098	60	1,158	514	360
19	2,599	694	0	694	736	284
20	1,489	461	0	461	547	173
21	797	0	27	27	0	2
22	2,621	1,029	125	1,154	376	401
23	2,631	967	79	1,046	388	343
24	432	0	0	0	0	0
25	2,910	1,049	125	1,174	405	389
26	2,937	988	25	1,011	407	344
27	2,631	886	112	998	418	347
28	2,027	1,008	146	1,153	466	385
29	N.M	1,008	11	1,019	433	332
30	N.M	984	137	1,121	453	364
April						
1	N.M	N.M	N.M	N.M	N.M	N.M
2	3,156	914	203	1,117	465	342
3	3,502	1,002	58	1,060	506	410
4	1,999	705	0	705	555	330
5	3,304	731	0	731	531	342
6	3,519	964	67	1,031	427	385
7	3,086	953	86	1,039	443	381
8	3,242	985	0	985	455	393
9	3,557	1,024	90	1,114	417	389
Average	2,382	823	57	879	445	309

N.M : Not Measured

HP : heat pump FC : fan coil unit

Table 3. Heat and electric energy flux measurements during nighttime.

Date 1800h-0559h next day	Heat released from HP	Heat released from FC	Heat released from HP&FC	Electricity consum ption (Wh m ⁻²)	Heat relesed from AH	Heat released from HP, FC, AH	Heat released from the soil	Heating load	Heating degree hour (°C · hr day ⁻¹)
	Q _{hp,h}	Q _{fc,h}	Q _{hp+fc,h}	Q _{e,h}	Q _{ah,h}	Q _{total,h}	Q _{soil,h}	Q _{load,h}	DH _n
March									
10-11	378	218	596	151	251	847	539	1,386	192
11-12	333	178	512	147	371	882	621	1,503	225
12-13	400	223	623	122	78	701	710	1,411	235
13-14	0	76	76	28	0	76	646	722	82
14-15	375	125	500	139	218	718	832	1,550	181
15-16	186	195	381	111	0	381	824	1,205	187
16-17	168	172	340	100	0	340	829	1,170	149
17-18	323	211	535	106	0	535	1,128	1,662	186
18-19	0	124	124	37	0	124	641	765	131
19-20	N.M	N.M	N.M	N.M	N.M	N.M	N.M	306	64
20-21	370	230	600	138	299	899	716	1,616	174
21-22	289	0	289	60	185	474	161	636	97
22-23	379	240	619	118	19	638	651	1,289	201
23-24	196	198	394	94	0	394	807	1,201	186
24-25	404	0	404	71	1,142	1,547	200	1,746	211
25-26	352	236	588	137	284	872	687	1,559	238
26-27	379	269	648	111	119	768	631	1,399	219
27-28	367	251	618	113	33	651	653	1,304	226
28-29	244	258	502	91	8	510	779	1,289	222
29-30	342	240	582	113	19	602	767	1,369	226
30-31	3	262	265	42	0	265	856	1,122	189
April									
31-1	N.M	N.M	N.M	N.M	N.M	N.M	N.M	N.M	N.M
1-2	294	242	536	96	5	541	690	1,231	189
2-3	1	203	204	37	0	204	641	846	168
3-4	0	139	139	23	0	139	542	681	131
4-5	305	241	546	124	81	627	249	876	186
5-6	314	230	544	119	0	544	324	868	202
6-7	158	213	371	86	0	371	361	732	197
7-8	302	225	528	124	0	528	254	781	203
8-9	164	218	382	82	0	382	430	811	181
Average	251	193	444	97	111	556	583	1,139	182

N.M : Not Measured

HP : heat pump, FC : fan coil unit, AH : hot air heater

Table 4. Coefficient of performance (*COP*) of the system, daily solar energy collection rate, and energy use ratio.

Date	<i>COP</i> for cooling $Q_{hp+fc,c}/Q_{e,c}$	<i>COP</i> for heating $Q_{hp+fc,h}/Q_{e,h}$	<i>COP</i> . for total1 $Q_{hp+fc,h}/(Q_{e,c}+Q_{e,h})$	<i>COP</i> for total2 $(Q_{hp+fc,h}+Q_{soil,c})/(Q_{e,c}+Q_{e,h})$	Solar energy collecting rate $Q_{hp+fc,c}/H$	Energy use ratio $(Q_{e,c}+Q_{e,h}+Q_{ah,h})/Q_{load,h}$ (%)
0600h-0559h next day	ε_c	ε_h	ε_{t1}	ε_{t2}	η	r
March						
10-11	3.2	3.9	1.2	2.5	53.6	52.8
11-12	2.9	3.5	1.2	2.2	40.0	53.6
12-13	2.9	5.1	1.2	2.4	46.3	42.1
13-14	2.9	2.7	0.3	1.7	36.6	37.1
14-15	4.1	3.6	2.7	4.1	18.6	26.0
15-16	3.4	3.4	0.8	2.1	43.4	38.2
16-17	2.7	3.4	0.9	2.3	50.1	34.0
17-18	2.7	5.0	1.3	2.5	52.2	25.1
18-19	3.2	3.4	0.3	1.6	44.6	52.0
19-20	2.4	N.M	N.M	N.M	26.7	N.M
20-21	2.7	4.3	1.9	3.7	31.0	37.8
21-22	14.5	4.8	4.6	4.6	3.4	39.0
22-23	2.9	5.2	1.2	1.9	44.0	41.8
23-24	3.0	4.2	0.9	1.8	39.7	36.4
24-25	–	5.7	5.7	5.7	0.0	69.5
25-26	3.0	4.3	1.1	1.9	40.3	52.0
26-27	2.9	5.9	1.4	2.3	34.4	41.0
27-28	2.9	5.5	1.3	2.3	37.9	37.8
28-29	3.0	5.5	1.1	2.0	56.9	37.6
29-30	3.1	5.1	1.3	2.3	N.M	33.9
30-31	3.1	6.4	0.7	1.8	N.M	36.1
April					0.0	N.M
31-1	N.M	N.M	N.M	N.M	N.M	36.0
1-2	3.3	5.6	1.2	2.3	35.4	52.9
2-3	2.6	5.5	0.5	1.6	30.3	51.9
3-4	2.1	6.0	0.4	2.0	35.2	62.5
4-5	2.1	4.4	1.2	2.3	22.1	58.2
5-6	2.7	4.6	1.1	1.9	29.3	63.9
6-7	2.7	4.3	0.8	1.7	33.7	66.3
7-8	2.5	4.3	1.0	1.9	30.4	58.1
8-9	2.9	4.6	0.8	1.7	31.3	
Average	3.3	4.6	1.4	2.4	35.1	45.5

N.M : Not Measured

Fig. 3. Coefficient of performance of the heat pump as affected by the inlet water temperature during cooling operation. Each value represents the hourly average.

Fig. 4. Coefficient of performance of the heat pump as affected by the inlet water temperature during heating operation. Each value represents the hourly average.

Fig. 5. Coefficient of performance of the fan coil unit as affected by inlet water temperature during heating operation. Each value represents the hourly average.

Fig. 6. Time course of (a) relative humidity, (b) solar radiation, (c) air temperature, and (d) CO₂ concentration in G_{ct} (◇) and G_{ex} (◆) on 16 April 2009. A solid line on the graph (c) indicates the ventilation temperature (30°C).

On the other hand, for the COP of the fan coil unit, as the inlet water temperature decreased, the COP decreased (Fig. 5).

3.5 Energy use ratio

The energy used in G_{ex} was 45.5% of that used in G_{ct} , giving a 54.5% saving (Table 4).

3.6 Changes in CO₂ and humidity

The cooling capacity of the experimental system was insufficient to completely control the air temperature rises, and ventilation was necessary on 13 days in March and 8 days in April. On April 14, a typical fine, warm day, as the solar radiation increased, the air temperature increased (Fig. 6b, c). The experimental system delayed the air temperature rise, so the ventilation started later and its duration was shorter in G_{ex} than in G_{ct} . As a result, the RH and CO₂ concentration were both higher in G_{ex} than in G_{ct} (Fig. 6a, d). This means the amount of CO₂ released from the house was larger in G_{ct} than in G_{ex} . So the effectiveness of CO₂ enrichment in G_{ex} was higher than that in G_{ct} .

4. Discussion

Kozai *et al.* (1983) developed a system to collect and store heat from a greenhouse in a water tank by

use of an air-water heat exchanger. The average COP of their system was 2.4. Hayashi *et al.* (1983) used a similar system that also released heat at night by use of a heat pump. The average COP during heating was 1.9. Oguni (1982) used a heat pump in the daytime to dehumidify the air, and used the heat held in the retained water for heating via the heat pump. The COP during heating was 2.3. In all cases, as the energy that is used to collect the heat increased, the COP during heating decreased.

In our experiment, to increase the cooling and heating capacity while minimizing the power consumption, we combined a low-power fan coil unit with a heat pump. During cooling (heat collection), the design favored the use of the heat pump, achieving capture of 34% of the heat, but at a high cost of electricity used, giving a COP (ϵ_{t1}) of only 1.5. Even when we added in the heat released from the soil surface to the air, the COP (ϵ_{t2}) reached only 2.2. Considering the results of earlier reports and our experiment, we conclude that the collection of excess heat during the daytime for use at night is ineffective for saving energy.

The use of cooling to limit the ventilation time has been studied in the Netherlands (Heuvelink *et al.*,

2008; de Zwart, 2008; Qian *et al.*, 2011). Minimizing the ventilation time extended the time during which CO₂ concentration and high humidity could be maintained and thus increased yield (Yasuba *et al.*, 2011). Ventilation introduces cooler, drier air, decreasing humidity and increasing water vapor pressure. Humidity in the greenhouse has a large effect on the photosynthetic rate, and higher humidity increases the photosynthetic rate by delaying stomatal closure (Yabuki and Miyagawa, 1970). Keeping the humidity high by fogging in the daytime increased the yields of tomato and strawberry by >20% (Iwasaki *et al.*, 2011). The CO₂ concentration and RH were higher in G_{ex} than in G_{ci}. Although we did not investigate the growth or yield of the crop, we are certain that the photosynthetic rate will improve by using our environmental control system.

Many air-air heat pumps are used in commercial greenhouses, especially in rose production, so we must also compare the energy efficiency of our system with these. Air-air heat pumps had a reported average COP during heating of 3.5 in Morioka (Kawashima *et al.*, 2008) and 3.0 in Miyagi (Iwasaki *et al.*, 2010). We obtained an average COP during heating (ϵ_h) of 4.7. We also obtained an average COP during cooling (ϵ_c) of 3.3, but there is little comparable information on air-air heat pumps. Data from an air conditioner manufacturer's technical manual (Mitsubishi Electric, 2011) show that when the outside air temperature is $\leq 10^\circ\text{C}$ and the inside temperature is 20°C (wet bulb), the COP is calculated to be 4.5.

Our results show that the COP of the heat pump changes widely with water temperature in both cooling and heating operations. If we set the upper limit of the water temperature during cooling at $30\text{--}35^\circ\text{C}$ and the lower limit at about 15°C , the COP could increase greatly. We could improve it further by optimizing the volume of the heat storage tank, the preset values of water temperature, and the method of operating the heat pump, fan coil unit, and soil-water heat exchanger.

The use of a ground-source heat pump (Bakiri, 2010; Benli, 2011) or an air-water heat pump relying on groundwater (Iwasaki *et al.*, 2010) has attracted attention. Takakura (2008) reported that in the Netherlands, they used an aquifer for seasonal heat storage and for cooling and heating the air in greenhouses. The temperature of groundwater is almost constant throughout the year, offering a more stable COP that is

usually higher than that of air-air heat pumps. The COP of a heat pump using underground water in Miyagi was 3.9 (Iwasaki *et al.*, 2010). To improve the operation of our environmental control system, we should be able to modify it to use groundwater when the water temperature in the heat storage tank moves outside the optimum range.

The effectiveness of any environmental control system should be evaluated on the consumption of energy, cost of production, and emission of CO₂ per kilogram of produce, because the retained heat should increase the yield. In future work, we will grow crops and relate any improvements in yield to the costs of cooling.

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