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Heating and Cooling System for Utilization of Surplus Air Thermal Energy in Greenhouse and its Control Logic

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Abstract

Purpose: Utilizing air thermal energy during over-heated time in the greenhouse is a necessary component to save greenhouse heating costs for nighttime. However, there is no practical way to implement the related principles. **Methods:** In this study, a heating and cooling system which utilizes the surplus air thermal energy in a greenhouse was developed. Available air thermal energy and heating load for this experimental glasshouse were estimated based on temperature conditions of the plant growth and weather data. **Results:** Estimated values were 400 MJ/day for maximum surplus air thermal energy and 340 MJ/day for maximum heating energy which were target values of the design as well. The system consists of a heat pump, fan-coil units and heat storage tanks which are divided into low and high temperature tanks. Moreover, a new control logic was developed for surplus air thermal energy utilization. **Conclusions:** This paper explains the details of conceptual design process of the system. Results of test operations showed that the developed system performed the recovery and supply of the thermal energy according to design purposes.

Keywords: Energy recovery, Energy saving, Greenhouse environmental control, Heat pump, Surplus heat

Introduction

Modern greenhouses are equipped with various heating and air conditioning devices such as heaters, coolers, fans, *etc*. Since heaters and coolers consume large amounts of energy in poorly insulated greenhouses, saving the energy has been a crucial task for producing the agro-products, particularly in the years of high oil price. The heating costs reached up to 49.5% of the total production costs for typical greenhouses in South Korea (RDA, 2010). Saving the heating energy is also desirable in the sense of alleviating the adverse effects of global warming. Numerous researches have been conducted to save the energy in greenhouse farming; for example, improvement of energy efficiency of a heating system (Kim et al., 2000; Kang et al., 2009), replacing the energy source to new and renewable energy (Ozgener and Hepbasli, 2005; Benli and Durmuş, 2009), alternation of the greenhouse structure (Djevic and Dimitrijevic, 2009). However, a limited number of reports are available on recovering the air thermal energy during over-heated hours and using it when necessary. Suh et al. (2009) named this energy as surplus solar energy and tried to estimate its amount. Lee et al. (2011) tried to capture the air thermal energy and store it in water tunnels in a greenhouse for a final use in heating applications at night. They reported that the developed system contributed to raise the air temperature by 4.3~4.4℃ in the greenhouse during the night of -8℃ ambient temperature.

In greenhouses, a considerable amount of thermal energy is discarded through the ventilators such as fans and

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windows even in the cold season. When air temperature exceeds the certain limit for a crop, the fans and windows start ventilation. This causes wasting of the thermal energy accumulated in the air. The surplus thermal energy can be recovered by heat exchangers located between ventilation inlets and outlets or by heat exchangers installed inside the greenhouse. Using heat exchangers for recovering the surplus energy has positive effects on saving energy costs as well as maintaining optimal temperature range in greenhouse farming.

This research aims to develop a heating and cooling system for utilizing the surplus air thermal energy. For this purpose, the concept of surplus air thermal energy was proposed and a heating-cooling system for an experimental greenhouse was designed based on the estimated surplus thermal energy, weather data, etc. Commercial environmental control systems were modified to utilize the surplus thermal energy. Many control logics for environmental controls have been already presented (Trigui et al., 2001; Aaslyng et al., 2005). Correspondingly, a new control logic for energy recovery and use was developed in this study. At the end, the heating-cooling system with new environment-energy control logic was tested.

Materials and Methods

Concept of the surplus air thermal energy

Solar radiation energy is partially stored in the air and results in temperature increase in greenhouses. In the case when solar energy is so abundant for crop photosynthesis, the air within the greenhouses is often heated up over the temperature limit of a crop even in the cold season. Suh et al. (2009) named the discarded energy through the ventilators as the surplus solar energy. Though this definition is easy to understand but scientifically speaking, the definition is not sufficiently clear. In this paper, surplus air thermal energy is defined as the imaginary energy difference between solar energy input and heat loss during the over-heated time. The solar energy input and heat loss are recognized as solar radiation and heating load, respectively. Figure 1 shows two curves describing the characteristics of a cold winter day (11st December, 2010). Although outdoor temperature was reported to be lower than 3℃, greenhouse air temperature increased to over 30℃. If temperature limit of a crop is set to 25℃, fans or windows would be operated or opened between 11:30 am and 3:30 pm. The shaded area shown in Figure 1 is the surplus air thermal energy presented in this paper.

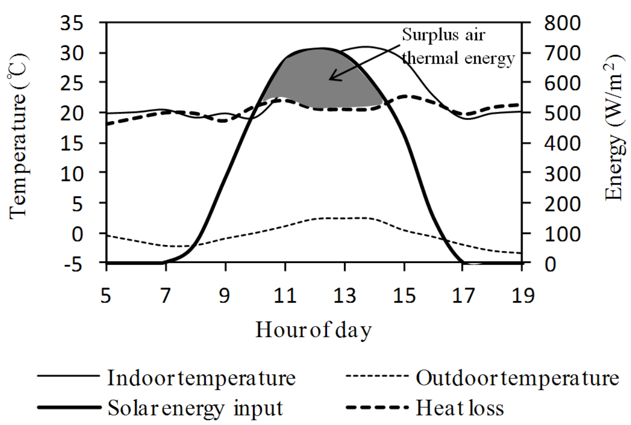


Figure 1. Concept of surplus air thermal energy (Data lines except heat loss are measured values. Heat loss line was calculated with 20°C of heating temperature and 25°C of optimal growth temperature.).

Development procedure

Development procedure of surplus air thermal energy utilization for a greenhouse system is shown in Figure 2. Given information are: type of cultivable crops with related growing temperatures at night and daytime, size and type of covering materials for the experimental greenhouse and weather data of the test site. Referring to existing data, amounts of available surplus air thermal energy and heating energy were estimated. After determination of

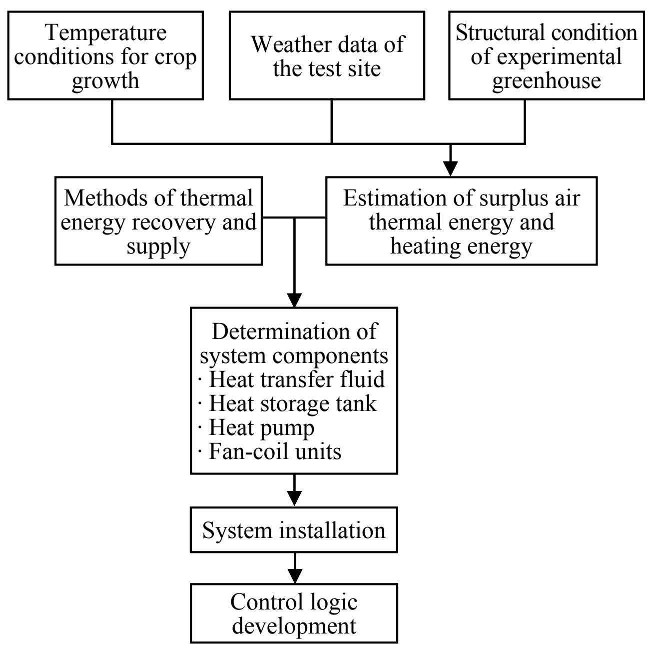


Figure 2. Development procedure of the greenhouse system for utilizing the surplus air thermal energy.

the proper method for heat recovery and supply in greenhouses, details of system components handling the estimated amounts of thermal energy were selected. Thereafter, the system components were installed in the greenhouse and control logic for system operation was developed.

System requirement for utilizing the surplus air thermal energy

There are two ways for recovering the surplus thermal energy: one is to use heat exchangers between ventilation inlets and outlets, and the other alternative is to use heat exchangers within a greenhouse. However, direct install of heat exchangers at the inlets and outlets is excluded because the greenhouse ventilation system involves some difficulties related to CO_2 enrichment and pest prevention. The basic idea of the system is to employ fan-coil units with running thermal fluid.

In order to use the recovered thermal energy for heating purposes, it needs that the energy shall be saved for later uses. For this purpose, some researchers suggested to use a heat storage tank system (Aye et al., 2010). However, if just one heat storage tank is employed, either a heating or cooling purpose has to be selected. This problem is resolved by using the heat pump system equipped with the high and low temperature heat storage tanks (HST and LST). The heat pump converts the recovered thermal energy (low density thermal energy) in the LST into the HST as high temperature energy. Consequently, the HST contents will be used as the heating energy storage and the LST content will also be used as the cooling energy storage or heat recovery.

In addition, the heat transfer fluid has to be chosen. The type of fluid was determined with consideration of economical and operational situation of the greenhouse.

Temperature control requirement

Some vegetables and flowers for greenhouse cultivation were investigated according to the optimal growth temperatures (Table 1). The recommended temperatures range from 15 to 30℃ at daytime and 5 to 20℃ at night time. For the heat transfer efficiency of the FCUs, temperature difference between coils and ambient temperature was set 10℃. In other words, the heat transfer fluid was maintained 10℃ higher for heating and 10℃ lower for cooling than the desired temperature. Thus, the temperature of the thermal fluid has to be over 40℃ for heating and below 5℃ for cooling. Based on the fluid temperature conditions, the temperature ranges of HST and LST in the heat pump system are determined.

Table 1. Optimal growth temperature of horticultural plants

Plant name	Daytime temperature	Night time temperature
Chrysanthemum (*Chrysanthemum morifolium*)	15℃	5℃
Strawberry (*Fragaria×ananassa Duchesne*)	20℃	10℃
Rose (*Rosa hybrida*)	25℃	15℃
Eggplant (*Solanum melongena* L.)	30℃	20℃

(NIHHS, 2010)

Estimation of heat storage capacity

Heating load of a greenhouse represents the net energy flow such as convection, conduction, condensation, infiltration, ventilation and thermal radiation from the greenhouse to the environment under steady state condition. Heat loss is represented in Eq. (1) (Hanan, 1998).

$$H_{loss} = hA_g(t_{i-t_o}) + 0.5\,VN(t_i - t_o) \tag{1}$$

where, h : Heat transfer coefficient of the greenhouse (W/m^2·℃)
A_g : Surface area of the greenhouse (m^2)
t_i, t_o : Inside and outside air temperature (℃)
V : Internal house volume (m^3)
N : Number of air exchanges per hour

The surplus air thermal energy defined in this paper can be written as in Eq. (2).

$$H_{re} = \alpha A_s I_s - \{hA_g(t_r - t_o) + 0.5\,VN(t_r - t_o)\} \tag{2}$$

where, α : Conversion ratio of solar radiation to heat in the greenhouse
A_s : Area affected by solar radiation (m^2)
I_s : Solar radiation intensity (W/m^2)
t_r : Air temperature for heat recovery (℃)

The LST should be able to recover the surplus air thermal energy. However, the coefficient α is not available in the reviewed literature. In order to design the heat storage tanks in this study, reasonable values for these coefficients were assumed.

Weather data for estimation of surplus thermal energy were achieved from the Suwon weather station, located 7.5 km away from the experimental site.

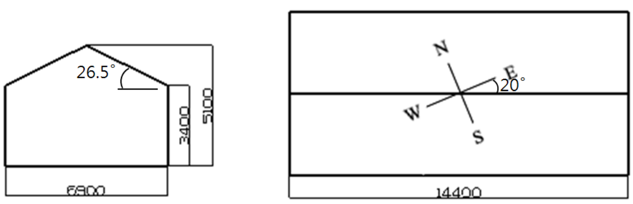
Experimental greenhouse

The experimental greenhouse is an even-span double layered glass (7 mm thick) house as shown in Figure 3 in Hwasung-City, Korea (Latitude of 37.2° N). Dimensions of the greenhouse structure are 6.9 m for width, 14.4 m for length and 3.4 and 5.1 m for height at the side walls and ridge, respectively (Figure 3). The experimental greenhouse is equipped with retractable thermal screening systems for the both side walls and a plane at the height of 2.9 m. The thermal screen was an aluminized vinyl shade screen. Based on design documents, isolation ratios are 72% and 80% for horizontal and vertical thermal screens, respectively. The air volume of the greenhouse is approximated to be 422.3 m^3 and is reduced to 288.1 m^3 at night time by spreading the screens. The specification of the experimental greenhouse is listed in Table 2.

Results and Discussion

Determination of the system components

Since the sizes of actual greenhouses are generally



(a) Front view (b) Top view and orientation

Figure 3. Dimension and orientation of the experimental greenhouse.

more than 1000 m^2, the large amount of heat transfer fluid is required to be circulated in heat exchanger units for practical use. Also, greenhouse is a structure provided to host the live plants inside. Hence, the heat transfer substance has to be cheap, safe and secure for the health of the plants. In this way, underground water as an economical and environmental-friendly option can be suitably used as the heat transfer substance. When water is used, temperature level of the LST has to be maintained at 7~15℃. This is a proper range of temperature for both efficient thermal energy recovery and stable operation of the heat pump. If the LST operating temperature drops below 7℃, efficiency of thermal energy recovery will be increased. However, because of probable risk of water freezing in heat pump evaporator, the LST operation under 7℃ is inappropriate. Operating temperature level of the HST has to be maintained between 35~50℃. If temperature of the HST drops below 35℃, greenhouse temperature control might be failed for 20℃ of heating temperature. On the contrary, with the HST of over 50℃, efficiency of the heat pump is significantly decreased.

The volume of heat storage tanks is determined using heating load and surplus air thermal energy of the experimental greenhouse. The overall heat transfer coefficient of the greenhouse which has double layered glasses was presented as 3.0 $W/m^2 \cdot ℃$ (ASAE, 1988). With the thermal screen, it is anticipated that the heat transfer coefficient is decreased by 1.0 $W/m^2 \cdot ℃$. For estimating the thermal energy input from the solar radiation, floor area was assumed to be the affected area by solar radiation. In a related manner, the conversion ratio of solar radiation to heat of the greenhouse was assumed to be 0.5 considering light transmissivity of the glass and Bowen ratio of the plant (Campbell, 1977). Thus, Eq. (1) is modified to Eq. (3) for the condition when heating is executed by thermal screens and Eq. (2) is also modified to Eq. (4) for daytime

Table 2. Specification of the experimental greenhouse

Item	Description
Type	Even-span
Location	Latitude of 37.2° N (Hwasung-City, Korea)
Orientation	East-West and 20° rotated to the east
Floor area	99.4 m^2
Inside volume (without screen)	422.3 m^3
Inside volume (with screen)	288.1 m^3
Covering material	Double-layered glass (7 mm thick)
Thermal screen	Aluminized vinyl shade screen, retractable, horizontal and vertical

conditions. Heating temperature of 15℃ and optimal growth temperature of 25℃ were selected for roses growth condition. Outside temperature, solar radiation and sunrise duration were acquired from the reports of Suwon weather station (Table 3) and heating duration was assumed to be 10 hour/day for December and February and 12 hour/day for January.

$$H_{loss} = 1.0 \times 267.3 \times (15 - t_{\min}) \times T_{hd} \quad (3)$$

$$H_{re} = 0.5 \times 99.4 \times I_{s,day} - 3.0 \times 267.3 \times (25 - t_{\max}) \times T_{sd} \quad (4)$$

where, t_{min}, t_{max} : Minimum and maximum outside temperature (℃)

T_{hd} : Heating duration (second)

T_{sd} : Sunrise duration (second)

$I_{s,day}$: Daily solar radiation (J/m^2)

Estimated heating load and surplus air thermal energy for the experimental greenhouse are shown in Figures 4 and 5, respectively. Since the HST needs to store thermal energy of 340 MJ/day, which is the maximum amount (See 2009-01 in Figure 2), the required volume of the HST is approximated to be 5.4 m^3 with considering of the temperature range (35~50℃). Since the maximum surplus air thermal energy was estimated to be 400 MJ/day (See 2009-02 in Figure 3), the required volume of the LST is 11.9 m^3 considering the related temperature range (7~15℃). Therefore, one commercial 5-m^3 FRP water tank for HST and two 5-m^3 FRP water tanks for LST were chosen as heat storage tanks. Each tank was insulated using the foaming polyethylene resin of 20-mm-thinkness. The heat pump was manufactured using a 6.5 kW-compressor, a 35.0 kW-Evaporator and a 27.0 kW-Condenser. Therefore, this heat pump can recover 58.5 MJ/h from the LST and store 81.9 MJ/h to the HST under the condition of COP 3.5.

Installation of the greenhouse system

Recovery of surplus air thermal energy was performed using fan-coil-units (FCUs). Ten FCUs were installed and placed in different spots within the greenhouse (Figures 6 and 8 (a)). Based on convective heat transfer principles, hot air rises to higher altitudes and upper zones. Hence, four FCUs were installed over the thermal screens at the height of 3.57 m. Therefore, the functionality of four upper FCUs was merely assigned to heat recovery and not

Table 3. Weather data in the experimental site

	Temperature (°C)			Sunrise duration* (hour)	Daily solar radiation* (MJ/m^2)
	Mean	Maximum	Minimum		
Dec. 2007	1.6	14.3	-6.5	9.2	10.4
Jan. 2008	-1.6	7.9	-12.1	9.5	12.4
Feb. 2008	-1.6	11.8	-10.4	10.4	16.8
Dec. 2008	0.9	14.5	-12.0	9.2	10.5
Jan. 2009	-2.6	12.5	-14.6	9.4	12.3
Feb. 2009	2.4	17.0	-9.1	10.1	16.0

* Maximum values (KMA, Each year)

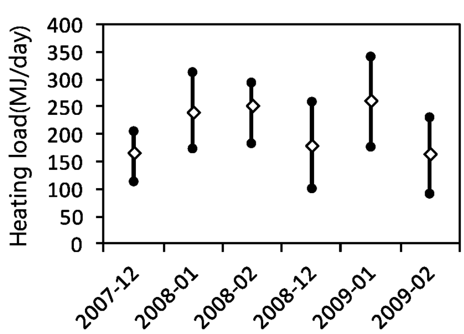


Figure 4. Estimated heating load for the experimental greenhouse

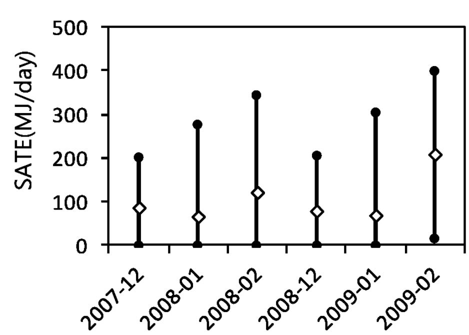


Figure 5. Estimated surplus air thermal energy (SATE) for the experimental greenhouse

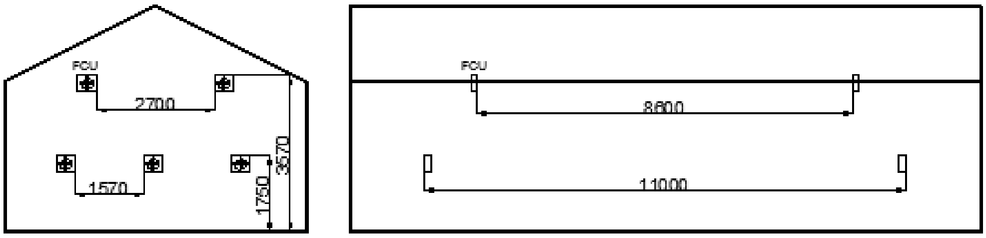


Figure 6. Positions of FCUs in the experimental greenhouse.

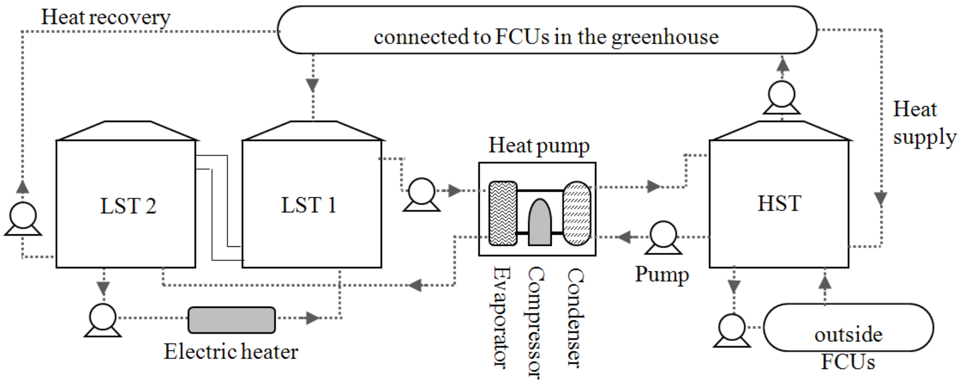


Figure 7. Schematic diagram of the equipment set-up.

to heat supply. Six other FCUs were installed at the height of 1.75 m while the domain of their operation involved both heat recovery and heat supply. Heating capacity of the selected FCU (CSTI-1, Chung-Ang, Korea) is 10000 kcal/h (41.9 MJ/h) with 80℃ inlet temperature. When water of 35℃ is used for heating, six FCUs transfer 77.4 MJ/h. With 15℃ water, ten FCUs absorb 64.5 MJ/h during heat recovery. Therefore, chosen FCUs are appropriate for experimental greenhouse condition.

The overall mechanical design and views of the system are shown in Figures 7 and 8. Two LSTs and one HST were connected to the heat pump and FCUs in the greenhouse. When surplus air thermal energy is generated, the water contained in the LST starts circulating to FCUs in the greenhouse and its energy is recovered into the LST. Low temperature energy of the LST is converted to higher temperature energy using the heat pump. Therefore, the HST stores the high temperature water and provides it for later heating purposes. When heating application is required, water in the HST is circulated to six lower FCUs and thermal energy is supplied to the greenhouse air, consequently. Chosen water pumps are 1 HP bronze casting pumps (PH-755W-B, Hanil electric, Korea) for prevention from corrosion damage and assuring of a significant flow rate.

(a) FCUs in the greenhouse

(b) LST and HST

(c) Heat pump

(d) Pumps and Pipes

Figure 8. Views of the developed greenhouse system.

Control logic

Control logic to operate the developed greenhouse system is shown in Figure 9. Flows of this control logic are

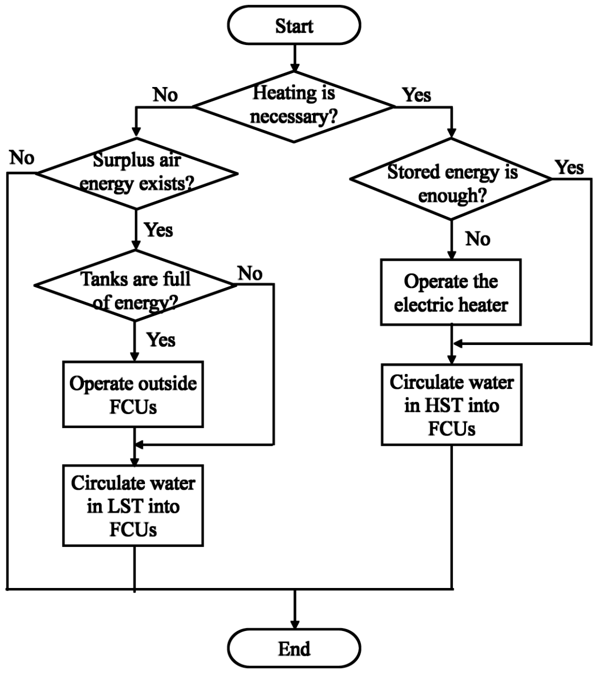


Figure 9. Control logic for heating and cooling with utilizing surplus air thermal energy.

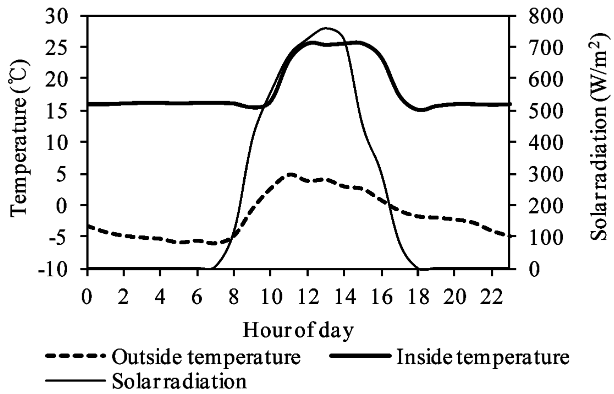


Figure 10. Greenhouse inside temperature under the system operation and outside weather condition on a day (11st February 2011) for developed system evaluation.

decided by temperature. Decision of heating and surplus energy recovery depends on greenhouse air temperature. When air temperature is higher than the optimal growth temperature at daytime, water in the LST is circulated into the FCUs and absorbs the surplus air thermal energy. If tank is full of stored energy, outside FCUs start to operate. On the contrary, when the air temperature is lower than the optimal growth temperature at night time, water in HST is circulated into the FCUs and thermal energy is supplied. If temperature of the HST is too low to heat the greenhouse, extra thermal energy is supplied by operating the electric heater. The heat pump operates based on LST and HST temperatures. At the set points of 15℃ and 50℃ for LST and HST, the heat pump works when temperature meets both higher than 15℃ for LST and lower than 50℃ for HST. Also, if stored thermal energy is insufficient, the electric heater is operated except between 10 pm and 5 am. This period for the electric heater off is to empty thermal energy stored in the HST. Through emptying stored thermal energy, enough heat storage capacity for recovering surplus air thermal energy is acquired. When the HST temperature becomes lower than the set value, it is empty state.

Energy flow and COP of the heat pump

The developed system was operated in February 2011 and the acquired hourly energy data on 11th February 2011, a typical cold winter day, was shown in Table 4. Some weather data inside and outside the test greenhouse are shown in Figure 10. Heating energy in Table 4 was calculated using the measured water flow rates and the temperature of water entering and leaving the FCUs. Power consumption of the heat pump system was also measured and used in calculating the COP. An electric heater supplied supplementary heating energy to the HST to keep its minimum temperature. The difference between the total heating energy and the total sum of the recovered energy and the supplementary energy means additional thermal energy supplied by the pumps for the FCUs and the heat pump. The heat pump was operated in the early morning to empty thermal energy stored in the LST and HST without the electric heater operation. The COP of the heat pump (Benli and Durmuş, 2009) was evaluated within the range of 1.8 to 3.8.

Table 4 shows how the developed system worked. From the midnight to 9 am, FCUs were operating for heating. At 4 am, the heat pump started to work to empty stored thermal energy without the electric heater operation. At 6 am, the LST temperature became too low so the supplementary heating started. At 11 am, the FCUs changed flow direction for energy recovery. The FCUs worked for cooling between 11 am and 4 pm. From 6 am, the FCUs worked for heating again. Between 8 and 9 pm, supplementary heating energy was applied to the LST. As a result, the developed system and control logic have operated properly for research purpose.

In Table 4, the total amount of surplus air thermal energy (83.2 MJ) comprised 14.2% of the total amount of heating energy (586.3 MJ) on the test day. This means

Table 4. Energy flow of the developed system and COPs of the heat pump on 11st February 2011

Time	Recovered energy (MJ)	Heating energy (MJ)	Supplementary heating energy (MJ)	COP of heat pump
0	0	28.6	0	
1	0	30.1	0	
2	0	29.6	0	
3	0	27.3	0	
4	0	32.8	0	3.4
5	0	34.7	0	3.1
6	0	50.7	33.1	3.2
7	0	52.5	41.0	3.3
8	0	64.8	40.2	3.6
9	0	29.0	40.6	3.7
10	0	0	41.2	2.6
11	3.9	0	33.2	3.6
12	23.5	0	41.0	3.8
13	31.8	0	18.6	3.5
14	22.5	0	1.1	2.6
15	1.5	0	0	3.0
16	0	0	0	
17	0	0	0	
18	0	23.8	0	
19	0	36.3	0	1.8
20	0	36.0	14.4	
21	0	40.7	20.9	2.8
22	0	31.8	0	
23	0	37.6	0	
Total	83.2	586.3	325.3	(Mean) 3.1

that the heating and cooling system for utilizing surplus air thermal energy cannot provide sufficient heating energy in cold and cloudy days, so that supplementary heating is required. However, the recovered energy is expected to contribute considerable portion of heating energy depending on weather condition even in a winter day, needless to say early spring and late fall.

Conclusions

This study was conducted to develop a heating-cooling system that saves air thermal energy during over-heated time in a greenhouse and use it later for heating. The main conclusions are as follows:

(1) Surplus air thermal energy which means maximum recoverable energy per day was defined as the imaginary energy difference between solar input energy and heat loss during the over-heated time.

(2) A heating-cooling system for an experimental glass-house was designed and developed. It consists of a heat pump, fan-coil units, heat storage tanks which are further divided into low and high temperature tanks, and a supplementary heater for extreme weather conditions.

(3) New temperature and energy control logic for utilizing the surplus air thermal energy was developed.

(4) Conceptual design process for developing this system was introduced step by step.

(5) The developed system was tested in a cold day (minimum temperature -6.1℃). The system worked as it was designed and its daily average COP of the heat pump system was 3.1.

(6) The developed heating and cooling system for utilizing surplus air thermal energy cannot provide sufficient heating energy in cold and cloudy days, so that supplementary heating is required.

The system has merits of providing a better environment for crops during the daytime by recovering the over-heated air thermal energy and saving heating energy at night time by using the stored thermal energy. These merits of the system during all four seasons will be evaluated and reported later.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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