Solar Thermal and Electric Desiccant Cooling System, Part 2: Experimental Investigation and Evaluation

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ABSTRACT

The combined solar thermal and electric desiccant cooling system is designed, fabricated, assembled and installed in the Laboratory of Building Environmental Engineering of Tohoku University. The performance of the combined system was observed and calculated. The performance of the whole system, thermal energy system and desiccant cooling system is presented in Part 1 of this paper. The second part (Part 2) of this paper presents the components evaluation and behavior for day time and night time operation of the system. The results show that the system components are functioning to their expected performances such as their stable behavior during the day-long operation of the total system.

Nomenclature

A	area [m^2]
COP	coefficient of performance [-]
C_P	specific heat [kJ/kg-K]
h	enthalpy [kJ/kg]
h_{Vap}	latent heat of evaporation [kJ/kg]
I	solar radiation [W/m^2] electric current [Ampere]
LER	latent energy ratio [-]
m	mass flow [kg/s]
Q_{Solar}	available solar energy in the surface of the collector [W]
$Q_{Collected}$	solar energy collected by the collector [W]
$Q_{Electric}$	electric energy supplied by electric heater [W]
Q_{Heater}	thermal energy transferred to working fluid [W]
Q_{In}	thermal energy supplied to the system [W]
Q_{Out}	thermal energy utilized by the system [W]
Q_{Loss}	thermal energy dissipated to the environment [W]
$Q_{Thermal\text{-}Side}$	thermal energy available in the heating coil [W]
$Q_{Desiccant\text{-}Side}$	thermal energy transferred to the air in the heating coil [W]
Q_{Load}	total cooling load of the desiccant cooling system [W]
Q_{Latent}	latent energy load of the desiccant cooling system [W]
$Q_{Sensible}$	sensible energy load of the desiccant cooling system [W]
SER	sensible energy ratio [-]
T	temperature [^{0}C]
V	voltage [Volt]

Greek Symbols

$\eta_{Collector}$	flat plate collector efficiency
$\varepsilon_{Electric}$	electric heater efficiency
ε_{Coil}	heating coil efficiency
ε_{HEX}	heat exchanger efficiency
$\varepsilon_{Evaporative}$	evaporative cooler efficiency

Subscripts

DB	dry bulb
WB	wet bulb

MIN minimum

1. INTRODUCTION

The combined solar thermal and electric desiccant cooling system is designed, fabricated, assembled, and installed in the Laboratory of Building Environmental Engineering (LBEE) of Tohoku University [1]. The major operation of the total system can be done during night time and day time. Steady state evaluation and testing of the system are done prior to doing the dynamic operation of the total system to determine the system behavior and performance and evaluate its limitations [2].

In this part (Part 2), the components of the total system are each evaluated to determine their effects on the performance of the whole system. The dynamic operation of the flat plate solar energy collector, the auxiliary electric heater, the temperature stratification in the thermal storage tank, the behavior of the heating coil, the performance of desiccant wheel dehumidification, the sensible heat exchangers and the evaporative cooler are presented. Based on the evaluation of each of the components, the performance of the whole system can easily be understood and construed.

2. SYSTEM COMPONENTS EVALUATION

2.1 Thermal Energy System

2.1.1 Flat Plate Collector

The available solar energy radiation striking the surface of the inclined flat plate collector is expressed as

$$Q_{Solar} = AI \tag{1}$$

The amount of collected solar energy that is transferred to the water flowing inside the tubes of the collector is expressed by Equation (2)

$$Q_{Collected} = m_{Collector} C_{P(Water)} (T_{Out,Collector} - T_{In,Collector}) \tag{2}$$

The effectiveness of the collection of available solar energy is an instantaneous efficiency shown by Equation (3)

$$\eta_{Collector} = \frac{Q_{Collected}}{Q_{Solar}} \tag{3}$$

The above equation shows the amount of solar energy collected during the period of operation of the solar collector.

2.1.2 Auxiliary Heater

The electric energy supplied by the electric heater is presented by Equation (4)

$$Q_{Electric} = IV \tag{4}$$

The amount of transferred electric energy to the water flowing in the electric heater tubes is presented by Equation (5)

$$Q_{Heater} = m_{Heater} C_{P(Water)} (T_{Out,Heater} - T_{In,Heater}) \tag{5}$$

The performance of the auxiliary heater is the ratio of Equation (5) to Equation (4) presented as

$$\varepsilon_{Electric} = \frac{Q_{Heater}}{Q_{Electric}} \tag{6}$$

2.1.3 Thermal Storage

The amount of thermal energy stored in the thermal storage tank is expressed as Equation (7)

$$Q_{In} = Q_{Out} + Q_{Loss} \tag{7}$$

2.1.4 Heating Coil

The available thermal energy from the hot water flowing in the heating coil is expressed by Equation (8) as

$$Q_{Thermal-Side} = m_{Coil,Water} C_{P(Water)} (T_{In,Water} - T_{Out,Water}) \tag{8}$$

The available thermal energy from the hot water flowing in the heating coil is transferred to the flowing air and expressed as Equation (9)

$$Q_{Desiccant-Side} = m_{Coil,Air} C_{P(Air)} (T_{Out,Air} - T_{In,Air}) \tag{9}$$

The effectiveness of the thermal energy transferred from the hot water flowing in the heating coil to the flowing air is expressed by Equation (10)

$$\varepsilon_{Coil} = \frac{Q_{Desiccant-Side}}{Q_{Therma-Side}} \quad (10)$$

2.2 Desiccant Cooling System

2.2.1 Desiccant Wheel

The evaluation of the desiccant wheel is based on the Latent Energy Ratio (LER) and of the Sensible Energy Ratio (SER). The Latent Energy Ratio is expressed by Equation (11)

$$LER = \frac{m_{Outdoor-Air} h_{Vav} (AH_{Outdoor-Air} - AH_{Processed-Air})}{m_{Coil,Air} C_{P(Air)} (T_{Out,Air} - T_{In,Air})} \quad (11)$$

The numerator of the equation is the total latent energy removed from the outdoor air passing the desiccant wheel while the denominator is the amount of regeneration energy needed for the removal of moisture adsorbed in the desiccant wheel expressed by Equation (9).

The Sensible Energy Ratio (TER) is expressed by Equation (12) as

$$SER = \frac{m_{Outdoor-Air} C_{P(Air)} (T_{Processed-Air} - T_{Outdoor-Air})}{m_{Coil,Air} C_{P(Air)} (T_{Out,Air} - T_{In,Air})} \quad (12)$$

The numerator of the equation is the increased air sensible energy content due to the removal of air latent energy content, heat carry-over from the regeneration side and of the heat of adsorption.

The denominator of the Equation (12) is the thermal energy supplied to the regeneration air of Equation (9). This thermal energy is needed for the removal of moisture adsorbed in the desiccant wheel.

2.2.2 Crossed-Flow Heat Exchangers

The performance of the sensible heat exchangers is based on the effectiveness of sensible energy transferred from higher sensible energy content air to the lower sensible energy content air as presented by Equation (13)

$$\varepsilon_{HEX} = \frac{(m_{Air} C_{P(Air)})\ (T_{Exit} - T_{Low})}{(m_{Air} C_{P(Air)})_{MIN} (T_{High} - T_{Low})} \quad (13)$$

2.2.3 Evaporative Cooler

The performance of the evaporative cooler is based on the saturation efficiency expressed by Equation (14)

$$\varepsilon_{Evaporative} = \frac{T_{DB(In)} - T_{DB(Out)}}{T_{DB(In)} - T_{WB}} \quad (14)$$

2.3 Total System

The performance of the system is based on the coefficient of performance of the desiccant cooling system (COP) presented in Equation (15)

$$COP = \frac{Q_{Load}}{Q_{Desiccan-Side}} \quad (15)$$

From Equation (15) the Q_{Load} is expressed as

$$Q_{Load} = Q_{Latent} + Q_{Sensible} \quad (16)$$

Equation (16) is the sum of the air sensible energy content and latent energy content expressed by Equations (17) and (18)

$$Q_{Latent} = m_{Air,Supply} h_{Vap} (AH_{Air,Outdoor} - AH_{Air,Supply}) \quad (17)$$

$$Q_{Sensible} = m_{Air,Supply} C_{P(Air)} (T_{Air,Outdoor} - T_{Air,Supply}) \quad (18)$$

The Q_{Load} can be expressed based on the enthalpy of moist air as

$$Q_{Load} = m_{Air,Supply} (h_{Air,Outdoor,moist} - h_{Air,Supply,moist}) \quad (19)$$

In terms of enthalpy, Equation (9) is expressed as

$$Q_{Desiccant-Side} = m_{Coil,Air} (h_{Out,Air} - h_{In,Air}) \quad (20)$$

3. SYSTEM COMPONENTS PERFORMANCE

3.1 Thermal Energy System

3.1.1 Flat Plate Collector

The performance of the flat plate solar collector for one day operation is presented in Figures 1 and 2. The energy striking the collector surface and the energy absorbed by the collector is presented in Figure 1. The available solar energy is calculated based on Equation (1) and the collected solar energy is based on Equation (2).

To evaluate its collector performance, Equation (3) is used and graphically shown in Figure 2. Based on the presented results, the solar collector has efficiency, during noon time, of around 70 percent.

3.1.2 Auxiliary Heater

The performance of the auxiliary heater is presented. The electric energy supplied to the auxiliary heater is almost constant at 3.3kW Equation (4). The energy transferred to the working water presented by Equation (5) is shown in Figure 3. Based on the results, the efficiency of the heater is around 90 percent calculated based on Equation (6) and shown in Figure 4.

3.1.3 Thermal Storage

Figure 5 shows the stratification of temperature inside the thermal storage tank. The stratification started after the start of the auxiliary heating operation at 3:00AM and suddenly dropped when the desiccant cooling system operates at 8:00AM. Stratification started again when the solar energy collection becomes high due to the advancing day time. The stratification of thermal energy vanished during the later part of the day when solar radiation is getting low.

3.1.4 Heating Coil

The thermal energy available from the thermal energy system represented by Equation 8 and the transferred thermal energy to the desiccant cooling system Equation (9) is shown in Figure 6. At the start of the operation, the energy transferred is high and going towards steady condition. The Effectiveness of thermal energy transferred is presented in Figure 7 showing over 90 percent efficiency during the operation.

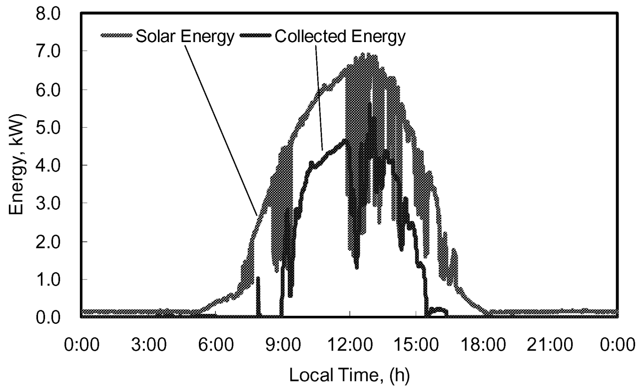

Figure 1: Energy Flow in the Solar Collector

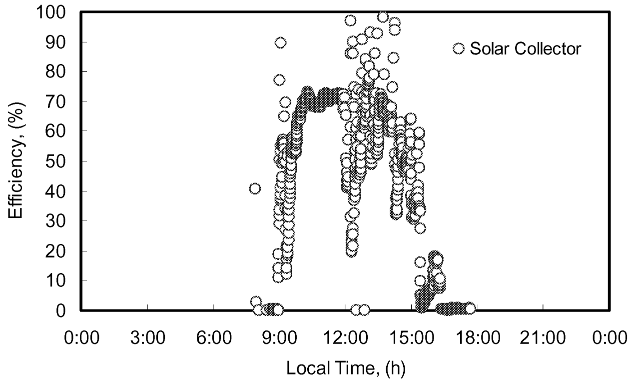

Figure 2: Instantaneous Efficiency in Solar Collection

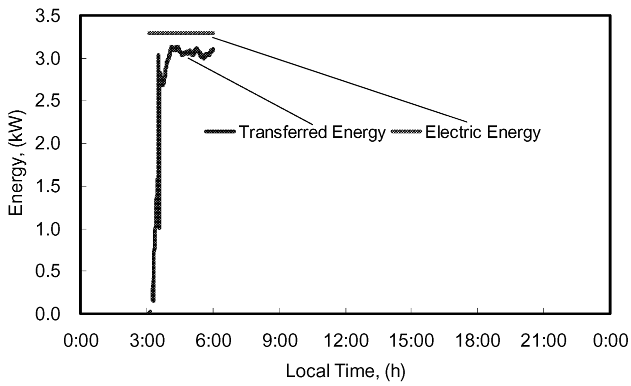

Figure 3: Energy Flow in the Auxiliary heater

3.2 Desiccant Cooling System

3.2.1 Desiccant Wheel

Figure 8 shows the latent energy ratio (LER) of the system Equation (11). Based on the results, the LER stabilizes when the system operation stabilizes. At the start of the system, the ratio is very high due to the adsorption of moisture in the desiccant wheel even when the regeneration temperature is not high enough.

The sensible energy ratio (SER), Equation (12), is shown in Figure 9. The result shows that at the start of the operation, the ratio is high and goes to stable condition until the end of the operation. The explanation is the same since moisture sorption in the desiccant wheel makes the air temperature high.

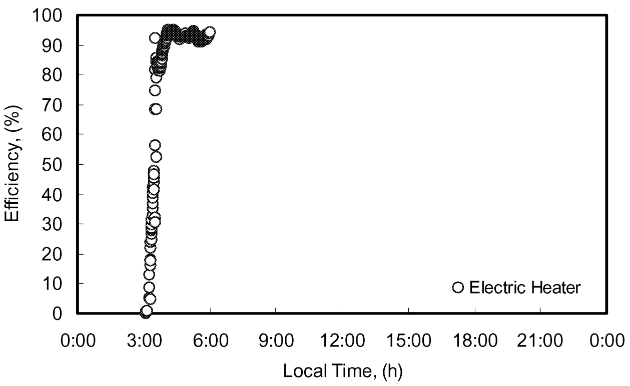

Figure 4: Instantaneous Efficiency in Auxiliary Heater

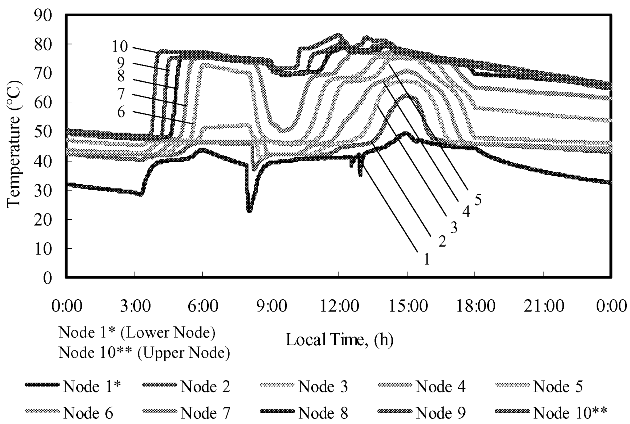

Figure 5: Stratification in Thermal Storage Tank

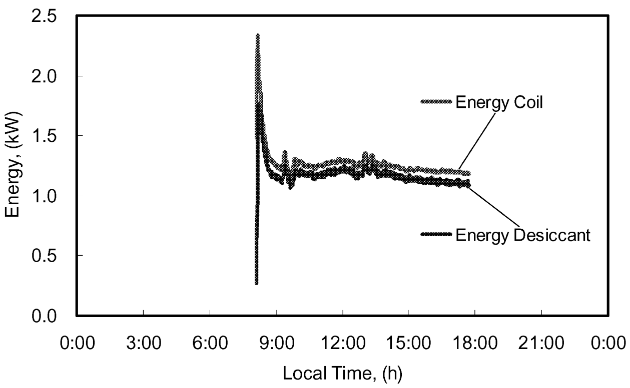

Figure 6: Energy Flow in the Heating Coil

3.2.2 Crossed-Flow Heat Exchangers

The performances of the two crossed-flow sinusoidal sensible heat exchangers were determined using the Equation (13). For the bigger heat exchanger, its over-all performance is presented in Figure 10 in which it has efficiency, during the steady operation, of around 70 percent.

For the small crossed-flow heat exchanger, the results are presented in Figure 11. Based on the results, it has an efficiency of around 60 percent during the steady operation of the system.

The pattern of the performance of both the bigger and the smaller heat exchangers is the same as shown in the figures.

3.2.3 Evaporative Cooler

The saturation efficiency of the direct evaporative cooler calculated using the Equation (14) is shown in Figure 12. The results show that the saturation efficiency during the operation is steady at around 90 percent.

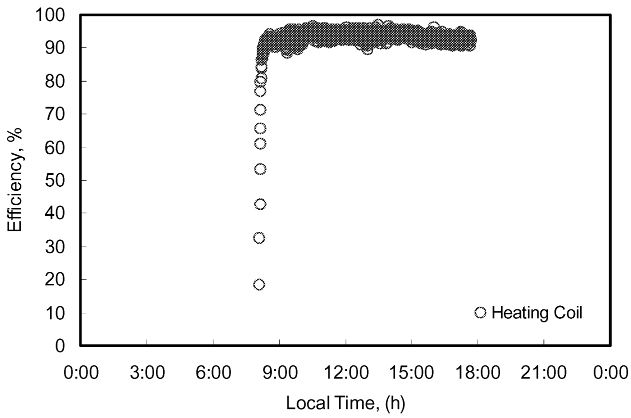

Figure 7: Instantaneous Efficiency in Heating Coil

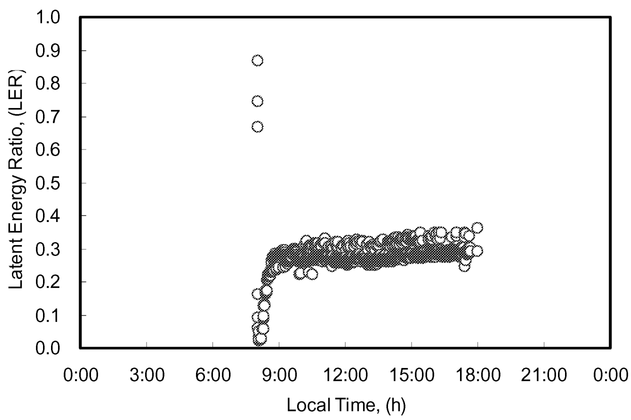

Figure 8: Latent Energy Ratio of the System

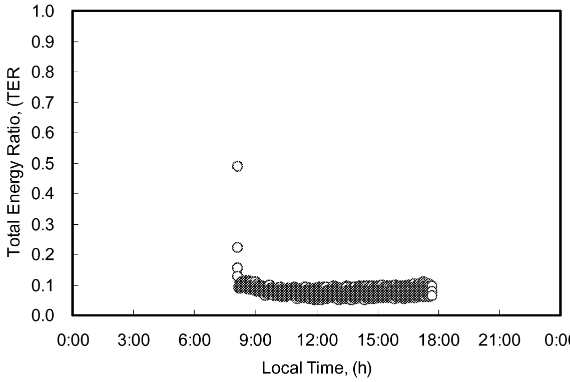

Figure 9: Total Energy Ratio of the System

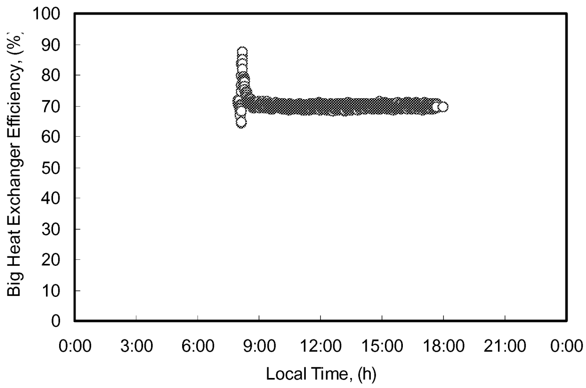

Figure 10: Efficiency of Big Heat Exchanger

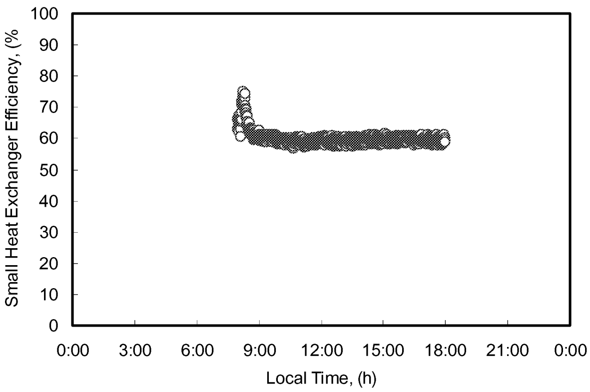

Figure 11: Efficiency of Small Heat Exchanger

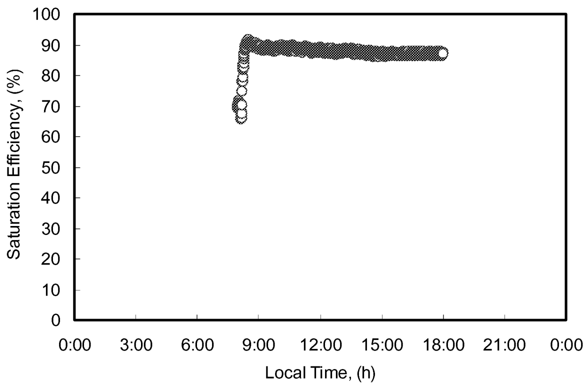

Figure 12: Efficiency of Direct Evaporative Cooler

3.3. Total System

Figure 13 shows the desiccant cooling system processes at 12:00 noon time of March 4, 2008. From the graph, the supply air (SA), Point 6, temperature and humidity are lower than that of return air (RA), Point 7. Using Equation (15), the COP of the desiccant cooling system is 0.37.

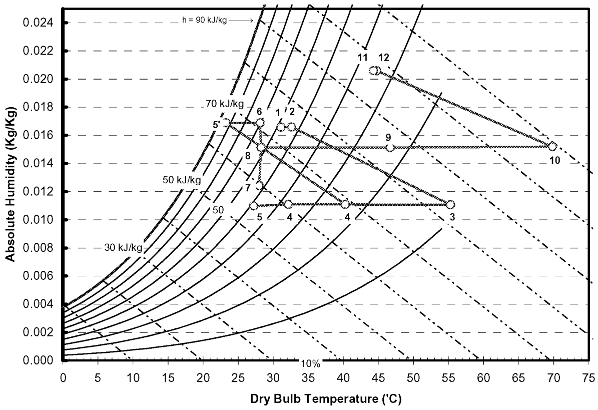

Figure 13: Desiccant Cooling System processes

5. CONCLUSIONS

The evaluation of the total combined solar thermal and electric desiccant cooling system is undertaken. The performance of its components is presented. Based on the presentation, the system is functioning to its expectations.

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