Solar Thermal and Electric Desiccant Cooling System, Part 1: System Development and Investigation

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ABSTRACT

Environmental degradation, depleting conventional energy resources, and exploding world population are indeed serious issues. Development of clean energy resources together with clean technologies for human comfort is a wonderful human creativity. This paper presents a developed system of combined solar thermal and electric desiccant cooling system. The total performance of the whole system as presented shows the thermal energy supplied to the system, the thermal energy transferred to the desiccant cooling system, and the performance of the desiccant cooling system. Based on the results the system consumed 105.80MJ of thermal energy for one day operation. The coefficient of performance of the desiccant cooling system (COP) is 0.25.

Nomenclature

A	area [m^2]
COP	coefficient of performance [-]
C_P	specific heat [kJ/kg-K]
E_{Aux}	auxiliary energy consumed by the system [W]
E_{Fans}	energy consumed by fans [W]
E_{Pumps}	energy consumed by pumps [W]
h	enthalpy of moist air [kJ/kg]
I	solar radiation [W/m^2]
	electric current [Ampere]
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_{Coil}	thermal energy available in the heating coil [W]
$Q_{Desiccant}$	thermal energy transferred to the air in the heating coil [W]
Q_{Load}	total cooling load of the desiccant cooling system [W]
T	temperature [^{0}C]
t	time [sec]
V	voltage [Volt]

Greek Symbols

ε_{Solar}	flat plate collector efficiency
ε_{Heater}	electric heater efficiency
ε_{Coil}	heating coil efficiency

1. INTRODUCTION

Climatic change due to artificial global warming is happening. Depleting conventional energy resources is happening due to increasing demand. Moreover, increasing world population, rapid urbanization and industrialization make human demand for comfortable conditions inevitable. These complex problems require serious consideration and decisive actions, worldwide, in this century for global sustainability.

This paper presents a study concerning the utilization of clean energy resources and development of clean technology. The study is based on the combined solar thermal and electric desiccant cooling system. The aim of the study is for the production of clean indoor environmental condition without any bad effects on the outside environment. The study utilizes the solar energy as a main clean energy source. The auxiliary electric heating is utilized during night time as a cheap source of thermal energy. Desiccant based cooling and dehumidification system is used as a clean technology. The desiccant cycle presented in this paper is a newly developed cycle. This paper (Part 1) presents the total system energy calculation and system performance. The second paper (Part 2) shows the components operational performance and calculation.

2. DESCRIPTION

2.1 Total System

The combined solar thermal and electric desiccant cooling system was designed, fabricated, assembled, and installed in the Laboratory of Building Engineering of Tohoku University [1]. The schematic diagram of the system is presented in Figure 1. In the figure, the total facilities consist of thermal energy system, desiccant cooling system and the controlled chambers. The major components of the thermal energy system are the solar thermal collector (flat plate collector), the auxiliary electric heater and the thermal storage tank. The components of the desiccant cooling system are the rotating desiccant wheel, sensible heat exchangers, and evaporative cooler. The controlled chambers are used for the artificial simulations of outdoor and indoor air conditions intended for different climatic conditions and indoor air conditions.

The total system can be operated in different operational procedures, the main purpose of which is to optimize the system operation under different weather conditions, human need and the time of operation.

Different operational procedures are summarized as follows [1]:

1.) Solar Energy Collection and Thermal Energy Storage
2.) Auxiliary Electric Heating and Thermal Energy Storage
3.) Solar Energy Collection and Desiccant Cooling Operation
4.) Thermal Energy Storage and Desiccant Cooling System Operation
5.) Auxiliary Electric Heating and Desiccant Cooling Operation
6.) Hot Water Production
7.) Thermal Energy System Water Removal Operation

Table 1 shows the technical description of the

Table 1: System Technical Description

Flat Plate Collector		**Desiccant Wheel**	
Total Area	10 m^2	*Diameter*	400 mm
Intercept Efficiency	0.844	*Thickness*	200 mm
Efficiency Slope	13.6 kJ/hr-m^2-K	**Big Heat Exchanger**	
Testing Flow Rate	120 kg/hr-m^2	*Height*	400 mm
Inclination Angle	35°	*Length*	300 mm
Thermal Storage Tank		*width*	300 mm
Tank Capacity	322 liters	**Small Heat Exchanger**	
Height	1.7 m	*Height*	400 mm
		Length	150 mm
Auxiliary Heater		*width*	150 mm
Heating Capacity	3 kW	**Chamber A**	
Water Pumps		*Temperature*	-10°C to 40°C
Flow Rate	90 kg/hr	*Humidity*	Any Value
Air Fans		**Chamber B**	
Flow Rate	200 m^3/hr	*Temperature*	10°C to 40°C
		Humidity	Any Value

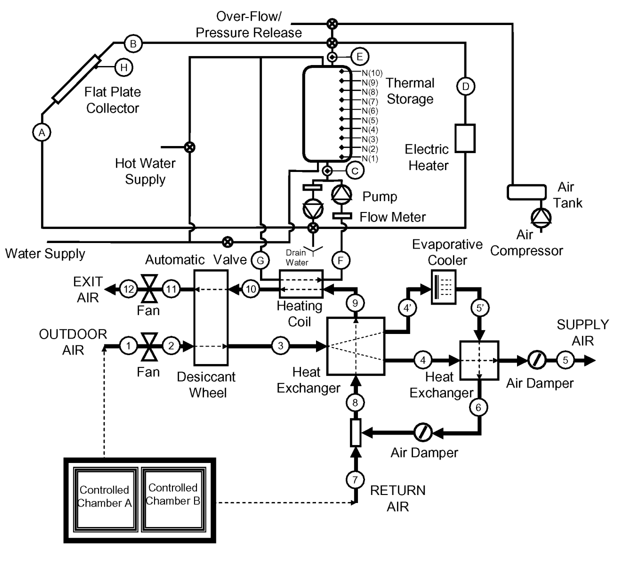

Figure 1: Total system schematic diagram.

experimental facilities. From the table, the specification of the thermal energy system is shown showing the description given by the equipment manufacturers. The desiccant cooling system system's capacity and the controlled chambers operational temperature limits are also shown.

To evaluate the system, steady-state operation and testing were done prior to its operation under real conditions. The results of the steady state operation and testing were presented previously.

2.2 Day Time

The system can be operated during day time and night time as presented by Enteria et al., 2008 [1]. For the day time operation, the solar energy collected is utilized for the operation of the desiccant cooling system which requires wheel reactivation (regeneration) temperature. The day time operation is shown schematically in Figure 2. This procedure is the operational procedure 3 of Section 2.1.

In the day time operation, during the early part of the day, the stored thermal energy accumulated in the night time operation of auxiliary electric heater (presented in the next section, Section 2.3), is used as the thermal energy source while the solar energy is not yet strong enough to support the thermal energy requirement of the desiccant cooling system.

During the day time operation, the thermal energy system and desiccant cooling system are set in the operational mode. When the solar energy is high and causes the flat plate surface temperature (Point H) in the Figure 1 to reach above the set-point value, the pump operates to circulate the water to the collector. During this operation, the solar energy collected is transferred to the working fluid (water) going to the heating coil for heat exchange with the air.

The utilized hot water will be moved back to the collector inlet, Point A, through the pump and flow meter. The circulation of water to the collector depends on the amount of solar radiation and the set-value of flat plate collector temperature, while the circulation of water to the heating coil depends on the set-value of Point F. During the day time operation, the two pumps operate and the flowing fluid is monitored by the two flow meters.

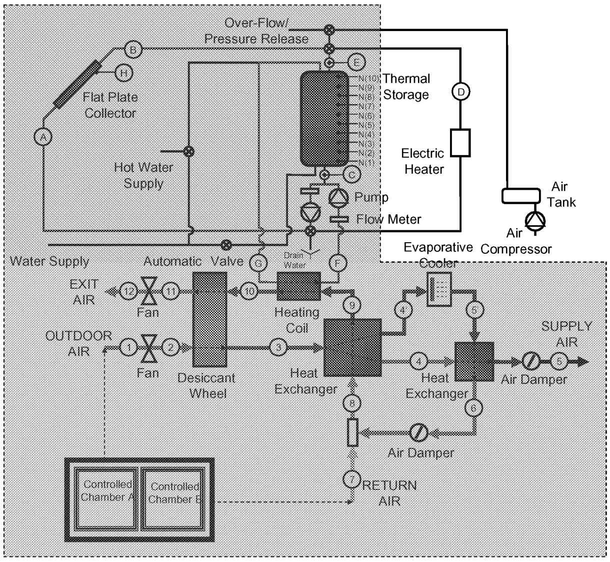

Figure 2: Day time operation of the system.

In this experimental evaluation, the operation of the desiccant cooling system is set at time of 8:00 in the morning to 18:00 in the late afternoon. In this operation, the air flow rates of the desiccant cooling system are at 200m^3/hr and 100m^3/hr. The desiccant wheel is set at its optimum speed of 15 RPH (Revolution per Hour), the evaporative cooler is set at saturation efficiency of 95 percent, the heating coil Point F is set at value of 50^{0}C and the solar collector at 80^{0}C.

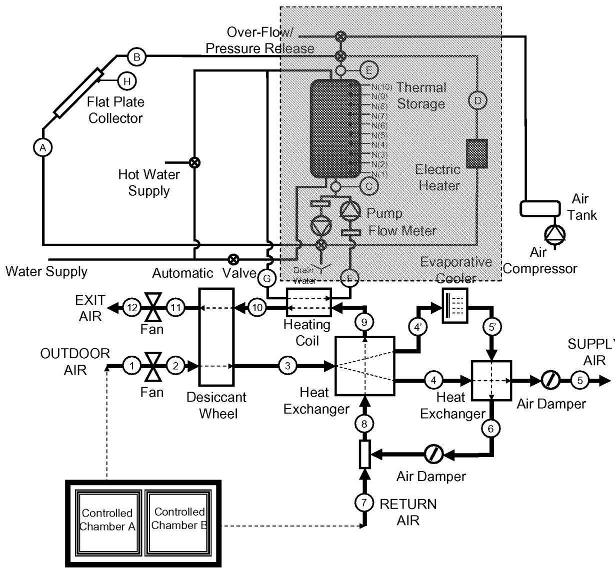

Figure 3: Night time operation of the system.

2.3 Night Time

The night time operation of the system is almost entirely the operation of the auxiliary thermal electric heater for thermal energy storage in the thermal tank. The schematic diagram is presented in Figure 3. The operational procedure is shown in Section 2.1 as procedure number 2.

The off-peak electricity being cheaper than that of the peak load period is a cheaper electric energy source for conversion to thermal energy and is an economical alternative for the operation of the thermally activated system. In this study, the auxiliary thermal electric heater is operated from 3:00 to 6:00in the early morning hours. The three-hour operation of the electric heater is for the initial operation of the desiccant cooling system.

In Figure 3, the thermal energy collected is transferred to the working fluid through the operation of the pump and the working fluid (water) flow to the top of the thermal storage tank. The water is looped to the bottom of the tank using the water pump. The flow of water is measured using the flow meter sensor. The complete storage of thermal energy is possible when the stratification of water temperature vanished. This stored energy will be ready for the initial operation of the desiccant cooling system while the solar radiation is not yet high enough during the early part of the day.

3. EVALUATION

3.1 Total System

The performance evaluation is based on the total system energy flow analyses presented in Figure 4. From the chart, the available energy supply came from the solar energy and the electric energy. The energy utilized by the system is the amount of energy collected by the flat plate collector and by the auxiliary heater. The thermal energy consumed by the desiccant cooling system is the effective energy transferred by the heating coil to the desiccant cooling system regeneration air. The cooling load is the amount of air energy removed from the outdoor air.

3.2 Thermal Energy System

The thermal energy system has two sources of thermal energy: the solar energy and the electric energy.

For the solar energy, the available solar energy is expressed by Equation 1 showing the amount of solar radiation striking the surface of the flat plate collector.

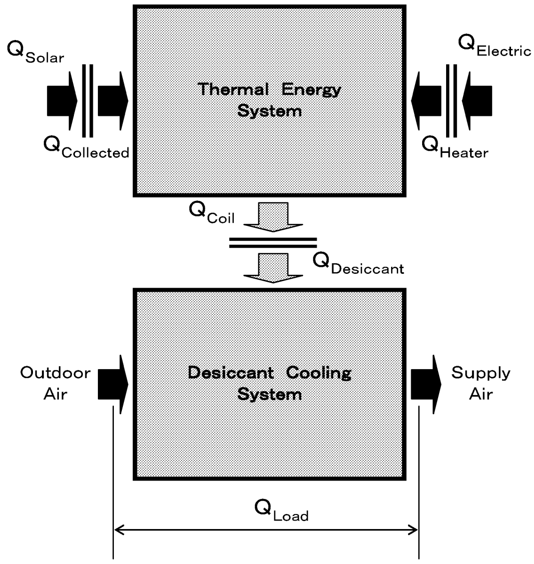

Figure 4: System Energy Flow.

$$Q_{Solar} = AI \quad (1)$$

The amount of utilized solar energy is presented by Equation 2 showing the solar energy transferred to the water flowing to the collector.

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

The efficiency in the utilization of available solar energy is shown in Equation 3.

$$\varepsilon_{Solar} = \frac{\int_{(start)}^{(end)} Q_{Collected} dt}{\int_{(start)}^{(end)} Q_{Solar} dt} \quad (3)$$

The available electric energy supplied to the electric heater is presented in Equation 4 as,

$$Q_{Electric} = IV \quad (4)$$

The amount of utilized energy from the

electric heater is presented in Equation 5

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

The effectiveness of transferring the electric energy to thermal energy of the auxiliary heater is shown in Equation 6

$$\varepsilon_{Heater} = \frac{\int_{(Start)}^{(End)} Q_{Heater} dt}{\int_{(Start)}^{(End)} Q_{Electric} dt} \quad (6)$$

3.3 Desiccant Cooling System

The performance of the desiccant cooling system is evaluated based on the total thermal energy transferred to the heating coil and the cooling load of the air flowing to the desiccant cooling system components.

The available thermal energy in the heating coil is presented as (Equation 7)

$$Q_{Coil} = m_{Coil,Water} C_{P(Water)} (T_{In,Water} - T_{Out,Water}) \quad (7)$$

The thermal energy transferred to the air in the desiccant cooling system is presented as (Equation 8).

$$Q_{Desiccant} = m_{Coil,Air} C_{p(Air)} (T_{Out,Air} - T_{In,Air}) \quad (8)$$

The ratio of Equations 8 and 9 for period of operation is the effectiveness of the thermal energy transferred to the desiccant cooling system regeneration air expressed as (Equation 9).

$$\varepsilon_{Coil} = \frac{\int_{(Start)}^{(End)} Q_{Desiccant} dt}{\int_{(Start)}^{(End)} Q_{Coil} dt} \quad (9)$$

The processing of outdoor air is presented as the cooling load

$$Q_{Load} = m_{SA} (h_{Outoor-Air} - h_{Supply-Air}) \quad (10)$$

The performance of the desiccant cooling system is presented in Equation 11. The equation is the ratio of the total cooling load of the system to the total energy supplied to the

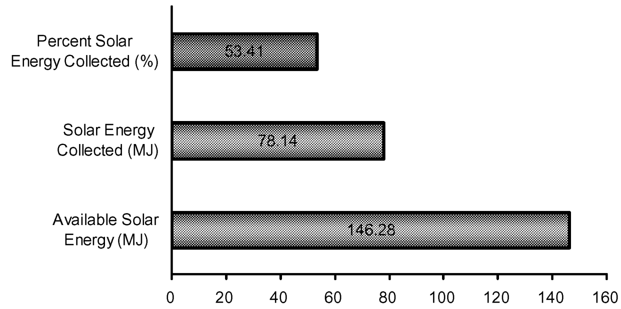

Figure 5: Solar Energy Collected.

$$COP = \frac{\int_{(Start)}^{(End)} Q_{Load} dt}{\int_{(Start)}^{(End)} [Q_{Desiccant} + E_{Fans} + E_{Pumps} + E_{Aux}] dt} \quad (11)$$

system expressed as

4. PERFORMANCE

4.1 Thermal Energy System

Based on the gathered data and evaluated on the above indexes (Section 3.2), the available solar energy (Equation 1), the solar energy collected (Equation 2), and the effectives of the solar energy collection (Equation 3) are presented in Figure 5.

In the above figure, the effectiveness of solar energy collection for one day operation is above 50 percent.

The energy available from electric heater is expressed by Equation 4, the electric energy converted to thermal energy is shown by Equation 5, and the effectiveness of conversion is expressed by Equation 6. The three equations using the gathered data are shown in Figure 6. From the data shown in Figure 6, the conversion of electric energy to thermal energy in electric heater is above 75 percent. It shows that the electric heater efficiency is high.

Figure 7 shows the total system energy supply, the total system available energy is the sum of solar energy collected and the energy from the electric heater (Equations 1 and 4). The total energy utilized by the system is the sum of the total energy transferred to the system (Equations 2 and 5).

In Figure 7, the total energy utilized by the system is approaching 60 percent in total which is the ratio of total energy collected to the total available energy. This value is due to the lower collection efficiency of solar collector which is only around 53 percent as presented in Figure 5. Even though, the collected electric energy is above 75 percent as presented in Figure 6. In addition, there is the contribution of thermal losses of the system.

The available thermal energy in the heating coil (Equation 7) and the thermal energy transferred to the regeneration air (Equation 8) and the effectiveness of transfer (Equation 9) is presented in Figure 8. From the evaluation, the efficiency of the heating coil is above 90 percent. This efficiency is high.

4.2 Desiccant Cooling System

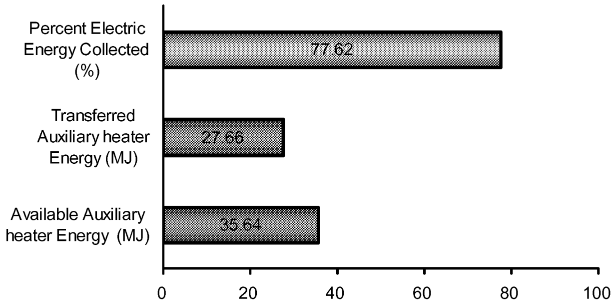

Figure 6: Electric Energy Supplied.

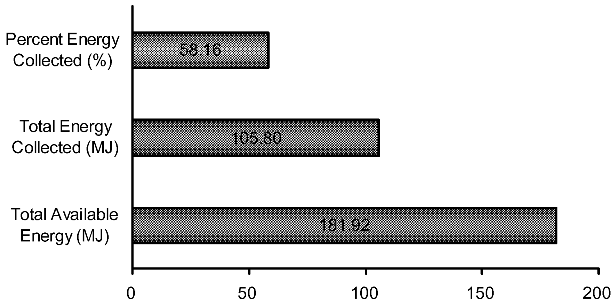

Figure 7: Total System Energy Supply.

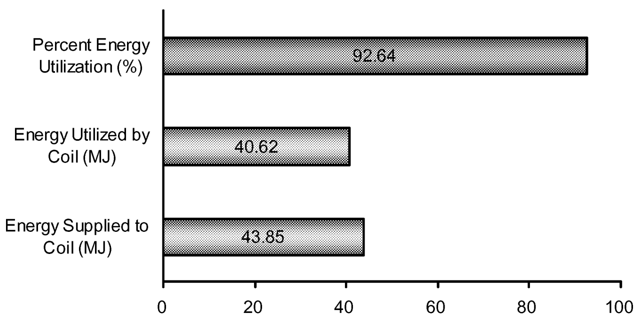

Figure 8: Total System Energy Consumption.

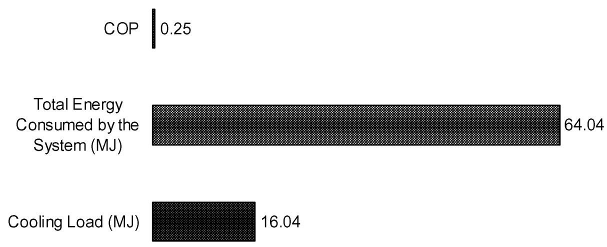

Figure 9: Desiccant Cooling Performance.

The performance of the desiccant cooling system is presented in Figure 9. The calculation of the energy utilized by the heating coil is expressed by Equation 8, the cooling load as Equation 10 and the COP is expressed by Equation 11. In the figure, the COP (Coefficient of Performance) of the desiccant cooling system is 0.25.

The energy consumed by fans is totaling 18MJ. The energy consumed by the water pumps totaled to 0.4MJ. The system accessories including the control system and other devices are assumed to consume 5MJ of electrical power.

5. CONCLUSIONS

The real operation of the combined solar thermal and electric desiccant cooling system was conducted. The total system performance was evaluated. Based on the results, the thermal energy system collected around 60 percent of available energy and the desiccant cooling system has a performance (COP) of 0.25.

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