Air Conditioning and Hot Water Supply System using Solar Chemical Heat Pump

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Abstract

From the viewpoints of energy and environmental problems, effective energy recycle utilization systems using Chemical Heat Pump (CHP) have been proposed. CHP can store heat by use of the chemical reaction (Chemical Heat Storage), and reform/release it as Cold/Hot heat. Solar Chemical Heat Pump (SCHP) is one of the example chemical heat pump systems developed. Solar heat collected by a solar collector is chemically stored by CHP. Cold/Hot heat generated in the heat releasing step of CHP can be used for air conditioning and hot water supply etc. In this study, we performed solar heat storage / heat pump experiments using SCHP in order to use 400*K* level solar heat effectively. As a result, it was shown that our original Solar Chemical Heat Pump (SCHP) unit using $CaSO_4/CaSO_4 \cdot 1/2H_2O$ reaction system could store solar heat at around 400*K* and release both cold heat of 101*kJ/kg-CaSO*$_4$ at around 278*K* and hot heat of 81.5*kJ/kg-CaSO*$_4$ at around 343*K* without adding extra energy.

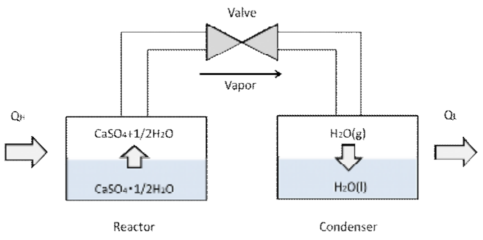
***Keywords**:* Solar chemical heat pump, Chemical heat storage, Solar energy, Calcium sulfate

1. Introduction

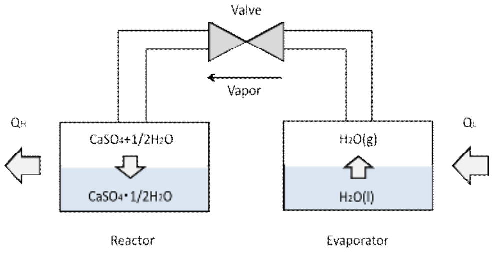
Using renewable energy is an effective way to solve energy and environmental problems. However, the amount and quality of renewable energy often change with time and season.

From those viewpoints, the technique to use renewable energy effectively is very important. The heat storage is one of the techniques to use renewable energy effectively. Heat storage has three types, Sensible Heat Storage, Latent Heat Storage and Chemical Heat Storage. Sensible Heat Storage uses the sensible heat due to the temperature change of the material. Latent Heat Storage uses the phase change energy such as dissolution - solidification, evaporation - condensation, sublimation etc. Sensible Heat Storage and Latent Heat Storage are already commercially used. Those distinct features are easily use but high heat loss in a long term storage. Chemical Heat Storage uses the chemical reaction energy. The distinctive features are high heat storage density and little heat loss in the long term storage. However, the appropriate design of the reactant and the equipment are necessary for effective utilization.

Chemical Heat Pump (CHP) operates based on the Chemical Heat Storage. As an example, the operating principle of $CaSO_4/CaSO_4 \cdot 1/2H_2O$ reaction system CHP is shown in Fig.1.



heat storing step



heat releasing step

Fig.1 Operating principle of $CaSO_4/CaSO_4 1/2H_2O$ CHP

The CHP is a closed system of coupled reactor and evaporator/condenser connected each other. Before using CHP, the reactor and the evaporator/condenser are evacuated by vacuum pump. The pressure of inside of the evaporator becomes the saturated water vapor pressure depending on water temperature.

In the heat storing step, the heat $Q_{H,S}$ is stored in the form of thermochemical energy by the decomposition of $CaSO_4 \cdot 1/2H_2O$ in the reactor.

$$CaSO_4 \cdot 1/2H_2O + 16.8kJ(Q_{H,S}) \rightarrow CaSO_4 + 1/2H_2O \quad (1)$$

The released water vapor flows into the condenser due to a pressure difference between the reactor and the condenser. The water vapor condenses there releasing low temperature heat $Q_{L,S}$.

$$H_2O\ (g) \rightarrow H_2O\ (l) + 41.7kJ(Q_{L,S}) \quad (2)$$

In the heat releasing step, the water vapor moves to the reactor by opening the valve due to the pressure difference between the evaporator and the reactor. The hydration reaction of $CaSO_4$ occurs and releases high temperature heat $Q_{H,R}$ in the reactor.

$$CaSO_4 + 1/2H_2O \rightarrow CaSO_4 \cdot 1/2H_2O + 16.8kJ(Q_{H,R}) \quad (3)$$

The evaporator is cooled down by evaporation latent heat of water $Q_{L,R}$.

$$H_2O\ (l) + 41.7kJ(Q_{L,R}) \rightarrow H_2O\ (g) \quad (4)$$

Many types of CHP systems have been already proposed by the authors [1-4].

CHP can be a possible key technique for the effective energy recycling systems as it has two important functions in both heat storage and heat pump technologies. The CHP can store thermal energy and release the energy at various temperature levels as cold/hot heat on demand. The CHP has following advantages: long term thermal storage, high energy storage density, no use of other energy sources, and large output temperature range.

2. Solar chemical heat pump (SCHP)

Solar chemical heat pump (SCHP) is one of the example chemical heat pump systems driven by renewable energy as shown in Fig.2. Solar heat collected by a solar collector is chemically stored by CHP. The cold/hot heat generated in the heat releasing step of CHP can be used for air conditioning and hot water supply system.

Studies on the solar chemical heat storage have been proposed by several researchers. Various materials such as decomposition of ammoniated salt, $MgO/Mg(OH)_2$, $CaO/Ca(OH)_2$, $2Co_3O_4/6Co_3O_4+O_2$ were used for solar chemical heat storage [5,6,8]. However, those reactions have several problems. The

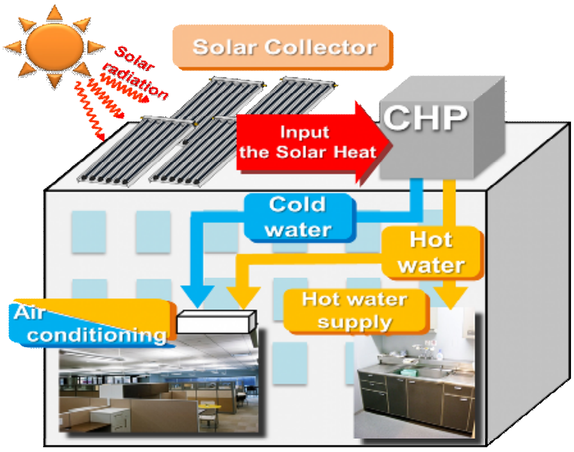


Fig.2 Example of SCHP system

decomposition of ammoniated salt system comparably has some corrosion etc. The $MgO/Mg(OH)_2$ and $CaO/Ca(OH)_2$, reactions require high temperature heat to decompose, so those need special apparatuses for high-temperature solar heat collection.

In order to solve the above problems of chemical reaction systems, we selected $CaSO_4/CaSO_4{\cdot}1/2H_2O$ reaction system [1,4,7] for SCHP driven by low temperature heat such as 400*K* level solar heat. The ideal heat storing density is around 124*kJ/kg* and the ideal heat releasing densities are 153*kJ/kg-CaSO₄* of cold heat and 124*kJ/kg-CaSO₄* of hot heat.

The reaction material $CaSO_4$ is prepared from gypsum ($CaSO_4{\cdot}2H_2O$). In general, the natural gypsum is well known as an inexpensive and safe material.

The $CaSO_4/CaSO_4{\cdot}1/2H_2O$ SCHP system is expressed by the equations in Fig.3. The SCHP can store solar heat at around 400*K*, which compound parabolic concentrator (CPC) solar heat collector can generate. The SCHP releases cold heat at around 278*K* and hot heat at around 353*K*.

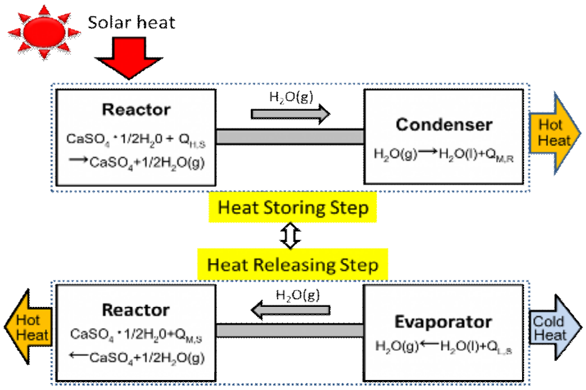


Fig.3 Operating principle of SCHP

The SCHP has two CHPs: one for heat storing and the other for heat releasing step. These CHPs swap these steps with each other and produce cold/hot heat continuously.

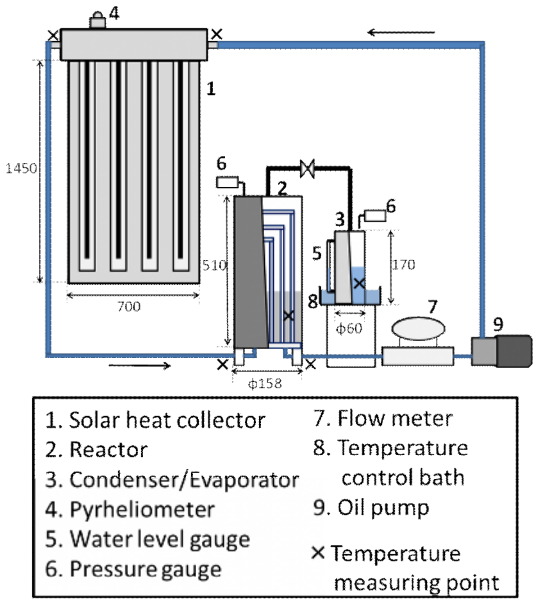
The system of our SCHP will be proposed to Solar Decathlon Europe 2014 from Chiba university team [9].

In this study, we preliminarily performed solar heat storage / heat pump experiments using our original SCHP unit in order to use 400*K* level solar heat effectively for cold/hot heat production.

3. Experiment

3.1 Experimental unit

An example of the experimental unit of SCHP is shown in Fig.4. This unit is used for heat storage step of CHP. The units were composed of CPC solar heat collector (1m^2), Reactor, Condenser/Evaporator, Flow meter, Pyrheliometer, Vacuum gauge, Water level gauge, Temperature control bath and Oil pump. We use silicone oil as a heat exchange media. The reactor is column form and 158*mm* outside diameter, 153*mm* inside diameter, 510*mm* in height. A copper pipe for heat exchange is contained inside of the reactor. The amount of $CaSO_4{\cdot}1/2H_2O$ in the reactor is 1*kg* and the particle size of the $CaSO_4{\cdot}1/2H_2O$ is 710-1000*μm.* The reactor and the condenser are evacuated to the designated pressures by closing the joint valves before starting the experiment.



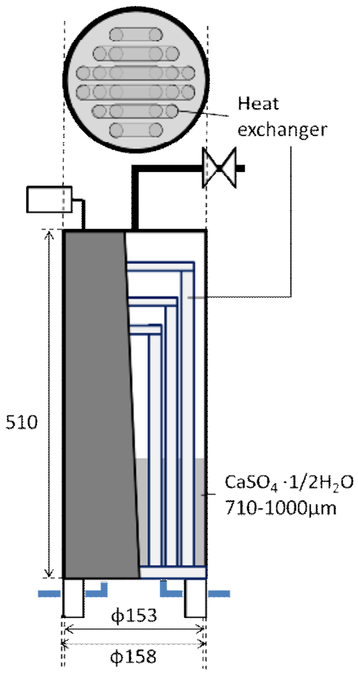


Fig.4 Experimental unit for SCHP system and the detail of reactor

3.2 Experimental procedure

In the heat storing step, the heat exchange media is sent to solar heat collector by the pump and catches the solar heat. The sensible heat of the heat exchange media is transferred to $CaSO_4 \cdot 1/2H_2O$ by the heat exchanger. The flow rate of the heat exchange media is 2*l/min*. When the pressure of reactor exceeds that of condenser, the dehydration reaction of $CaSO_4 \cdot 1/2H_2O$ occurs by opening the valve. The released water vapor moves to the condenser due to a pressure difference between the reactor and the condenser. Water vapor condenses there and release low temperature heat. Solar heat storage is completed by closing the valve. The dehydration conversion is calculated from the changes of water level in the condenser. The dehydration conversion is calculated by the changes of water level in the condenser. The amount of heat storage is calculated by the dehydration conversion of $CaSO_4 \cdot 1/2H_2O$.

After the heat storing step, the heat exchangers of the reactor and the evaporator/condenser are changed for the following heat-releasing step to set the temperature at appropriate one.

In the heat releasing step, the water vapor moves to the reactor by opening the valve due to the pressure difference between the evaporator and the reactor. The hydration reaction of $CaSO_4$ occurs and releases high temperature heat in the reactor. The evaporator is cooled down by releasing its latent heat. The amount of released heat is calculated by the hydration conversion of $CaSO_4$. The temperature changes and the pressure changes in the reactor and the evaporator/condenser are measured by thermocouples and pressure gauges.

4. Results and discussion

4.1 Heat storing step

Fig.5 shows the amount change of insolation and temperature changes of the heat exchange media at inlet and outlet of reactor at Chiba, Japan, June, 2013. The day was sunny; the average amount of solar radiation was almost 1kW/m^2 in 11:00-13:30. The temperature of the heat exchange media is upgraded to 408*K* by the solar heat.

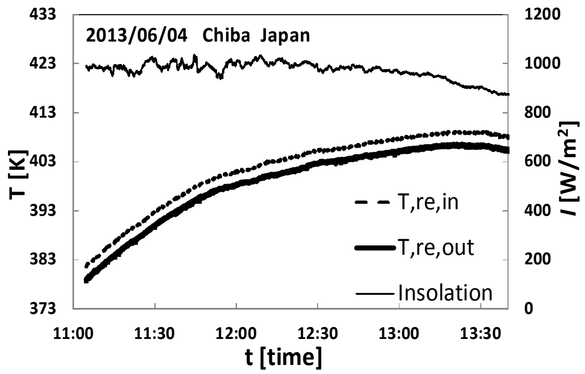


Fig.5 Temperature changes of heat exchange media and amount change of insolation

The efficiency of the solar heat collection E_{col} was calculated from the flow rate of heat exchange media F_{hem}, specific heat of heat exchange media c_{hem}, temperature deference of heat exchange media between inlet and outlet of solar heat collector, the amount of solar Insolation *I* and heat collection area *A* through following formula Eq. (5).

$$E_{col} = F_{hem}\ c_{hem}\ (T_{col,out}-T_{col,in})\ /\ I\ A \qquad (5)$$

The efficiency of the solar heat collection is about 40% in the daytime average. In comparison with other solar heat collection systems, the collected heat temperature is high. It probably causes the decrease of the heat collection efficiency. Improvement of the solar heat collector and the improved insulation of the system are required.

Fig.6 shows an example of the result of SCHP heat storing step experiment. When the temperature of $CaSO_4 \cdot 1/2H_2O$ is over 393*K*, temperature of H_2O in the condenser is 293*K*, by opening the valve (time = 0), the dehydration occurs and the temperature of $CaSO_4 \cdot 1/2H_2O$ is going down. The temperature profile shows the decomposition reaction of $CaSO_4 \cdot 1/2H_2O$ and the solar chemical heat storage by SCHP. However, the dehydration conversion was only about 20% in 30*min* in this case. The improvement of the solar heat collector, the heat exchanger and the thermal insulation of the system are required to increase the heat collection efficiency and the efficiency of SCHP

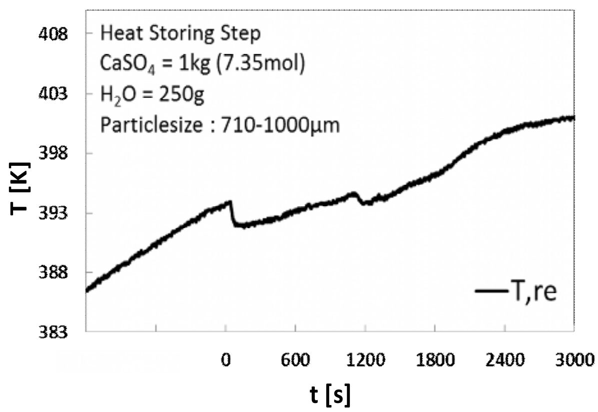


Fig.6 Temperature changes of reactor in heat storing step

4.2 Heat releasing step

Fig.7 shows an example of the result of SCHP heat releasing step experiment. The reactor and the evaporator are set at 294*K* initially for heat releasing reaction. In the reactor, hydration of $CaSO_4$ occurs and generates hot heat up to 343*K*. In the evaporator, the water vapor evaporates and generates cold heat down to 278*K*.

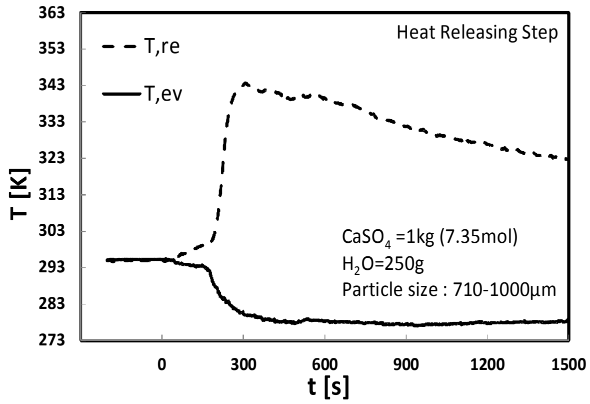


Fig.7 Temperature changes of reactor and evaporator in heat releasing step

Fig.8 shows the hydration conversion changes of $CaSO_4$. The hydration conversion reaches about 66% in 30*min*. The amount of the released hot heat is 81.5*kJ/kg-*$CaSO_4$ and the released cold heat releasing is 101*kJ/kg-*$CaSO_4$ in 30*min*.

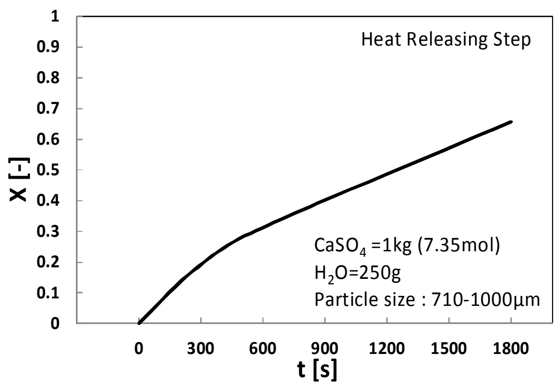


Fig.8 Hydration conversion changes of $CaSO_4$ in heat releasing step

5. Conclusions

The results of experiments show that Solar Chemical Heat Pump (SCHP) unit using $CaSO_4/CaSO_4 \cdot 1/2H_2O$ reaction system can store solar heat chemically at around 400*K* and generate/release both cold heat of 101*kJ/kg-*$CaSO_4$ at around 278*K* and hot heat of 81.5*gkJ/kg-*$CaSO_4$ at around 343*K*, those can be used for air conditioning and hot water supply etc. without adding extra energy.

The improvement of the solar heat collector, the heat exchanger and the thermal insulation of the system are required to increase the heat collection efficiency and the efficiency of SCHP.

6. References

6.1 Article in Journals

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6.2 Web-Based Articles

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Nomenclature

Q	heat amount [kJ]
F	flow rate [l/min]
c	specific heat [kJ/kg•K]
T	temperature [K]
I	Insolation [W/m^2]
A	area [m^2]
E	efficiency [-]
t	time
X	conversion [-]

Subscripts

re	reactor
co	condenser
ev	evaporator
col	solar heat collector
R	heat releasing step
S	heat storing step
in	inlet
out	outlet
hem	heat exchange media
H	high
L	low