

Application of Phase Change Material in Solar Assisted Ground-source Heat Pump System

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Abstract: Aimed at the heat supply's fluctuation of solar assisted ground-source heat pump (SAGHP) system, an energy storage tank is installed. In order to adjust the large discrepancy between the supply and the demand of heat and meanwhile to enhance the stability of the system, phase change material (PCM) that has the characteristic of storing and emitting heat is used. Studying operation mode and conversion conditions of the SAGHP system combined with a latent heat energy storage tank (LHEST), the system operates at an optimised running condition. The system's overall average heating coefficient of performance (COP) is enhanced and almost gets to 6.5.

Keywords: heat storage, phase change material (PCM), solar assisted ground-source heat pump (SAGHP), Latent heat energy storage tank (LHEST)

NOMENCLATURE

A_{SC}	Collection area [m^2]
C_{pl}	Specific heat of PCM in liquid phase [$kJ/kg \cdot K$]
C_{ps}	Specific heat of PCM in solid phase [$kJ/kg \cdot K$]
I_{pj}	Daily mean solar radiance [$kJ/m^2 \cdot day$]
I_{ypj}	Monthly mean solar radiance [$kJ/m^2 \cdot day$]
M_{PCM}	Mass of PCM [kg]
N	Number of days in a month
Q_{hs}	Storage heat in LHEST [$kJ/m^2 \cdot day$]
Q_{sc}	Collection heat in solar collector [$kJ/m^2 \cdot day$]
q_{PCM}	Storage heat of per kilo PCM [kJ/kg]
r_f	Latent heat of fusion [kJ/kg]
T_1	Initial temperature of PCM heat storage [$^{\circ}C$]
T_2	Final temperature of PCM heat storage [$^{\circ}C$]
T_m	Melting temperature of PCM [$^{\circ}C$]
η_{sc}	Mean collection efficiency of solar collector [%]

1. INTRODUCTION

How to use natural, non-polluting "green energy" — solar energy already becomes people's concern topic. Energy storage is much more important since the energy source — solar energy is intermittent and variable. There are several technological difficulties in how to develop and utilize in large scale of solar energy, especially collection, storage and transfer are main problems in solar energy utilization.

Energy storage can adjust the time or rate mismatched between energy supply and demand that have the strong timeliness. Meanwhile, it leads to make the system more effective by reducing the wastage of energy and improving performance of the system. Heat storage can divided into sensible heat energy storage, latent heat energy storage and chemical reaction heat energy storage. Among these three methods, latent heat energy storage is the most attractive and popular because it has the approximately constant temperature level in charge and discharge process and is easily controlled [1]. Mohammed M. Farid et al. [2] studied that there are two most common groups of PCMs — organic and inorganic. The conclusion is the melting point of a PCM is the most important criterion for selecting a PCM for passive solar applications. M.N.A. Hawlader [3] investigated the preparation and characterization of encapsulated paraffin-wax. The results of this study are micro encapsulation efficiency depends on the process parameter and coacervated and spray-dried microcapsules are suitable for a solar energy storage material.

Though research work has made a great progress in solar assisted heat pump (SAHP) system with an energy storage tank (EST) in other countries [4,5] and has some extent referential value to the research work in this field in our country, the achievement isn't completely suitable for our country due to geography position and different condition among countries. Research in SAHP system with EST is at experimental initial stage in domestic. How to choose PCMs and how to control operation conversion conditions all need to study thoroughly.

Table 1: The property of PCM ($\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$).

Specific heat (kJ/kg·°C)		Thermal conductivity (w/m·°C)			Melting temperature (°C)	Latent heat of fusion (KJ/Kg)	Density (Kg/m ³)	Rate of volume (%)
Solid	Liquid	Solid	Liquid	Transition				
1.46	2.13	1.088	0.539	0.7	29.9	187.49	1710	13.3

2. CHOICE OF PHASE CHANGE MATERIALS (PCMs)

2.1 Choice of PCMs

Different PCMs may be chosen in different system since various PCMs have different physical and chemical properties and the costs of PCMs are various too. As the working medium of energy storage system, PCM will influence the operation effect of the system directly. PCMs should be considered of several factors when choosing. (1) Suitable fusion temperature; (2) large quantity latent heat of fusion; (3) suitable conductivity (high thermal conductivity); (4) constant fusion temperature and good fusion reversibility; (5) non-poisonous, non-harmful to people; (6) compatible with the vessel- no corrosion to the vessel; (7) non-combustible and high security; (8) fast rate of crystallization and crystal growth rate; (9) small volumetric expansion; (10) high density; (11) easily buying and low price.

PCM that is satisfied the following condition fully is difficult to find. When PCM is chosen in practice, it should be satisfied with the first three factors, especially the first one. PCM's fusion temperature decides its optimised working temperature range and this range should be identical to the working temperature range of the system. This is the first important factor when choosing PCMs. For example, for a solar energy storage system, its working temperature range is from 30°C to 100°C, on the basis of the temperature, calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$) which fusion point is 29°C to 30°C and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ which fusion point is 30°C to 32.4 °C can be chosen as PCMs.

2.2 PCM of the experimental system

PCM selected in this system is $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$. The reason is explained as following:

(1) Phase change temperature of $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$ is identical to the operation temperature range of the system. Phase change latent heat and thermal conductivity are high. The property of PCM ($\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$) is listed in Table one which accords to the requirement of SAHP system.

(2) $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$ is non-poisonous and non-polluting, and its solution is neutral.

(3) The price of $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$ is low, about 900 yuan.

2.3 Quantity of PCM

The quantity of $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$ is according to the heat which energy storage tank stores in advance. The time the experiment tests that is from March to April. According to the solar radiance condition of Harbin, China (lat. 45°41'; long. 126°37'), the average solar

radiant intensity per month I_{m}' is 492764 kJ/m² mon, so the average solar radiant intensity per day I_{d}' is :

$$I_{\text{d}}' = \frac{I_{\text{m}}'}{N} = \frac{492764}{30} = 16425.5 \text{ (kJ/m}^2 \cdot \text{day)} \quad (1)$$

Collection area and presumed efficiency of the solar collector is 11.9m² and 55%, respectively. Collection heat of solar energy Q_{sc} per day is:

$$\begin{aligned} Q_{\text{sc}} &= I_{\text{d}}' \times A_{\text{sc}} \times \eta_{\text{sc}} \\ &= 16425.5 \times 11.9 \times 0.55 \\ &= 107504.9 \quad (\text{kJ/day}) \end{aligned} \quad (2)$$

Considering the storage of collector and heat loss of pipe, etc, presumed storage efficiency is 65%, Heat storage of EST Q_{hs} is:

$$\begin{aligned} Q_{\text{hs}} &= Q_{\text{sc}} \times 0.65 \\ &= 107504.9 \times 0.65 \\ &= 69878.2 \quad (\text{kJ/day}) \end{aligned} \quad (3)$$

When PCM stores heat, its temperature transition range is 28 °C to 50 °C, heat storage of PCM per kilogram q_{PCM} is:

$$\begin{aligned} q_{\text{PCM}} &= c_{\text{pl}} \times (T_2 - T_m) + c_{\text{ps}} \times (T_m - T_1) + r_f \\ &= 2.13 \times (50 - 29.9) + 1.46 \times (29.9 - 28) + 187.49 \\ &= 233.0 \quad (\text{kJ/kg}) \end{aligned} \quad (4)$$

According to Q_{hs} and q_{PCM} , the total quantity of PCM M_{PCM} is:

$$\begin{aligned} M_{\text{PCM}} &= Q_{\text{hs}} / q_{\text{PCM}} \\ &= 69878.2 / 233.0 \\ &= 300.0 \quad (\text{kg}) \end{aligned} \quad (5)$$

2.4 Selection of PCM' vessel

PCM ($\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$) was encapsulated in 120 polyethylene plastic kegs. The keg is cubic, its size is 140mm×120mm×70mm, its thickness is about 1mm. Each keg contains about 2kg PCM. Its characteristics is: 1) not being corroded by PCM; 2) steady construction; 3) thin vessel wall; 4) high toughness of material, the variety of PCM' volume has little influence to container's sealing; 5) easily sealing, low price.

3. EXPERIMENTAL STUDY OF SAHP SYSTEM WITH LHST

3.1 Operation mode of SAHP system with LHST

The SAHP system with LHST was built on the basis of the SAGHP system existed at energy conservational laboratory in Harbin Institute of

Technology (HIT). The system consists of solar collector, LHEST, heat pump (solar energy or soil is as low grade heat source), vertical U shaped long pipe soil exchanger, fan coil, circulation pump, flow meter, galvanometer, valves, temperature sensor (copper-constantan-thermocouple), temperature measure meter and etc. Fig.1 shows a schematic diagram of SAHP with LHEST. It combines SAHP system, ground-source heat pump (GSHP) system and latent heat energy storage (LHES) system organically and it remedies each heat source's lack. It can operate yearly that enhances utilization of unit and efficiency of operation. GSHP system is an auxiliary heating mode or main heating mode when SAHP system cannot supply heat thoroughly. LHES system regulates the thermal balance of heat of collector, heat supply of heat pump and heating load of building; enhances collector's collection efficiency; increases heating hours of SAHP system and improves the heating coefficient of performance of the system finally. Operation modes include: i) storage heat of LHEST; ii) heating by solar energy; iii) heating by LHEST; iv) storage heat of LHEST.

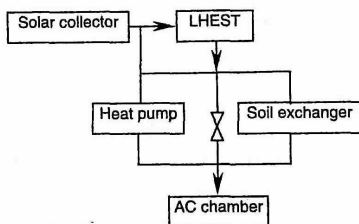


Fig1: Schematic diagram of SAHP system with a latent heat storage tank

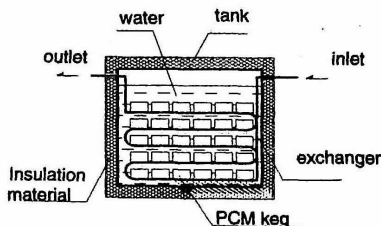


Fig2: Schematic diagram of PCM tank

3.2 Working principle of EST

Fig.2 shows schematic diagram of EST. PCMs are encapsulated in plastic kegs that are on the heat exchanger. Water in the LHEST exchanges heat with plastic kegs, in the meanwhile, plastic kegs exchanges heat with heat-transfer medium in serpentine coil and transfers heat to the system. The LHEST recovered the defaults of enduring pressure of storage tank and easily stratification of PCMs. The LHEST connects the system through heat exchanger; it need not endure the system's pressure. PCMs are encapsulated in the kegs and increase the heat-exchange area.

3.3 Operation modes and condition of experimental system of SAHP system with LHEST

The conversion of operation modes is on the basis of outlet temperature of collector, outlet temperature of storage tank, outlet temperature of fan coil and indoor temperature.

The first mode occurs when the outlet temperature of solar collector is higher 30°C or is 3°C higher than the temperature of LHEST and indoor temperature is higher than 19°C (Storage modes).

The second mode occurs when the outlet temperature of LHEST is equal to or higher than the inlet temperature of LHEST. It stops storage heat. Solar energy supplies heat directly when indoor temperature is lower 21°C and the temperature of solar collector is 5°C higher than indoor temperature (Heating mode).

The third mode occurs when it is at night, cloudy or rainy times and meanwhile it is lower 19°C inside. LHEST supplies heat or starts GSHP supplying heat.

3.4 Analysis of experimental data

In order to reflect the operation condition of apparatus and operation performance of the system, two fine days (3,24,2004 and 3,25,2004) were chosen to analysis. The maximum and minimum temperature of the two days were 4°C, -2°C and 10°C, -2°C, separately. Wind direction is west and wind power is less than three degree. It was all day fine on 24th; it is windy between twelve thirty to fourteen and it was fine other times on 25th.

Operation modes in these two days were storage mode → heating mode (solar energy supplies heat directly) → heating mode (storage tank supplies heat directly) → storage mode. Experimental results of the system operated on 24th and 25th march are listed in Table 2.

Table 2: Experimental results of system operated on 24th and 25th Mar

Date	24th	25th
Item		
Storage heat of LHEST (KJ)	76597.9	64874.2
Emission heat of LHEST (KJ)	76264.4	56550.5
Supply heat of fan coil (KJ)	54063.7	52132.0
System electricity consumption (KJ)	5482.0	5554.6
Collection efficiency of collector (%)	0.36	0.32
Storage efficiency of LHEST(%)	0.48	0.47
Emission efficiency of LHEST(%)	0.44	0.31
Total storage efficiency of LHEST(%)	0.21	0.14

Curves of survey points' temperature of tank are shown in Fig 3.

It can be concluded from Fig 3:

(1) Temperature of water in the tank and temperature of PCM varies near fusing point (28-30°C) of PCM when it is at initial period of charging. Though the temperature doesn't go up quickly at this stage, it

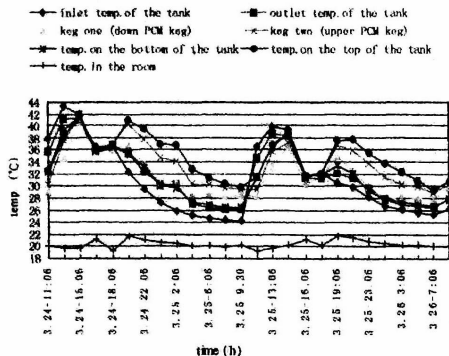


Fig3: Curves of survey point temperature of tank

has got the maximum storage heat per hour. It is 60% of total storage heat or more. When it gets to some extent, the heat that LHEST got is more than the heat PCM absorbed, the temperature of LHEST is rising. Latent heat energy storage is the main mode of storing heat of LHEST at this stage.

(2) During the later period, PCM that occurs phase change is less and less, the temperature of LHEST rises quickly; heat collected by collector descends rapidly. Sensible heat energy storage is the main mode at this stage.

(3) In the charge and discharge process, the flow of the charge process is more than that of discharge process. In the meantime, conductance of heat exchanger and storage efficiently of LHEST is high in the charge process.

(4) To the whole system, utilizing LHEST to supply heat is the most conservation method. When the system is running, utmost using storing and releasing heat to heating is the best way. In operation period, total supply heat is 1390.69HJ, it is 62% of heating load of architecture; solar energy utilized effectively is 1220.93MJ, it is of 53% of heating load of architecture. Table 3 shows the coefficients of common heat pumps. It demonstrates that the cop is 6.49, it is far more than other systems. So the conservation effect of the SAGHP system with a LHEST is obvious.

Table3: Comparison of the cop with different heat pump

Type	COP
SAGHP with LHEST	6.49
Air-source heat pump	about 3
Water-source HP	4.6
G-S HP	about 3
SAHP	Above 4

4. CONCLUSIONS

PCMs should first be selected based on their melting temperature. In the SAGHP system with LHEST, $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$ is as PCM, its melting temperature is 29°C to 30°C that satisfied the system's working temperature range. It is encapsulated by 120 little plastic kegs in the LHEST, meanwhile it increases the heat exchange area. The LHEST recovers former water tanks' defaults of enduring system's pressure and PCMs easily stratification.

In order to reflect the operation condition of apparatus and operation performance of the system, two fine days were chosen to analyse. It can be concluded from the analysis.

(1) At the initial period, storing latent heat is the main process, though the temperature of the LHEST doesn't go up quickly, it has the maximum storage heat per hour, which is 60% of total storage heat at this stage.

(2) At the later period, storing sensible heat is the main process; the temperature of the LHEST goes up quickly, PCM that occurs phase change is less and less.

(3) Compared with the discharge process, the flow, the conductance of heat exchanger and storage efficiency of LHEST in the charge process is higher.

(4) To the whole system, using LHEST to store and release heat heating is the most conservation method. The coefficient of performance is 6.49 that is far more than other systems. So the conservation effect of SAGHP system with LHEST is obvious.

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