Numerical Simulation of a Latent Heat Storage System of a Solar-Aided Ground Source Heat Pump

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Abstract: In this study, the rectangular phase change storage tank (PCST) linked to a solar-aided ground source heat pump (SAGSHP) system is investigated experimentally and theoretically. The container of the phase change material (PCM) is the controlling unit of the phase change heat transfer model. It was solved numerically by an enthalpy-based finite difference method and was validated by experimental data. $CaCl_2$•$6H_2O$ was used as the PCM in the latent heat storage system of SAGSHP system. In the tank, the PCMs are encapsulated in plastic kegs that are setting on the serpentine coil. The experiments were performed from March 12 to April 10, 2004 in the heating season of the transition period. In order to reflect the effects of the system, two days were chosen to compare the numerical results with experimental data. The inlet and outlet temperature of the water in the PCST, temperature of PCM and storage and emission heat of PCST were measured. The trends of the variation of numerical results and experimental data were in close agreement. Numerical results can reflect the operation mode of the system very well.

Key words: numerical simulation, enthalpy method, phase change material (PCM), thermal energy storage

1. INTRODUCTION

As we all know, solar energy is intermittent and fluctuant, so the SAGSHP heating system operates unstably. The problem should be solved when solar energy is used to heating .It is an effective method to arrange energy storage tank in SAGSHP heating system. When solar radiance is great and the energy that the system got is surplus, then the surplus energy is saved in the energy storage tank; when solar radiance is less and the heat for heating is not enough, then the stored energy is emitted for heating. A phase change storage tank is added in the system, in which phase change material is $CaCL_2.6H_2O$, the discrepancy between the supply and the demand is adjusted through the charge and discharge of PCST, when the heating that the system supplies is inadequate, the auxiliary heat sources are used (such as air-source heat pump, ground-source heat pump and electric heating machine etc) to assist heating. In cold weather area, such as in Harbin, China, solar energy combined with ground-source heat pump can operate efficiently and the effect of energy conservation is obvious.

Distribution of temperature, change of enthalpy, movement of solid-liquid boundary, stratification convection of material and two-phase conduction are all very difficult to study when PCM is having phase change. The control equation has been established by the application of the enthalpy method. According to the enthalpy method, the temperature and the enthalpy are two variables, density of material and property of phase change need not to be presumed, phase change boundary need not to be handled (it means movement of solid-liquid interface need not to be followed). So the enthalpy method was used to establish the model of phase change storage tank.

2. MATHEMATICAL MODEL

2.1 Structure of PCST

The structure of PCST is shown in figure 1. PCM ($CaCL_2.6H_2O$) was encapsulated in polyethylene plastic container, the size of which is 140 mm×120mm×70mm and the thickness of the wall is 1mm. Each container contains about 2kg, and the total number of which is 125. They were well distributed on the serpentine coil heat exchanger. Outside and inside diameters of serpentine coil are 32mm and 25.5mm separately. There are 9 rows and the total length of the serpentine coil is 46.25m. The material of PCST is polyethylene, which size is 1160 mm×980 mm×700 mm. Polystyrene is used as heat-insulation material that thickness is 100mm.

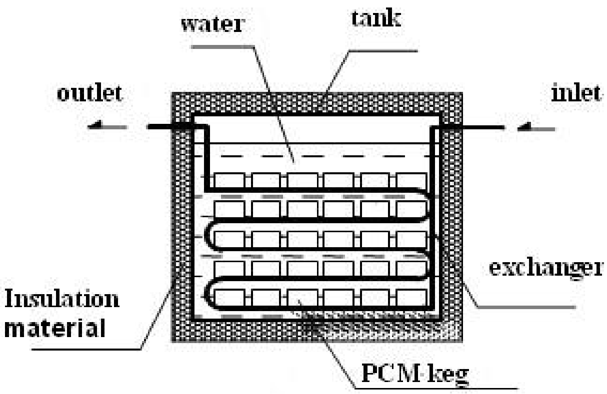

Fig 1. Schematic diagram of PCM tank

2.2 PCM

Many factors will influence the experiment and many of them are difficult to describe or no rules to follow. Some assumptions are used to simplify the model as long as the main characteristic is not influenced and the thermal properties can be reflected correctly. The following assumptions are made:

1) The PCM are treated as a body of uniform and equivalent physical and thermal properties. The PCM is homogeneous and isotropic;

2) Storage unit in the PCST is independent;

3) Temperature in the PCST is homogeneous in storage process and it is stratified in the discharge process;

4) PCM's fusion is constant, that is to say phase change process is isothermal;

5) Natural convection can be negligible since the container is small when PCM melts.

Temperature field and solid-liquid variation of PCM are central symmetric from the above assumptions. 1/8 of container is as discussing object to be divided into three-dimensional grid. It shows in Fig.2.Three of the six walls of discussing object exchange heat with surrounding as convection, they belong to the third type boundary condition; the other three walls contact with the PCMs, they can be considered as insulated.

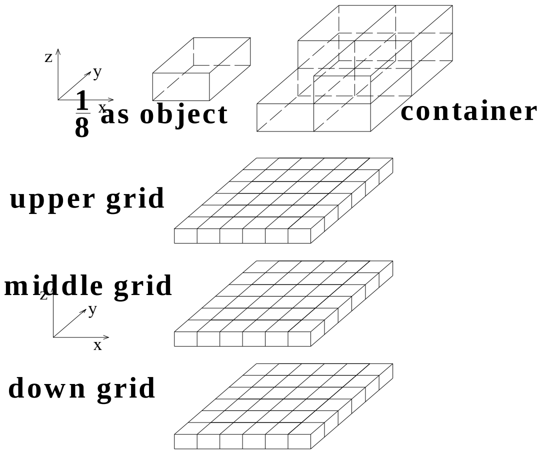

Fig 2. Schematic diagram of grid partition instorage container

2.3 Establishing of Control Equation

Control equation of phase change heat transfer can be written as following:

$$\frac{d}{dt}\int_V \rho h \bullet dV + \int_S \rho h v \bullet dA = \int_S k\nabla T \bullet dA + \int_V \dot{q} \bullet dV \qquad (1)$$

According to the above assumptions, there are no heat sources of energy inside the control volume. $\dot{q}=0$, there is no natural convection, and there is no mass transfer. So v=0 equation (1) can be simplified as following:

$$\frac{d}{dt}\int_V \rho h \bullet dV = \int_S k\nabla T \bullet dA \qquad (2)$$

Phase change process is isothermal on the basis of the assumptions. So equation is discrete directly. Temperature field gotten through this way can be well approached to experimental results in precision area. For nodes inside, phase change heat transfer control equation can be written as:

$$\frac{\partial H}{\partial t} = div(\frac{\lambda}{\rho} gradT) \quad (3)$$

The enthalpy in the above equation can be divided into sensible heat and latent heat shown as following:

$$H = h + L \cdot f_L = \int_{T_m}^{T} c \cdot dT + L \cdot f_L \quad (4)$$

For isothermal phase change, liquid coefficient can be defined as:

$$f_l(T) = \begin{cases} 1 & (T > T_m) \\ 0 & (T < T_m) \end{cases} \quad (5)$$

Change equation (3) into three-dimensional coordinate, and then there is:

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}(\frac{\lambda}{\rho} \cdot \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\frac{\lambda}{\rho} \cdot \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\frac{\lambda}{\rho} \cdot \frac{\partial T}{\partial z}) - L \cdot \frac{\partial f_l}{\partial t} \quad (6)$$

To boundary node, according to energy balance we can get

$$\frac{\partial H}{\partial t} = div(\frac{\lambda}{\rho} \cdot gradT) + \alpha \cdot A \cdot \Delta T \quad (7)$$

With the same principle, it can be also transferred into three-dimensional form.

2.4 Comparison of Simulation Results and Experimental Results

In order to reflect how simulation results approach experimental results, experimental data begins from 12th, Mar.,2004 to 10th,Apr.2004, the system had run for 30days. 1ST Apr. and 4th Apr. were cloudy and rainy days, storage time was short or there was no storage in the PCST in these two days. Ground source heat pump was as the sole heating method to heat. And two days' operation data & simulation data were chosen to draw the schematic diagram. It was from 9:30 24th Mar., 2004 to 9:30 26th Mar., 2004. Operation condition of simulation process was the same as the experimental process. The operation modes were "storage process of PCST→heating by solar energy directly→heating by PCST→storage process of PCST".

Comparison of inlet and outlet temperature between simulation data and experiment data is in fig 3 and fig 4. In storage process, simulation data is higher than experimental ones of inlet and outlet temperature of PCST; in discharge process, simulation data is a little lower than experimental ones of inlet and outlet temperature of PCST. It can be explained by following: it is assumed that temperatures of PCST and PCM are constant (28.5^{o}C). PCMs are all in solid form when it is in simulation process. PCMs are not solid thoroughly. The temperature of PCM increased rapidly, but the temperature of PCST increased slowly in storage process in experimental process. Since experimental value of PCM is higher than numerical value of PCM, temperature in PCST is high too in emission process

Fig 5 shows the comparison between experimental & numerical data of temperature of PCM. It can be seen from the figure that when the temperature of CaCL2.6H2O descended to freezing point, it did not solidified but from some point (it is 28.5oC in fig 5) since CaCL2.6H2O has cooling phenomenon when it is in heating mode in experimental process. This phenomenon of PCM is negligible in simulated process. So the experiment values of the temperature of PCM in PCST heating period are a little lower than those of the numerical one.

Comparison of storage & emission heat of PCST between experimental values and simulated values is shown in fig 6. Since PCMs are all solid form in simulation and there are a few liquid PCMs in experiment, simulated value of storage heat of PCST is bigger than that of experimental value; and simulated value of emission heat of PCST is smaller than that of experimental one.

3. RESULTS

Based on the enthalpy method, one eighth of encapsulate container is as research object, phase change heat transfer mathematical model of solar assisted heat pump heat storage system was established. Parameters of inlet & outlet temperatures of PCST, temperature of PCM and storage & emission heat of PCST were calculated. Compared the results of experiment and simulation, the results of simulation approached experiment and the trends are the same. The isothermal phase charge heat transfer model can describe phase change heat transfer process correctly and reflect the operation situation of the system objectively.

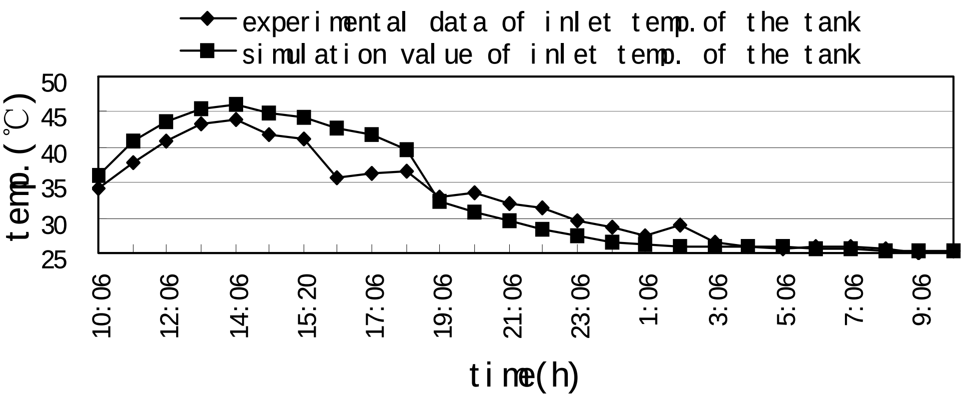

Fig 3. Comparison of inlet temperature of the tank between simulation value and experimental data

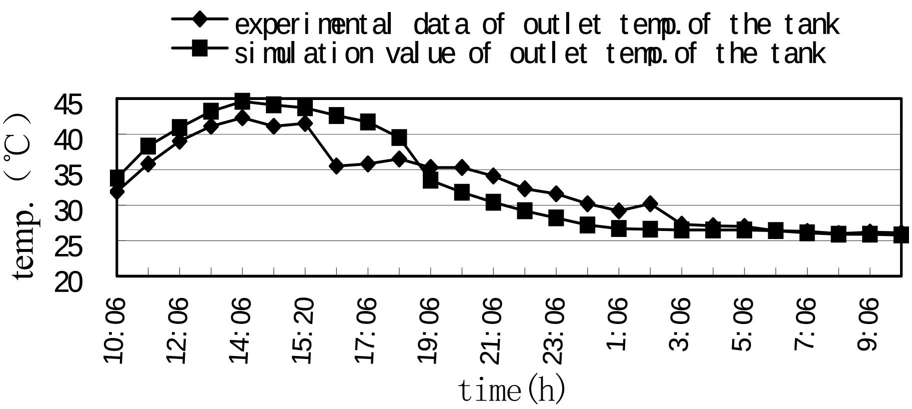

Fig 4. Comparison of outlet temperature of the tank between simulation value and experimental data

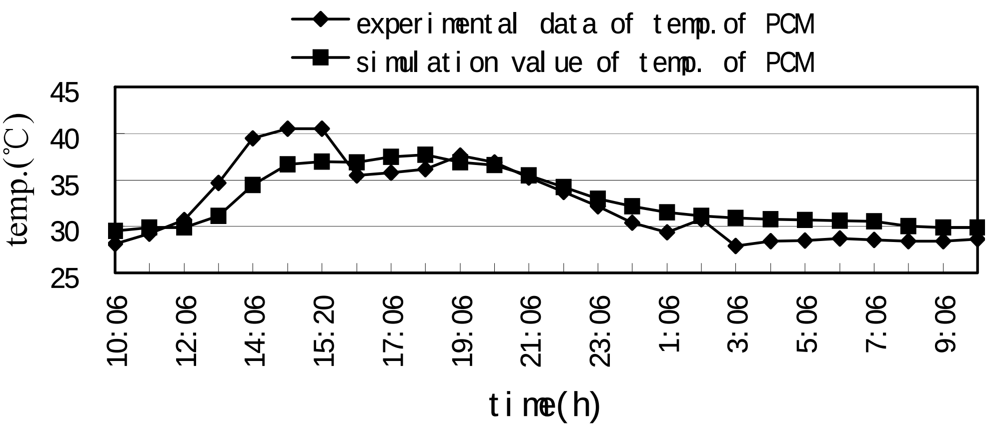

Fig 5. Comparison of temperature of PCM between experimental & numerical data

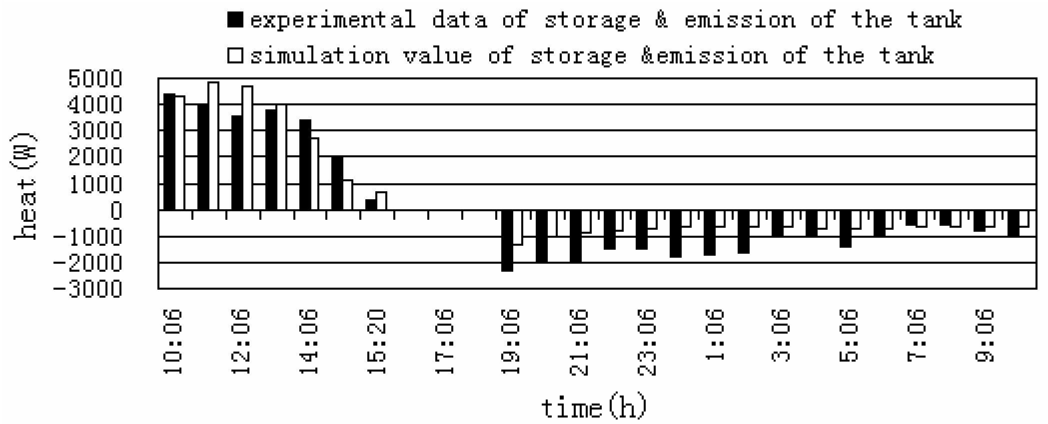

Fig 6. Comparison of storage & emission of the tank between experimental and simulated values

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