VAPOR CHAMBER ENERGY STORAGE SYSTEM WITH Al_2O_3 AND WATER MIXTURE AS MEDIUM

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Abstract

This article experimentally investigates the thermal performance of the vapor chamber energy storage system with Al_2O_3 and water mixture as thermal storage medium. The energy storage system is composed of the vapor chambers, the charge and discharge heat exchanges and an energy storage tank. Thermal energy is stored or released from heat exchangers to storage tank through vapor chambers. Vapor chamber utilizes evaporation and condensation to transfer heat, which provides an effective heat spreading area between heat exchanges and energy storage tank. The energy storage tank utilizes the aluminum oxide (Al_2O_3) which mixes with water as the energy storage material. The experimental parameter is the inlet water temperature of heat exchanges with constant mass flow rate of 0.5 kg/min. The results indicate that with 10 ^{o}C increment for the temperature difference between the inlet water and the energy storage tank, the heat in charge and discharge processes increase from 40% to 50%, respectively. This study also analyzes the mixture ratio of energy storage material. The results demonstrate that the optimal mixture ratio of aluminum oxide and water is 1.25, and the heat storage quantity of the system compared to the energy storage tank without aluminum oxide can be increased by 6%.

Keywords: vapor chamber, energy storage, heat exchanger

1、introduction

The energy storage system [1-3] whether heat storage or cold storage was used to slove the peak load problem [4]. With the storage of energy increase, the energy storage volume became larger. These results caused additional space for the energy storage devices and cost increment. To reduce the above mentioned problems effectively, there was energy storage system combined with the building materials [5-7]. The material was widely used as energy storage medium and it had the advantage of less space, high specific heat and high thermal conductivity. Therefore, the quantity of energy storage can be considered more.

Vapor chamber, brought up by Zuo and Dussinger[8], was also remarkable for its capability of diminishing the thermal concentration problem effectively. It provided an effective averaged heat spreading area between heat source and heat dissipation module [9-10]. The capillary structure of vapor chamber can overcome the energy storage system with the two-phase closed loop heat exchanger [11-13]. Therefore, the energy storage system combined with the vapor chamber and the building material can reduce the peak load problem and costs. Traditional energy storage system was designed with active control which mixed the working fluid with pump. However, this system cannot be used when the pump or electromagnetic valve fails.

In addition, the energy storage material with the hydrophilic material can absorb water and heat of chemical reaction in low temperature. Then, it releases water and heat of chemical reaction in high temperature. The materials are cheap, easily accessible, stable, high structural strength and green for earth. As the hydrophilic material is mixed with water, it becomes an energy storage material. Besides, the temperature increase of the hydrophilic material and water is not only caused by the sensible heat storage, but also the chemical energy storage. When the energy storage material is used in ice storage air conditioning system, the sensible heat storage, chemical energy storage and latent heat storage are also involved.

For the above-mentioned defects of the conventional energy storage system, this article experimentally investigates the thermal performance of the vapor chamber energy storage system, as shown in Fig. 1. The system can store energy in the energy storage tank under no additional electric power and release the energy in need. Moreover, this study also analyzes the mixture ratio of energy storage material to realize the effect of the energy storage characteristics.

Fig. 1. The vapor chamber energy storage system.

2. Experimental investigations

2.1. Charge and discharge

The experiment is to test the perfornance of vapor chamber energy storage system. This experiment can be divided into 4 cases, charge heat, discharge heat, charge cold and discharge cold. Figure 2 depicts the experimental apparatus of the vapor chamber energy storage system. The experimental parameter is the inlet water temperature of heat exchanges with constant mass flow rate of 0.5 kg/min. The vapor chamber energy storage system is composed of the vapor chambers, the charge and discharge heat exchanges and an energy storage tank. Vapor chamber utilizes evaporation and condensation to transfer heat, which provides an effective heat spreading area between heat exchanges and energy storage tank. The vapor chamber is consisted of 6 small vapor chambers which are constructed of upper and lower assemblies made of Cu1100. The exterior size of vapor chamber is 280 ×185 × 178 mm^3. The arrangement of the upper and lower assemblies are 2 × 3 each level. The structure of the heat exchange is aluminum alloy. The energy storage tank is made of acrylic plate and its exterior size is 300 × 250 × 100 mm^3. The 5 kg of pure water is used as energy storage material inside the storage tank. In this study, the T-type thermocouple is used to measure the temperature. There are 20 temperature measurement points, two thermocouples ($T_{w,i}$, $T_{w,o}$) are located in the heat exchangers inlet and outlet, and the others are placed into energy storage tank at different locations. These points are average divided into 3 levels to obtain the temperature distribution (T_1~T_{18}). Thermostatic bath connected to the vapor chambers by duct is located outside of the system. The main function of this thermostatic bath provides the steady heat or cold source during the experiment. Water pump drives the water in circulation, and its specification is 1/2 hp. The first experimental procedure is as follows:

Step 1: Turn on the thermostatic bath, set up the water temperature to supply the inlet temperature of heat exchangers.

Step 2: Control the initial water temperature in the storage tank or thermostatic bath.
Step 3: Open the water pump; adjust the water mass flow rate of 0.5 kg/min.
Step 4: Turn on the data recorder, and start the experiment for one hour.
Step 5: End of the experiment, turn off the thermostatic bath and pump.
Step 6: Repeat steps 1 to 5, adjust the other inlet water temperature of heat exchange which is different in the thermostatic bath or storage tank temperature. The different inlet water temperature of heat exchanger and initial water temperature in storage of each case are listed in Table 1.

The stored heat or released cold ($Q_{\mathrm{k,n}}$) and released heat or stored cold ($Q_{\mathrm{g,m}}$) in the storage tank are related to the mass and the difference in temperature between initial and final temperature of water in the storage tank.

$$Q_{k,n} = \sum_{i}^{t_{k,n}} M_w C_{p,w} (T_{w,i+\Delta t} - T_{w,i}) \tag{1}$$

$$Q_{g,m} = \sum_{i}^{t_{g,m}} M_w C_{p,w} (T_{w,i} - T_{w,i+\Delta t}) \tag{2}$$

where $k = h$ represents heat and $k = c$ represents cold; $n = ch$ represents charge and $n = dis$ represents discharge; $g = h$ represents heat and $g = c$ represents cold; $m = ch$ represents charge and $m = dis$ represents discharge; M_{w} is the mass of energy storage material, $C_{\mathrm{p,w}}$ is specific heat; $T_{\mathrm{w,i}}$ means initial water temperature and $\mathrm{T}_{\mathrm{w,i+\triangle t}}$ is the average temperature per time in the storage tank, where $\triangle$t is 4 seconds.

The store cold or release heat ($Q_{\mathrm{g,m}}$) in the storage tank also can be related to the mass and the difference in temperature between initial and final temperature of water in the storage tank.

The overall heat transfer coefficient of system can be expressed as:

$$M_W C_{p,w} \frac{dT}{dt} = U_{j,p} A(\overline{T}_f - T_w) \tag{3}$$

where M_{w} represents the mass of energy storage material; $C_{\mathrm{p,w}}$ is specific heat of water; dT/dt means the temperature variation in the energy storage tank per time; $U_{\mathrm{h,p}}$ is the overall coefficient, where $j = h$ represents heat and $j = c$ represents cold; $p = ch$ means charge and $p = dis$ is discharge; $\overline{T}_f$ is the average temperature of the inlet and outlet of heat exchanger; T_{w} represents the water temperature of storage tank.

Table 1. Experimental parameters under different case studies.

Case	Initial temperature of energy storage tank , °C	Inlet water temperature of heat exchanger, °C	Mass of energy storage material, kg	Mass flow rate of thermostatic bath, kg/min
A (heat storage)	20	40, 50 and 60	5	0.5
B (heat release)	30, 45, 60	20		
C (cold storage)	20, 25	5, 0 and -5		
D (cold release)	5	25,30 and 35		

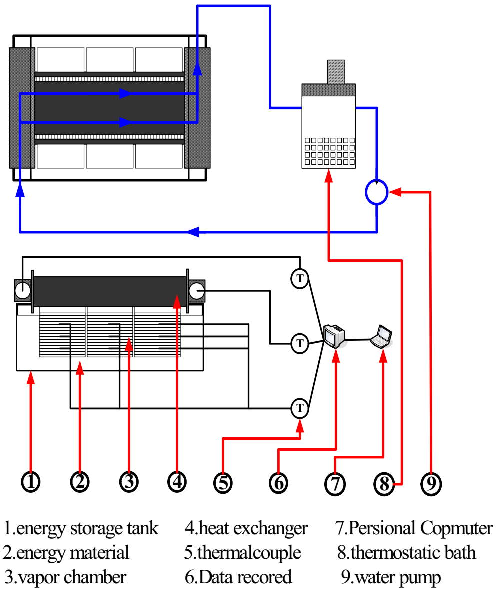

Fig. 2. The experimental apparatus of the vapor chamber energy storage system.

2.2. Al_2O_3 and water mixture as thermal storage medium

In this part, the thermal performance of Al_2O_3 with water mixture is tested. The experimental apparatus of this tested are shown in Fig. 3. The experimental parameter is the mixture ratio of Al_2O_3 and water. This experiment is consisted of copper box, insulation, heater, Al_2O_3 with water solution inside the copper box and power supply. The insulation material which coated on the copper box can reduce the heat loss. The specification of the copper box is 100 mm long, 100 mm wide and 80 mm high. There are 2 points which are located upper (T_u) and lower (T_l) positions in the Al_2O_3 and water mixture, as shown in Fig. 3. The 80 × 15 mm^2 heating area of the heater is powered by a D.C. power supply. In this study, the power is constant of 16.4 W. The second experimental procedure is as follows:

Step 1: Adjust the voltage and current of power supply to control the heating power is 16.4 W.

Step 2: The mixture ratio of water and Al_2O_3 are measured by electronic scales; the solution of water and Al_2O_3 fills into the copper box.
Step 3: Open data recorders, start the experiment for 20 minutes.
Step 4: Repeat steps 1 to 3, adjust the mixture ratio of water and Al_2O_3.

The relation of energy storage($Q_{h,ch}$), heat input of heater (Q_{in}) can be expressed as:

$$Q_{h,ch} = \sum_{i=0}^{t_{h,ch}} M_w C_{pw} (T_{i+\Delta t} - T_i) + \sum_{i=0}^{t_{h,ch}} M_{al} C_{p,al} (T_{i+\Delta t} - T_i) \qquad (4)$$

$$Q_{in} = P t_{ch} \qquad (5)$$

Because of heat loss, so the effective heat input Q_{eff} can be expressed

$$Q_{eff} = Q_{in} - Q_{loss} \qquad (6)$$

Finially, heat of chemial reation (Q_{chemi}) can utilize energy balance equation:

$$Q_{chemi} = Q_{h,ch} - Q_{eff} \qquad (7)$$

where M_{al} represents the mass of Al_2O_3; $C_{p,al}$ is the specific heat of Al_2O_3; t_{ch} means charge time.

According to the uncertainty analysis proposed by ISO standards [14], the uncertainties of temperature measurement and mass flow meter were ±0.2°C and ±0.1%, respectively.

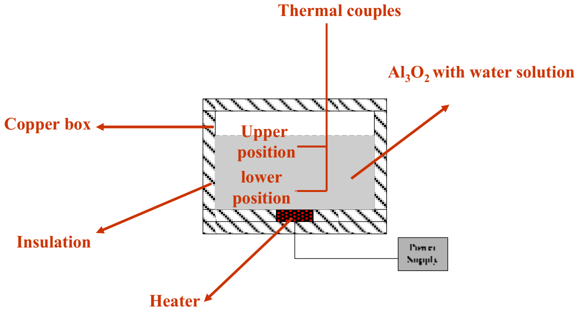

Fig. 3. The experimental apparatus of Al_2O_3 with water mixture.

3. Results and discussion

3.1. Charge and discharge

In the case A, the inlet water temperature of heat exchanger can be set as 40 °C, 50 °C and 60 °C, respectively. Figure 4 shows the temperature of energy storage tank increases from 20°C to 38 °C under the inlet water temperature of the heat exchangers is 60 °C. With the increase of time, the temperature of energy storage material also increases. It means that heat transfer rate also increases, as shown in Fig. 5. Figure 5 also indicates that with the increase of time, the temperature of energy storage material increase. It causes temperature difference between the inlet water temperature of heat exchangers and energy storage material to get smaller. The curve slope of the increase becomes slower with the change of time. Figure 6 depicts the inlet water temperature increases from 40 °C to 60 °C with constant mass flow rate, and the overall heat transfer coefficient maintains a constant. The thermal storage and temperature difference between inlet water temperature of heat exchanger and energy storage material do not influence the overall heat transfer coefficient.

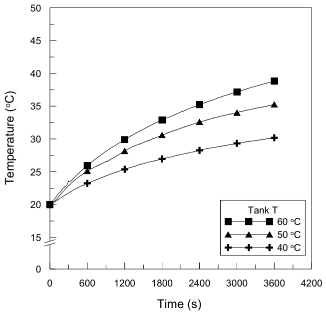

Fig.4. The temperature variation of energy storage tank with time under heat storage procedure.

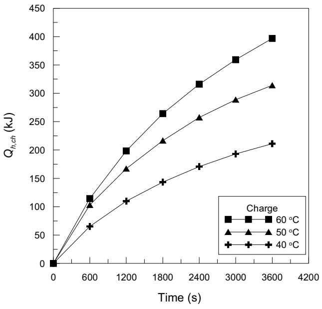

Fig.5. The quantity of heat storage in heat storage procedure.

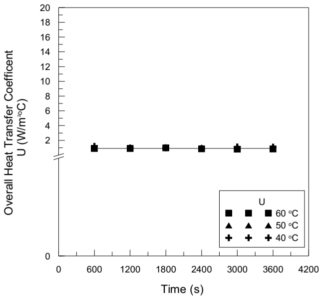

Fig. 6. The overall heat transfer coefficient variation in heat storage procedure.

In the case B, the initial temperature of energy storage tank is set as 30 °C, 45 °C and 60 °C, respectively. As shown in Fig. 7, the temperature of energy storage material is decreasing from 60 °C to 38 °C with time increase. Fig.7 also indicates that with the energy storage material initial temperature increases, the heat exchangers water temperature difference between imports and exports have gradually increase. Heat transfer rate has also the trend of increase in this case. The phenomenon can address the relationship between discharge of heat and time curve, shown in Fig. 8. Moreover, in Fig. 9, the overall heat transfer coefficient is also constant in this case.

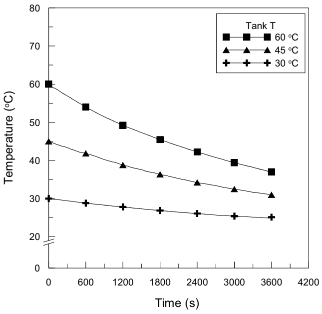

Fig. 7. The temperature variation of energy storage tank in heat release procedure.

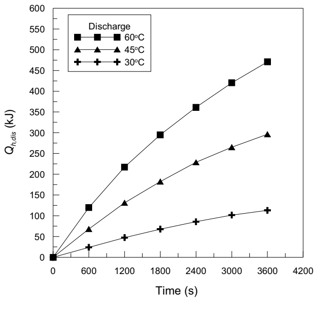

Fig. 8. The quantity of heat release in heat release procedure.

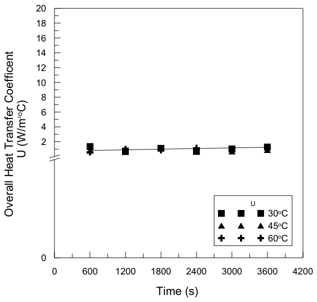

Fig. 9. The overall heat transfer coefficient variation in heat release procedure.

In the case C, the initial temperature of thermostatic bath can be adjusted as 5 °C, 0 °C and -5 °C, respectively. The energy storage material temperature variation is shown in Fig. 10. The range of temperature decrease in energy storage material is increase as the inlet temperature of heat exchanger reduced. As shown in Fig. 11, when the system is under cold storage operation, the temperature between storage material temperature and the thermostatic bath becomes smaller. The heat transfer rate is also drop. Therefore, the curve slope increases slowly with the time. The overall heat transfer coefficient is also constant in this case, shown in Fig. 12.

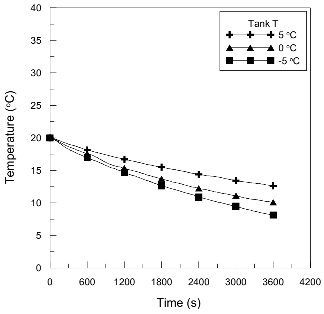

Fig. 10. The temperature variation of energy storage tank in cold storage procedure.

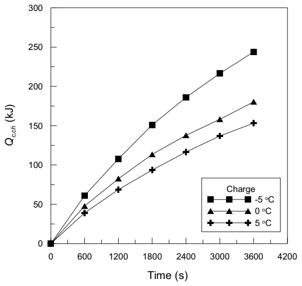

Fig. 11. The quantity of cold storage in cold storage procedure.

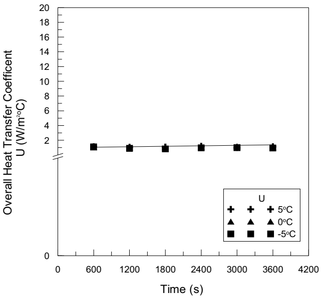

Fig. 12. The overall heat transfer coefficient in cold storage procedure.

In the case D, the initial temperature of thermostatic bath is designed as 25 °C, 30 °C and 35 °C, respectively. The variation of energy storage material temperature with time is shown in Fig. 13. The energy storage material temperature increases from 5 °C to 22 °C under the thermostatic bath temperature of 35 °C. The heat transfer rate becomes small in the end of experiment. This is because the temperature difference of energy storage material and thermostatic bath gets smaller and smaller as shown in Fig. 14. Moreover, the overall heat transfer coefficient is also constant in this case, shown in Fig. 15.

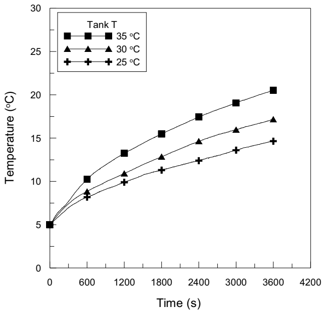

Fig. 13. The temperature variation of energy storage tank in cold release procedure.

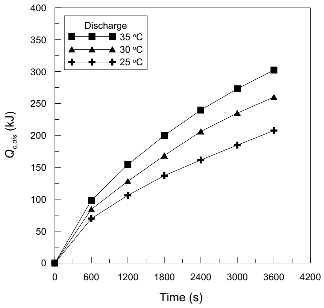

Fig. 14. The quantity of cold release in cold release procedure.

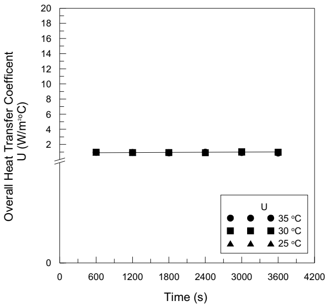

Fig. 15. The overall heat transfer coefficient variation in cold release procedure.

3.2 Al_2O_3 and water mixture as thermal storage medium

Figure 16 shows the temperature distributions of Al_2O_3 and water under different ratios. With the increase of Al_2O_3 ratio, the change of the temperature becomes larger. The temperature raise becomes larger under the same power input due to the specific heat of Al_2O_3 is small. Figure 16 also describes the slopes become smaller at 270 second under 1:1_upper and at 380 second under 1:1_lower, respectively. The main reason of the slope change is separation of the Al_2O_3 and water. The more Al_2O_3 dissolved effectively in water, the more energy is storage.

The heat storage quantity of energy storage material under different rations of Al_2O_3 with water are shown in Fig. 17. In this figure, mixing ratio of 5:4 is compared to water only. With the additional of Al_2O_3, the quantity of heat storage increased significantly. Figure 17 also shows that when the mixture ratio of Al_2O_3 and water is 5:4, the heat storage quantity compared to without Al_2O_3 has 6% increment.

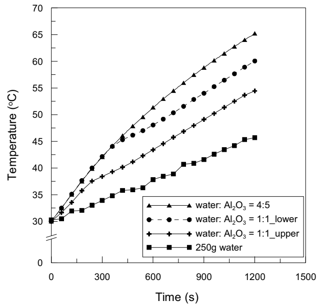

Fig. 16. The temperature variation of energy storage material under different additional of Al_2O_3.

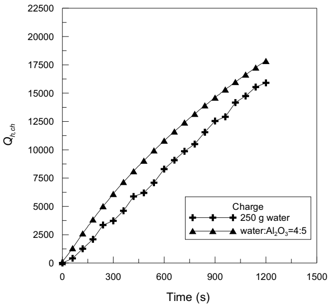

Fig. 17. The heat storage quantity of energy storage tank under different mixture ratio of Al_2O_3.

4. Conclusions

This article experimentally investigates the thermal performance of the vapor chamber energy storage system with Al_2O_3 and water mixture as the thermal storage medium. The vapor chambers provide an effective heat spreading area between heat exchanges and energy storage tank. The main parameter is the inlet water temperature of heat exchangers with constant mass flow rate of 0.5 kg/min. The results indicate that with 10 °C increment for the temperature difference between the inlet water and the energy storage tank, the heat in charge and discharge processes increase from 40% to 50%, respectively. The experimental results demonstrate that the overall heat transfer coefficients range is from 0.9 to 1.1 W/°C under the different cases. The experimental results also show that the optimal mixture ratio of Al_2O_3 with water is 1.25. The water will be completely absorbed while the mixture ratio of Al_2O_3 and water is over the 1.75. The heat storage quantity of the system compared to the energy storage tank without Al_2O_3 can be increased by 6%.

References

[1] Hasnain, s. M. "Review on Sustainable Thermal Energy Strorage Technologies, Part 1: Heat Storage Material and Techniques," Energy Conversion and Management, (1998) 1127-1138.

[2] Van den Branden, G., Hesius, M., and D'Haeseleer, W.,"Comparison of Heat Storage Systems Employing Sensible and Latent Heat," International Journal of Energy Research, (1999) 605-624.

[3] Laven, Z., and Thomson, J., "Experimental Study of a Thermally Stratified Hot Water Storage Tanks," Solar Energy, (1977) 519-524.

[4] Fraid, M. M., and Husain, R. M., “An Electrical Storage Heater Using the Phase-Change Method of Heat Storage,” Energy Conversion and Management, (1990) 219-230.

[5] Chow, L. C., Zhong, J. K., and Beam, J. E., “Thermal Conductivity Enhancement for Phase Change Storage Media,” International Communications in Heat and Mass Transfer, (1996) 91-100.

[6] Schroeder, J., and Gawron, K., “Latent Heat Storage,” International Journal of Energy Research, (1981) 103-109.

[7] Sari, A., and Kaygusuz, K., “Thermal Performance of Eutectic Mixture of Lauric and Stearic Acids as PCM Encapsulated in the Annulus of Two Concentric Pipes,” Solar Energy, (2002) 493-504.

[8] Z. J. Zuo, P. M. Dussinger, Heat pipe vapor chamber cold plate modeling, fabrication and testing, ASME, Fairfield, NJ, USA, Anaheim, CA, USA, (1998) 281-286.

[9] Wei, J., Chan, A., and Copeland, D., “Measurement of Vapor Chamber Performance” 19th IEEE SEMI-THERMAL Symposium, (2003).

[10] Sauciuc, I., Chrysler, G., Mahajan, R. and Prasher, R., “Spreading in the Heat Sink Base: Phase Change System or Solid Metals?,” IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES, (2002).

[11] S. A. Nada, H. H. El-Ghetany, H. M. S. Hussein, “Performance of a two-phase closed thermosyphon solar collector with a shell and tube heat exchanger,” Applied Thermal Engineering, (2004) 1959-1968.

[12] M. Ahmad, G. Berthoud, P. Mercier, “General characteristics of two-phase flow distribution in a compact heat exchanger,” International Journal of Heat and Mass Transfer, (2009) 442-450.

[13] S.H. Noie, S. Zeinali Heris, M. Kahani, S.M. Nowee, “Heat transfer enhancement using Al2O3/water nanofluid in a two-phase closed thermosyphon,” International Journal of Heat and Fluid Flow, (2009) 700-705.

[14] ISO, (1995), Guide to expression of uncertainty in measurement, International Organization for Standardization, Switzerland.