二重管形 潛熱蓄熱裝置의 傳熱特性에 對한 實驗的 分析

Experimental Analysis on the Heat Transfer Characteristics of the Double Pipe Heat Exchanger for Latent Heat Storage

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摘 要

高密度의 熱에너지를 貯藏하기 爲한 潛熱蓄熱裝置를 設計, 製作, 作動하는 경우 潛熱蓄熱裝置의 使用目的에 適合한 最適設計와 그 效率的인 利用을 爲해서는 그 傳熱特性이 糾明되어야 한다. 本 研究에서는 實用化에 必要한 二重管形 潛熱蓄熱裝置의 放熱過程에서의 傳熱特性을 二次元的으로 實驗 分析하였으며, 時間變化에 따른 潛熱材의 溫度變化와 凝固率이 實驗分析値와 理論分析値에 있어서 잘 일치하였다. 한편 凝固率, 放熱率, 물의 溫度變化에 對한 分析을 하였다.

I. Introduction

It is important for the efficient utilization of the solar thermal energy to cover the time gap between the supply and demand.

For this purpose, an efficient heat storage technique, especially high density heat storage system is necessary.

There are serveral methods for heat storage such as sensible heat storage, latent heat storage and chemical heat storage. Among them, latent heat storage system has some advantages that it can store higher density heat at constant temperature.

For the optimal design of the latent heat storage system by using the PCM and efficient operation of the system, heat transfer characteristics of latent heat storage systems have to be analyzed.

Therefore, in this study, the heat transfer characteristics of the double pipe heat exchanger for latent heat storage, which is valuable to the industrial applications, were analyzed experimentally.

A. System configuration

The latent heat storage system for the computer simulation and the experiments is shown in Figure 1, which is the double pipe heat exchanger. The phase change material, i.e. calcium chloride hexahydrate, is filled in the outside of the inner tube. And water flows through the inner tube inside.

In this case, the temperatures of water and the phase change material vary depending on time and distance during heat charging and discharging process.

It is important for the optimum operations and the design of the system, the temperature variation, the location of the moving boundary interface, the heat storage efficiency and the solidification rate, et cetera, depending on time during heat charging and discharging process have to be analyzed.

Therefore, the computer simulation and

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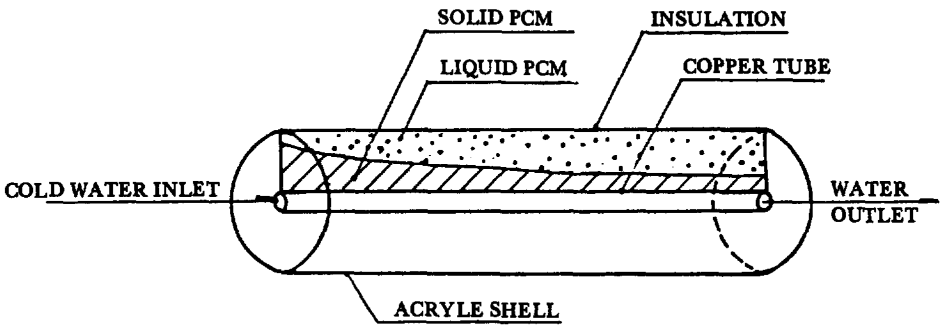

Fig. 1. Configuration of the double pipe heat exchanger

the experiments are performed based on the heat conduction model during cooling process.

The computer simulation starts with settning of the governing equation, i.e. energy equations of the phase change material and the coolant. And the set of the initial conditions and the boundary conditions, nondimensionalization of the equations, coordinates transformation, setting of the finite difference equations by the finite difference method, solving the coefficients matrix, calculating the temperature history depending on time, solidification rate and the heat storage efficiency by the numerical integral, et cetera, are performed and calculated(1).

B. Governing equations

In order to set the energy equations which governs the heat transfer mechanism from the phase change material to the coolant, the energy conservation equation has to be taken within the tube which has the convection boundary.

After taking the energy balance equation about the finite control volume in the tube, the governing equation in the inner tube can be expressed as follows.

$$\frac{\partial Tw}{\partial t} = -\frac{\partial Tw}{\partial Z} * U + \frac{Kw}{\rho w \cdot Cpw} * \frac{\partial^2 Tw}{\partial Z^2} + \frac{2*Hw}{\rho w * Cpw * Ri} * (Tt - Tw) \quad \text{........... (1)}$$

The governing equations of the phase change material consisted of two parts of the liquid phase and the solid phase because the thermophysical properties of the phase change material are different at each phase.

The basic equations can be expressed as follows.

Liquid region:

$$\rho\ell * Cp\ell * \frac{\partial T\ell}{\partial t} = K\ell * \left(\frac{1}{R} * \frac{\partial T\ell}{\partial R} + \frac{\partial^2 T\ell}{\partial R^2} + \frac{\partial^2 T\ell}{\partial Z^2}\right) \quad \text{........................ (2)}$$

Solid region:

$$\rho_s * Cps * \frac{\partial Ts}{\partial t} = Ks * \left(\frac{1}{R} * \frac{\partial Ts}{\partial R} + \frac{\partial^2 Ts}{\partial R^2} + \frac{\partial^2 Ts}{\partial Z^2}\right) \quad \text{........................ (3)}$$

The governing equations need the initial conditions and the boundary conditions for the unique solution of the problem. The initial and the boundary conditions are summarized as follows.

Initial conditions; t=0

$Ri < R < Ro$	: $T\ell = Ti$
$Z=0$	: $Tw = Twin$, $\partial T\ell/\partial Z=0$
$R=Ri$	: $Tt = Ti$, $K\ell * (\partial T\ell/\partial R) = Hw*(T_t - T_w)$
$R=Ro$	: $\partial T\ell/\partial R=0$
$Z=Zmax$	: $\partial T\ell/\partial Z=0$

Boundary conditions; $t > 0$

$Z=0$	: $Tw=Twin$, $\partial Ts/\partial Z = \partial T\ell/\partial Z=0$
$Z=Zmax$	: $\partial Ts/\partial Z=\partial T\ell/\partial Z=0$
$R=R0$	: $\partial T\ell/\partial R=0$
$R=Ri$	: $Ks*(\partial Ts/\partial R) = Hw*(Tt-Tw)$ .... (4)
$R=Rm$	: $Ts=T\ell=Tm$

$$K\ell*(\frac{\partial T}{\partial R}*Air+\frac{\partial T}{\partial Z}*A\ell z)-Ks*(\frac{\partial Ts}{\partial R}*Asr+\frac{\partial Ts}{\partial Z}*Asz)=\rho m*Hf*Amr*\frac{d\delta s}{dt} \quad \cdots\cdots\cdots\cdots(5)$$

II. Experimental equipments, materials and methods

For the two dimensional analysis of the double pipe heat exchanger for latent heat storage, the experimental equipments were constructed as shown in Figure 2.

The tube is made of copper whose thermal resistance is low, and its thickness is 1 mm and outer diameter is 10 mm. The outer pipe is made of acrylic resin whose thermal conductivity is similar to that of calcium chloride hexahydrate and helpful for the insulation. The dimension of the outer pipe is taken as the thickness of 3 mm, the outer diameter of 100 mm and the height of 300 mm. The total volume was 2080 cubic centimeter.

The auxiliary container, whose inner diameter is 3 mm, is installed on the upper part of the shell, which is purposed for the volume expansion of the phase change material during the phase change and checking the solidification rate. The auxiliary container may be installed on the side of the shell in the horizontal shell and tube type (2).

In this case, the temperature of the phase change material may be failed to be axisymmetric distribution.

The density difference between the solid phase and the liquid phase state causes the volume expansion during the heat charging process and this gives stresses to the system if there were not for the auxiliary container.

The mineral oil, which is lighter than the phase change material and not reacted with it, is filled in the auxiliary container and therefore forms free surface.

The solidification rate can be calculated by checking the height of the mineral oil. A drain cock is installed at the bottom of the outer pipe. The outside of the container is efficiently insulated by the insulation material (Toilon).

The temperature measurement system is consisted of E-type thermocouple and the reader.

The phase change material for the experiments is calcium chloride hexahydrate which is imported from Switzland. It is regent grade and the melting point is 28°C. The thermophysical properties were studied at the former part of this paper. The density of the solid phase is 1415 kg/m^3 and that of the liquid phase is 1680 kg/m^3, which are measured. The weight and the volume of the phase change material are measured accurately for

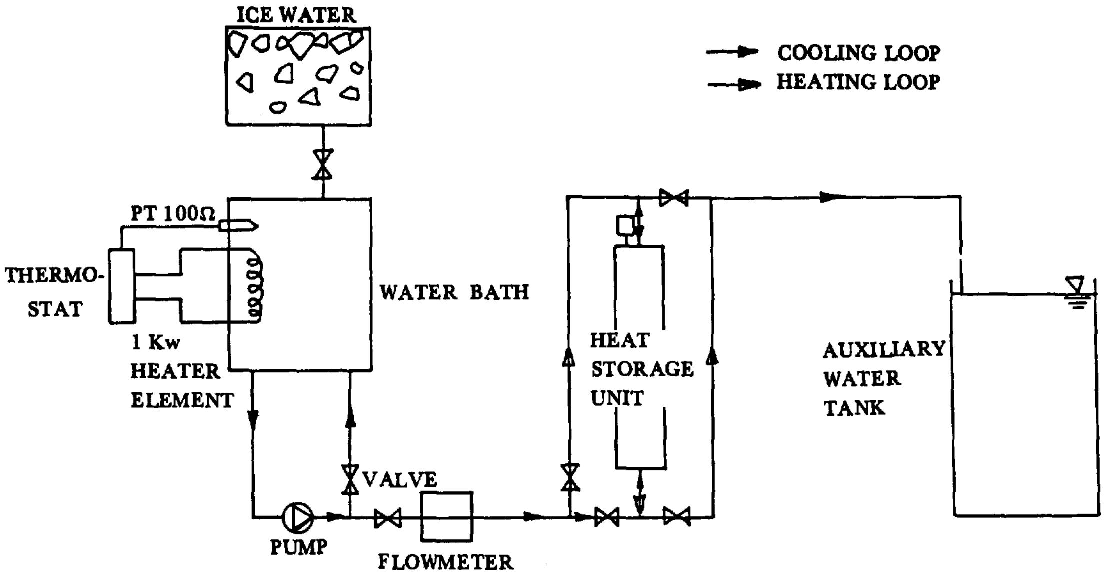

Fig. 2. Schematic diagram of the experimental apparatus

the density.

The mineral oil, which is lighter than the liquid state of PCM and not reacted with the phase change material, is used for the compensation of the air hole which would be arised in the solid state.

Although the specific heat and the latent heat capacity may be measured by the energy conservation law, most of the properties are referred to the reference(3) because the material is regent grade.

The experiment is started with melting the phase change material at 37°C which is higher than the melting point.

The liquid material is poured cautiously in the PCM container.

The fine straw has to be used for the air ventilating because the container system is a closed system without the entrance of the auxiliary mineral oil container.

In a few minutes for the temperature regulation, the coolant is supplied through the inner tube from the constant temperature bath. The temperature of the coolant is 7°C, which is produced in the water bath.

By releasing the valve, the coolant flows through the inner tube from the lower part to the upper part of the tube. The direction of the flow has to be considered because the solidification from the the lower part can give the free surface on the upper part of the tube. The solidification from the upper part may arise the vacuum in the PCM container because the center of the system would be empty by the volume depression caused by the density difference between the solid and the liquid phase.

Also the water flow direction of the heat charging process has to be from the upper part to the lower part of the tube.

If the phase change material were liquified from the lower part of the tube, the volume expansion from the density change with the phase change would give the stresses to the system.

From the instant of the valve releasing, the temperature of the phase change material, the coolant and the height of the mineral oil in the auxiliary container were measured at every five minutes.

Ⅲ. Comparison of the theoretical predictions and the experimental results

The experiment was performed to find the heat transfer characteristics of the latent heat storage system during heat discharging process and for the validation of the theoretical model and the numerical analysis. The first validation can be done by the temperature history of the phase change material, i.e. calcium chloride hexahydrate. The temperature histories of the four points in the phase change material are shown in Figure 3.

The experimental results and the theoretical predictions were conformable.

The chi-square test showed that of the

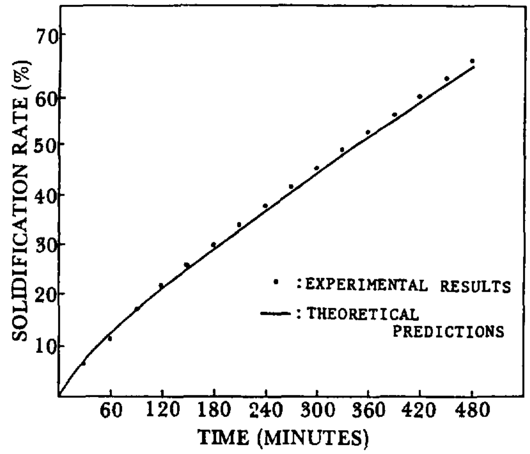

Fig. 4. Comparison of theoretical predictions with the experimental results as function of time for two dimensional analysis

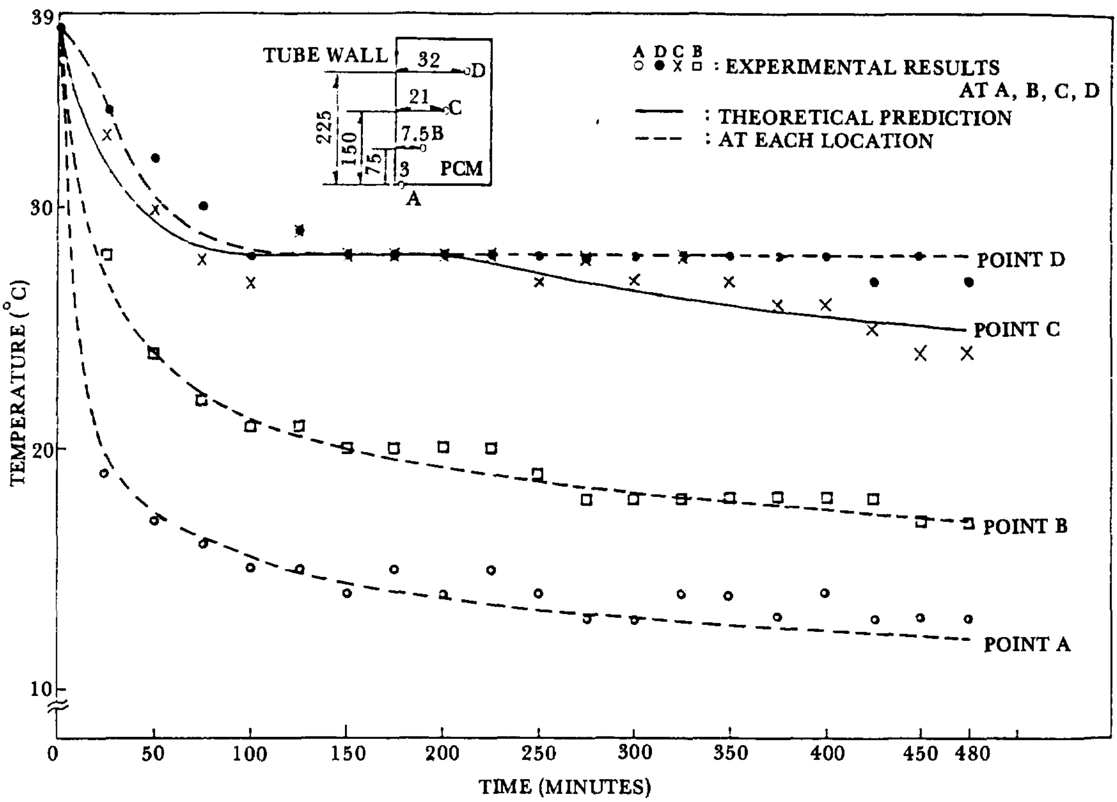

Fig. 3. Experimental and theoretical temperature history of the PCM depending on time.

experimental data were well agreed with the theoretical data at the 0.05 level of significance.

The effects of the latent heat capacity were more clearly seen at long distance from the inner tube wall. The duration of the latent heat discharging period was about two hours at the C point.

The second validation was done by the solidification rate of the PCM depending on time.

As shown in Figure 4, the solidification rate of the experiment was well agreed with that of the theoretical analysis.

Therefore, the theoretical model and the numerical analysis for the double pipe heat exchanger for the latent heat storage are reasonable.

IV. Results and discussion

On the experiments, after being supplied of the cooling water, there is a delay of two minutes before any solidification of PCM is observed.

Following this delay, the initial solidification occurs very rapidly from the lower part of the copper tube.

The shape of the solidification front is the same as dendrite phenomenon. According to Lou(4), Glauber salt without the thickening agent crystallizes from a supersaturated solution as color-less, long, needle-shaped, monoclinic crystals which may be 2 cm or more in length.

In contrast to the mixtures without thickening agents the large monoclinic crystals on longer observed, but are replaced by a more homogeneous solidification in the thickened mixture.

In this experiments, there are not thickening agents in calcium chloride hexahydrate because they are regent grade and supercooling or phase separation is not observed. The length of dendrite may be 5 mm and less with time. Meanwhile Saito (5) analyzed the one dimensional heat conduction by modelling the solidification process as three types of region of solid phase, region of liquid and region of partial solidification which is dendrite region. In this study, regardless of the consideration of the dendrite region, the theoretical results is well agreed with the experimental results.

Solidification rate as function of time is an important index of the latent heat utilization. As shown in Figure 5, solidification rate increases nearly contantly and reaches approximately 70 % in 8 hours. Therefore, this system may be modified for the more efficient utilization of the latent heat.

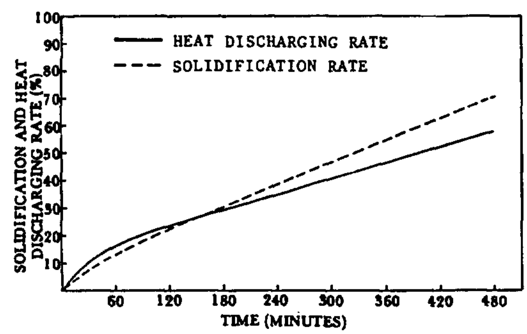

Fig. 5. Solidification and heat discharging rate as function of time

Heat discharging rate is increasing very rapidly at the beginning of discharging process and then slow down within one hour. This is the reason why the discharged sensible heat is big at the beginning and becomes nearly unchangeable at the amount of 75 kJ as shown in Figure 6.

Contrary to this, the amount of the latent

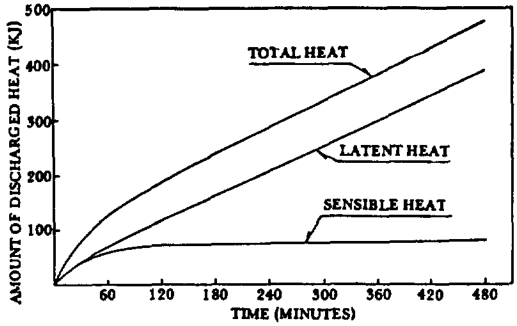

Fig. 6. Amount of discharged heat as function of time on the experiments on two dimensional analysis

heat grows continuously with time. The discharging heat is consisted in mainly latent heat in approximately half hours.

Therefore, the role of the sensible heat is not heavy comparative to that of the latent heat for the latent heat storage system.

Also it is recommended that the initial temperature of PCM is near the melting point.

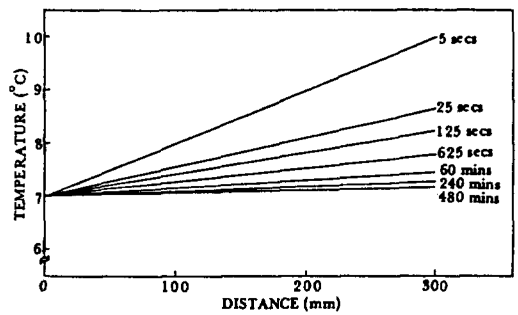

Fig. 7. Temperature variation of water as function of the distance from the entrance of water with time

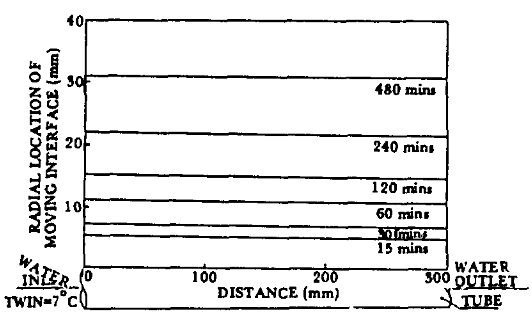

Fig. 8. Location of the moving interface as function of time

Water temperature varies linearly from the entrance of the inner tube to the outlet of the inner tube as shown in Figure 7.

Depending on time, the outlet temperature fall down rapidly at the beginning of the discharging process. Within an hour, the outlet temperature approaches near the inlet one.

Therefore, if coolant, i.e., water or air is used for the domestic purpose or air heating system, the system dimensions or operating conditions have to be changed for the higher outlet temperature. For example, the length of the system, the initial temperature of PCM or mass flow rate, et cetera, may be considered. Their effects will be studied at the next chapter.

Location of the moving interface is shown in Figure 8.

Its progress speed decreases with time.

The interface is slightly declined along the tube axis at beginning of the discharging process. The declination of the interface become nearly zero within about an hour.

V. Concluding remarks

For the optimal design of the latent heat storage system and efficient operation of the system, the heat transfer characteristics of the latent heat storage system have to be analyzed.

In this study, the heat discharging characteristics of the double pipe heat exchanger were analyzed experimentally. The results can be summarized as follows.

1. The statistical analysis showed that the theoretical and the experimental results of the volume change rate and the temperature variations were wel l agreed.

2. In experiments, solidification process speed nearly constant depending on time and solidification rate reached approximately 70 % in eight hours.

Heat dischanging rate was less than the solidification rate in general.

The discharged sensible heat was great at the beginning of the heat discharging process and became nearly unchangeable at the amount of 75kJ. Contrary to this, the discharged latent heat grew continuously with time.

The initial temperature was recommended to be near the melting point because the contribution of sensible heat to total dischaged heat was very small comparatively to the latent heat.

Water temperature was varied linearly from the entrance to the outlet of the inner tube. And the water outlet temperature fell down rapidly at the beginning of the heat discharging process.

The outlet temperature becomes 7.7°C in 10 minutes of cooling process.

If the water were used for domestic purpose or air conditioning systems, the system dimensions or operating conditions have to be modified for the higher outlet temperature. The shape of the moving interface was nearly linear.

The analysis of the effect of the parameters and the variables must be left to a later date.

NOMENCLATURE

1. English letters

Aℓr, Aℓz, Amr, Asr, Asz: Area of the infinitesimal control volume

Cp: Specific heat

Hf: Latent heat capacity

Hw: Convection heat transfer coefficient

K: Thermal conductivity

R: Radius

Ri: Inner radius of the inner tube

Ro: Inner radius of the outer pipe

t: Time

T: Temperature of PCM

U: Water velocity

Z: Axial coordinate

Zmax: Length of the double pipe heat exchanger

2. Greek letters

δs: Distance of moving interface from the outer diameter of tube

ρ: Density

3. Subscript

i: refers to initial or inner

ℓ: refers to liquid

m: refers to melting

o: refers to outer

s: refers to solid

t: refers to the inner tube

w: refers to water

win: refers to water inlet

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