A Latent Heat Storage by Use of PCM with Different Melting Temperature

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1 Introduction

One energy problem originates from the unstable supply and the increasing demand. The countermeasure of this problem is to develop the new energy resources(atomic, solar, coal, wind, tidal, wave,geothermal, biomass) and to utilize the energy effectively(saving,storage, conversion, transportation, heat recovery). The other problems the environmental one; the direct influence(poisonous exhaust gas, water pollution, radioactive) and the indirect influence(destruction of nature, global warming potential, weakening of physical strength). The countermeasure of this problem is the removal of public hazards(anti-pollution treatment, use of clean energy), the matching with nature(closed cycle, ecological system) and the political action.

The effective energy utilization is very useful not only for the reduction of the energy consumption but also the preservation of the global environment. There are two categories for the effective energy utilization; the quantitative one that is to reduce the energy consumption directly and the qualitative one that is to improve the energy demand/supply unbalance. The qualitatively effective utilizations consequently connected with the quantitative reduction of the energy consumption.

2 Effective Energy Utilization

2.1 Quantitatively Effective Utilization

The decrease of the energy consumption may be possible if we bear it in mind or the energy cost is raised, but generally speaking the absolute reduction of the energy consumption is difficult.

The heat recovery has been widely conducted in the industrial process; distillation process, iron industry, waste treatment process,etc. The improvement of the thermal equipment efficiency has been also conducted; heat exchanger, evaporator, condenser, combustion furnace, etc.

2.2 Qualitatively Effective Utilization

The unbalance between the energy supply and the energy demand is ofen encountered. The time unbalance of the energy is noticed in the case that the energy supply is alternated(solar energy) or the energy consumption is changed (daytime and night, winter and summer), and for this case the energy storage is needed. The unbalance of the location is in the case that the energy is consumed in the place different from the energy supply(middle east for the oil), and for this case the energy transportation is required. The unbalance for the energy form occurs in the case that the required energy form is different from the supplying energy form, and for this case the energy form has to be converted.

3 Thermal Energy Storage (TES)

3.1 General View

The main purpose of the energy storage is to improve the demand/supply unbalance of time as mentioned before. Furthermore, by using the energy storage, the energy can be supplied supplementally, the energy cost can be reduced, and the energy can be used just when it is demanded. The supplemental supply is necessary for the unexpected interruption of the energy supply and the transient operation. The energy cost is reduced by the fact that the heat recovery is easy to conducted, the scale of the energy equipment can be reduced and the utilization of the low cost energy is possible.

The method of the energy storage is classified according to the form of the input energy;

a.thermal energy storage(sensible, latent, chemical)

b.potential energy storage(pumped hydraulic, compressed air)

c.electrical energy storage(battery, super conduction coil)

d.mechanical energy storage(flywheel)

e.fuel energy storage(hydrogen, synthetic fuel)

The definition of the thermal energy storage is that the energy form at input and/or output is thermal. The stored energy is not always thermal. To promote the thermal

energy storage technique, it is important that the elemental technique, the system and the practical use are developed simultaneously.

The thermal energy has been widely used and the technique on the thermal energy is well-developed. This situation is the good background for the development of the thermal energy storage the main factors of the thermal energy storage are, efficiency (=output/input), stored energy density, response and life time. The thermal energy storage is classified into sensible, latent and chemical ones.

3.2 Sensible Heat Storage

The sensible heat storage is the way to store the thermal energy by the temperature rise of a material. The important factors for the material are the heat capacity and the temperature range. Water has the highest heat capacity, and is safe and cheep, then water is the most attractive material for the sensible heat storage. But the upper limit of the temperature is low although this limit can be raised if pressurized.The soil is used for the long period storage. The ceramics is used for the high temperature storage.

The water tank is the most popular sensible heat storage. It is preferable to separate the hot water from the cold water; this is called "stratified".

3.3 Latent Heat Storage

The latent heat storage is the way by melting/solidification of a material. The constant temperature output and the larger energy density are expected in the latent heat storage. The problems are the lower heat transfer rate and super-cooling at solidification.

The materials used for the latent heat storage are the organic material(paraffin), the inorganic material(NaOH, NaCl, $MgCl_2$) and salt hydrate(NaOH·$10H_2O$). The equipment used for the latent heat storage is the capsule type and the shell and tube type.

3.4 Chemical Energy Storage

The chemical reaction can be used to store the thermal energy. The chemical energy storage is shown in Fig.1. The chemical energy storage has the very large energy density, does not need the thermal insulation and is possible and applicable for transportation and heat pump. The substance used for the chemical heat storage is, for example, absorbent, hydrate, hydroxide, ammonium complex, metal hydride, carbonate, organic material and clathrate.
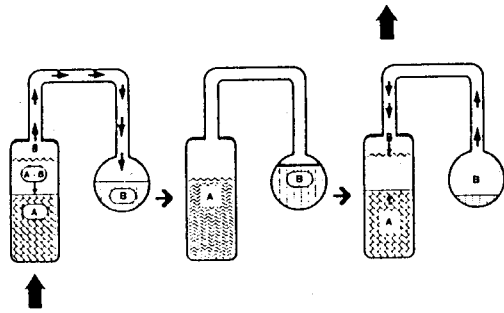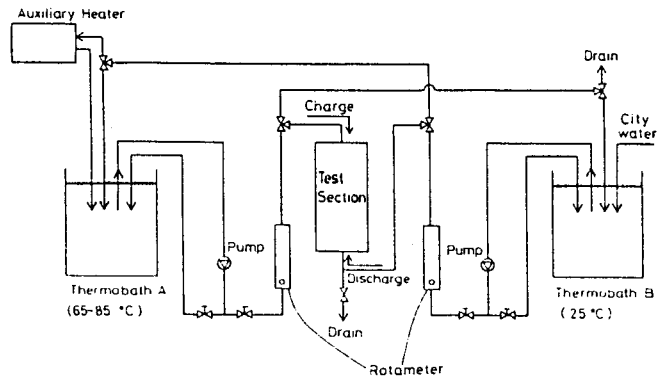
Fig.1 Chemical energy storage

Fig.2 Experimental apparatus

4 Latent Heat Storage by PCM with Different Melting Temperature

4.1 Introduction

One disadvantage of the latent heat storage is its low charging and discharging rates owing to the low thermal conductivity of the phase change material(PCM) as mentioned before. This problem can be somewhat improved by enhancement of an overall heat transfer coefficient by the use of finned tubes or iron filings.

The temperature difference between PCM and the heat transfer fluid also affects the heat transfer rate. The temperature of the heat transfer fluid decreases as it flows downstream. This leads to the decrease in charging and discharging rates at downstream. To improve this problem, the use of PCM with different melting temperatures is discussed. The employment of this type provides more constant heat flux to all PCMs even though the temperature of the heat transfer fluid decreases. This decrease can be compensated for by use of a lower melting temperature of PCM.

4.2 Experimental

(1) Apparatus

A sketch of the apparatus used in this study is illustrated in Fig.2. The apparatus consists of the heat storage tank, and the high-temperature and low-temperature thermobath. Water as heat transfer fluid was supplied to the heat storage tank from the thermobath by a pump and its flow rate was measured by rotameters. The capacity of the thermobath was sufficiently large so as to provide continuous flow of water at a constant temperature. During the heat charge process, hot water from high-temperature thermobath was supplied to the top of the heat storage tank. Most of the heat of water were transferred to the PCM.

During the heat discharge process, cold water from the low-temperature thermobath was supplied to the bottom of the heat storage tank.

The heat storage tank is shown in more detail in Fig.3. The tank was constructed from 10-mm thick acrylic sheets with dimensions 414 mm long, 198 mm wide and 150 mm deep. The 105 tubes containing PCM were arranged in 15 rows and on 7 lines(this is called heat storage section). The extensions of 70 mm at both ends of the tank were necessary to provide uniform distribution of the water velocity in the heat storage section.

Fig.3 Heat storage tank

Table 1 Properties of PCM

		PCM-1	PCM-2	PCM-3
Melting temperature	[℃]	42-44	50-52	60-62
Heat of fusion *	[J·kg⁻¹]	1.68×10^5	2.00×10^5	2.09×10^5
Density (s)	[kg·m⁻³]	844	848	861
Density (l)	[kg·m⁻³]	760	767	778
Specific heat (s) *	[J·kg·K⁻¹]	2052	1650	1850
Specific heat (l) *	[J·kg·K⁻¹]	2411	1863	2384
Thermal conductivity (s)	[w·m·K⁻¹]	0.4	0.4	0.4
Thermal conductivity (l)	[w·m·K⁻¹]	0.15	0.15	0.15
Viscosity	[Pa·s]	4.9×10^{-1}	5.6×10^{-1}	6.3×10^{-1}
Expansion coefficient (l)	[K⁻¹]	8.3×10^{-4}	7.7×10^{-4}	7.1×10^{-4}

* measured

The heat storage section consists of three parts, and each part contains 5 rows of the capsules. The capsules in each part were filled with PCMs having the different meltingpoints (sloped type). The melting temperatures of each PCM were 60℃(row 1-5), 50 ℃(row 6-10), and 42℃(row 11-15), respectively. The physical properties of each PCM are listed in Table 1.

The heat storage section with PCM having the same melting temperature(uniform type) was also used. All the capsules were filled with PCM having a melting temperature of 50 ℃.

The capsule was a horizontal cylindrical copper of 18 mm O.D. and 16 mm I.D. The effective length of PCM within the capsule was 150 mm. The volume change during the melting and solidification of PCM was buffered by the movable acrylic plug and by air in the capsule.

The temperatures at 4 points in water and 9 points in PCM were measured by Cu-Co. thermocouple.

(2) Results

The temperature histories of PCMs in three rows(1st, 8th and 15th) on the middle line are shown in Fig.4. The PCM temperature increases gradually around its melting temperature and rapidly after melting. The melting of PCMs starts in the first row and then gradually in other rows. The melting time in the 15th row for the sloped type is shorter than the uniform type. This result indicates that the charging rate can be enhanced by use of the sloped type.

The melting times for the sloped and uniform type at the water flow rate of 1 l/min are shown in Fig.5. The melting is completed from the upstream row to the downstream row in each part. The maximum melting time for the sloped type(20 min in the 15th row) is shorter than that for the uniform type(24 min in the 15th row). The shortened maximum melting time is attributed to the more constant difference between the water temperature and the melting temperature of PCMs.
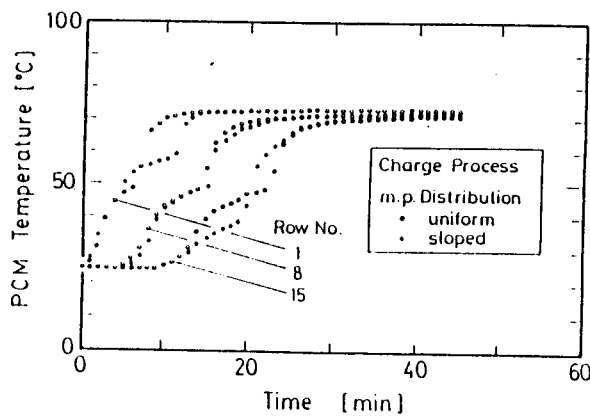
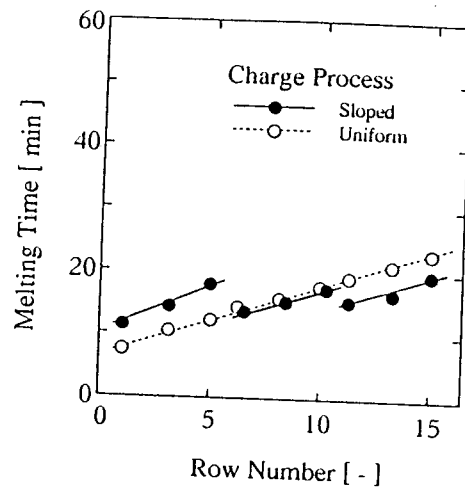Fig.4 Temperature of PCM(charge)

Fig.5 Melting time

The temperature histories of the PCM in the discharge process are shown in Fig.6. The PCM temperature decreases gradually around its melting temperature, and rapidly after its solidification. The PCM in the 15th row solidifies first owing to the reverse flow direction of water compared to the charge process. The solidification time in the first row for the sloped type is shorter than the uniform type. This result indicates that the discharging rate can be enhanced by use of the sloped type.

The solidification times for the sloped and uniform type distribution at the water flow rate of 1.0 l/min are shown in Fig.7. The maximum solidification time for the sloped type (17 min in the 1st row) is shorter than that for the uniform type (23 min in the 1st row).
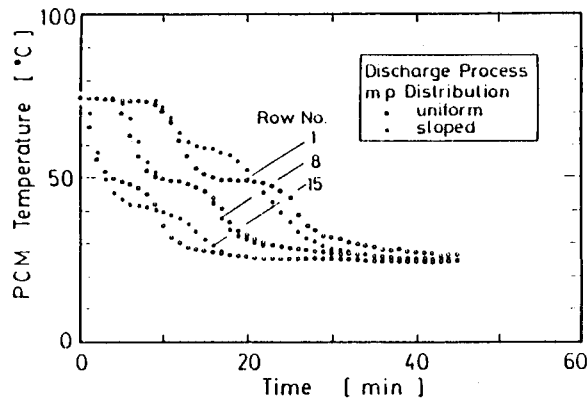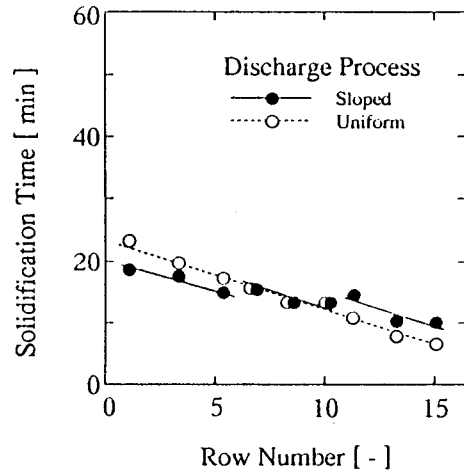
Fig.6 Temperature of PCM(discharge)

Row Number [-]

Fig.7 Solidification time

4.3 Numerical Analysis

(1) Basic Model

The numerical model of the thermal performance for a heat storage module is shown in Fig.8. The heat storage module consists of the horizontal cylindrical capsules containing PCM. The capsules are fixed in the heat storage module in an in-line arrangement with 15 rows. Water is used as heat transfer fluid. The model dimensions are the same as those of the experimental apparatus.

This model is based on the assumptions that; (a)the gradient of the water temperature and velocity normal to the flow direction is ignored, (b)the temperature gradients in PCM are ignored(the neglecting of temperature gradients is compensated for by the employment of an overall heat transfer coefficient between PCM and water), (c)heat losses from the storage module to the surroundings are negligible, and (d)PCM behaves ideally(PCM has a definite melting temperature, and the supercooling and degradation are not accounted for).

The energy equation for the water flowing across the capsules is formulated in one-dimensional and unsteady state,

$$\varepsilon \rho_w Cp_w \frac{\partial T_w}{\partial t} + \rho_w Cp_w u \frac{\partial T_w}{\partial x} = \frac{\partial}{\partial x}\left(k_w \frac{\partial T_w}{\partial x}\right) + Q$$

(1)

where Q is the heat flow between PCM and water. The estimation of the heat flow requires a knowledge of the overall heat transfer coefficient. This was obtained from the formula of the natural convection[1-3] and heat conduction. The temperature of water can be calculated from the finite difference form by use of the explicit method. The temperature of PCM can be estimated from the heat flow between PCM and water.

(2) Comparison with Experimental Results

Comparisons of measured and calculated results for the maximum melting and solidification

time with the different water flow rates are given in Figs.9 and 10, respectively. Both the maximum melting and solidification time for the sloped type are lower than those for the uniform type. The charging and discharging rates can be enhanced by use of the sloped type with different melting temperatures especially at small flow rates of water.
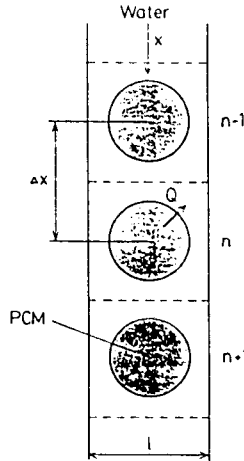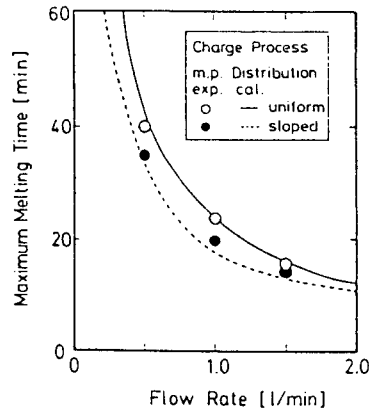

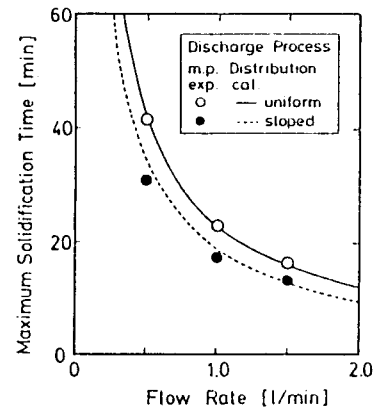
Fig.8 Model

Fig.9 Maximum melting time

Fig.10 Maximum solidification time

(3) Charging and Discharging Rates

The melting point difference of PCMs(ΔT), which is defined as the difference between the highest and lowest melting point of PCMs as shown in Fig.11, has enormous effects on the charging and discharging rates. The effects of the melting point difference of PCMs on the times required for the charge and discharge processes are shown in Figs.12 and 13, respectively. The time required for the charge process (described as melting time) is defined as the time when all PCMs melt down, and that of the discharge process (described as solidification time) is defined as the time when all PCMs solidify.
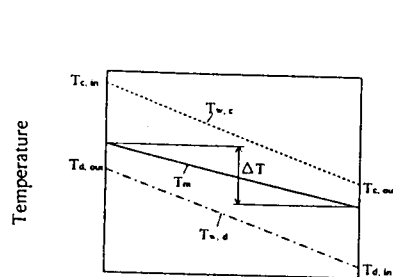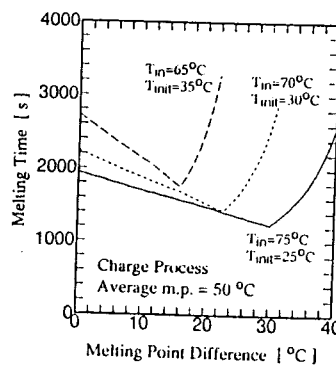

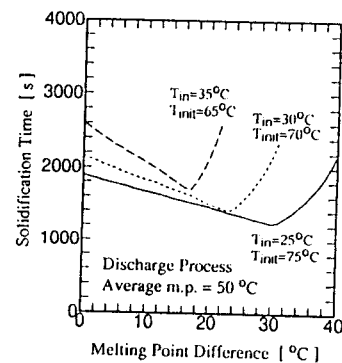Fig.11 Position of flow direction

Fig.12 Melting time

Fig.13 Solidification time

The melting or solidification time has an optimum for the melting point difference of PCMs. Both of the times decrease with an increase in the melting point difference below the optimum, and increase sharply above the optimum. These increased times are attributed to the extremely small difference between the water temperature and the melting point of PCMs at the water inlet.

The inlet water temperature also affects the melting and solidification times, and the optimum of the melting point difference.

The optimum of the melting point difference of PCMs is obtained when the difference between the water temperature and the melting point of PCMs is nearly constant along the fluid flow direction. The melting point difference at the optimum condition can be written in Eqs.(2) and (3) for the charge and discharge process, respectively.

$$\Delta T_c = \frac{NTU}{1+NTU/2}(T_{c,in} - T_{m,av}) \tag{2}$$

$$\Delta T_d = \frac{NTU}{1+NTU/2}(T_{m,av} - T_{d,in}) \tag{3}$$

where NTU is hA/mCp_w.

(4) Exergy Analysis[4-6]

The exergy destroyed during the charge process can be written as

$$E_{dc} = E_{in} - E_{out} - E_s \tag{4}$$

and that during the discharging process

$$E_{dd} = E_s - E_r - E_{out} + E_{in} \tag{5}$$

This expression is developed for evaluating the exergy efficiency. The exergy efficiency during the charge process is defined as the ratio of the charged exergy(E_s) to the net exergy supplied($E_{in} - E_{out}$) and that during the discharge process is defined as the ratio of the net discharged exergy ($E_{in} - E_{out}$) to the initial charged exergy(E_s). The exergy efficiency during the charge discharging process is shown in Figs.14 and 15, respectively. The normalized melting point difference in these figures is that divided by the optimum one.

The exergy efficiency of the complete cycle with the charge and discharge process can be defined as the ratio of the net discharged exergy to the net charged exergy, that is, the product of the exergy efficiencies of the charge and discharge processes. The cycle efficiency of the exergy is shown in Fig.16. It is noted that the highest cycle efficiency is near the optimum melting point difference. The fast charging and discharging rate or the smallest difference between the inlet water temperature and the melting point of PCMs leads to the highest exergy efficiency.