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Heat Transfer Characteristics of the Spherical Capsule Storage System Using Paraffins

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Key Words : Spherical capsule storage system, paraffin, n-Tetradecane, n-Hexadecane, Reynolds number, inlet temperature, heat transfer coefficient

Abstract

The present study is to investigate the effect of experimental parameters on the heat transfer characteristics of a spherical capsule storage system using paraffins. N-Tetradecane and mixture of n-Tetradecane 40% and n-Hexadecane 60% were used as paraffins. Water with inorganic material was also tested for the comparison. The experimental parameters were varied for the Reynolds number from 8 to 16 and for the inlet temperature from -7 to 2℃.

Measured local temperatures of spherical capsules in the storage tank were utilized to calculate charging and discharging times, dimensionless thermal storage amount, and the average heat transfer coefficients in the tank. Local charging and discharging times in the storage tank were significantly different. The effect of inlet temperature on charging time was larger than that on discharging time, but the effect of Reynolds number on charging time was smaller than that on discharging time. Charging time of paraffins was faster by 11～72% than that of water with inorganic material, but little difference of discharging time was found among them.

The effect of Reynolds number on the dimensionless thermal storage was less during charging process and more during discharging process than the effect of inlet temperature.

The effect of the inlet temperature and the Reynolds number on the average heat transfer coefficient of the storage tank was stronger during discharging process than during charging process. The average heat transfer coefficients of the spherical capsule system using paraffins were larger by 40% than those using water.

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Nomenclature

A : Surface area of a spherical capsule, m^2
D : Diameter of a storage tank, m
D^+ : Diameter ratio (=D/d)
d : Diameter of a spherical capsule, m
h : Average heat transfer coefficient, $W/m^2 \cdot K$
k : Thermal conductivity, $W/m^2 \cdot K$
Nu : Nusselt number $(h_o d/k_f)$
n : Number of spherical capsules
Q : Thermal storage amount, kJ
Q^+ : Dimensionless thermal storage amount $(=Q/Q_{tot})$
q : Heat transfer rate, W
R : Radius of a storage tank, m
R^+ : Dimensionless radius of a storage tank (=r/R)
Re : Reynolds number, $(=\rho vd/(1-\varepsilon)\mu)$
r : Distance from the center of a storage tank, m
T : Temperature, ℃
t : Time, s
v : Mean velocity of coolant, m/s

Greek letters

ε : Porosity
μ : Viscosity of coolant, $kg/m \cdot s$
ρ : Density of coolant, kg/m^3

Subscripts

f : Coolant
f_I : Inlet condition of coolant
m : Melting
o : Outside of a capsule
s : Surface of a capsule
tot : Total

Superscript

+ : Dimensionless

1. Introduction

A thermal storage system can provide efficient use of energy by minimizing the unbalance of electric demand between day-time and night-time in summer. The thermal storage system is classified as either sensible heat storage system or latent heat storage system. Since the latent heat storage system requires smaller installation area and expense due to higher thermal storage density and discharge at the constant phase change temperature, the latent heat storage system is superior to the sensible heat storage system.

Latent heat storage system can be classified as either static or dynamic system. There are ice-in-coil, ice-on-coil, ice-ball, ice-lens systems, etc. for the static system, and ice-harvest, ice slurry, phase change material slurry system, etc. for the dynamic system.

Ice ball system, as a latent heat storage system, has the advantages of large heat transfer area and easy installation. Saitoh(1) reported that the spherical capsule (among spherical, plate, cylindrical, coil shape, etc.) showed the best thermal storage performance by using n-Heptadecane($C_{17}H_{36}$) as a phase change material. Kamiya(2) and Choi et al.(3) investigated the overall thermal storage characteristics of the spherical capsule system with respect to the temperature difference between the inlet and outlet of the storage tank.

Chen and Yue(4) and Saitoh and Hirose(5) studied one dimensional axial model of the storage tank. Benenati and Brosilow(6) reported that the radial porosity distribution in the rockbeds system varies over a distance of 4.5~5 rock diameters from the wall of tank and the difference decreases near the center of tank. Lerou and Froment(7) reported that the velocity and heat transfer amount at the wall were larger than those at the center due to the different porosity distribution by experimentally investigating radial velocity and temperature distributions of the rockbeds storage tank with the diameter ratio of 10. Even though the rockbeds system is different from the spherical capsule storage system, it has the similar arrangement with spherical capsule system. Thus, thermal storage characteristics of capsules of the storage tank may be different in the radial direction due to the different porosity hence an investigation on the local thermal storage characteristics is required.

The commercial thermal storage system utilizes water with inorganic material. It has the solidification temperature near 0℃ which is unnecessarily low and usually has supercooling which causes bad thermal performance. Arnold(8) investigated supercooling and thermal characteristics of spherical capsules with water by changing the diameter of capsule. The thermal storage materials having higher melting point than water and similar latent heat with water are clathrates, paraffins, etc. Clathrate has the problems of CFC restriction and supercooling. The clathrate with the melting point from 5 to 15℃ was investigated by Chung et al(9) and Kim et al(10). Paraffin has the advantages of wide range of melting temperature, little supercooling, and little phase separation. Lim et al(11) and Kim(12) investigated thermal performance of paraffins for heating. The investigation on the paraffins (higher melting point than water and relatively large latent heat) is required for providing efficient thermal storage system.

The present study experimentally investigated the effects of Reynolds number and inlet temperature on the heat transfer characteristics of a spherical capsule storage system using paraffins.

2. Experimental Apparatus and Procedure

2.1 Experimental parameters

Reynolds number and inlet temperature were varied for different paraffins in this study. The present study used two types of paraffins : n-Tetradecane($C_{14}H_{30}$) and a mixture of n-Tetradecane 40% and n-Hexadecane($C_{16}H_{34}$) 60%. Paraffins are non-poisonous, chemically stable and have little supercooling for nucleation and small volume change during phase change process. Choi et al(13) measured melting temperature and fusion energy of n-Tetradecane and n-Hexadecane. The present study used commercial grade paraffins with the purity of 94%.

Melting temperature and fusion energy of distilled water and paraffins were measured by the differential scanning calorimeter(DSC) as shown in Fig.1. The melting temperature of distilled water measured by the DSC was 0.81℃ when the heating rate was 1℃/min. Since the melting temperature of distilled water is 0℃ in the literature, the temperature difference of 0.81℃ should be corrected for the melting temperature of paraffins. The corrected melting temperature and fusion energy were 3.64℃ and 172.1kJ/kg for n-Tetradecane and 6.81℃ and 120.9kJ/kg for the mixture of n-Tetradecane 40% and n-Hexadecane 60%. Water with inorganic material was also used for comparison with paraffins.

Reynolds numbers obtained using diameter of the capsule and porosity in the storage tank were 8, 12 and 16 and inlet temperatures were set at -7, -4, -1, 2℃ during charging process and 10℃ during discharging process considering operation condition of commercial systems. The diameter ratio of the storage

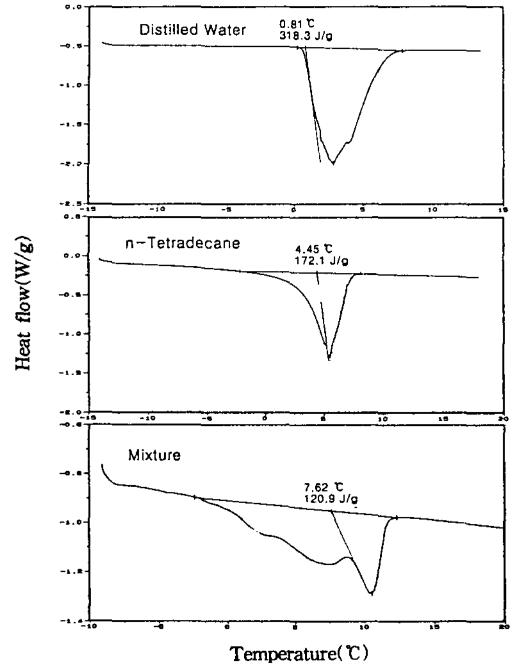

Fig.1 Melting temperature and fusion energy of PCM's by the DSC

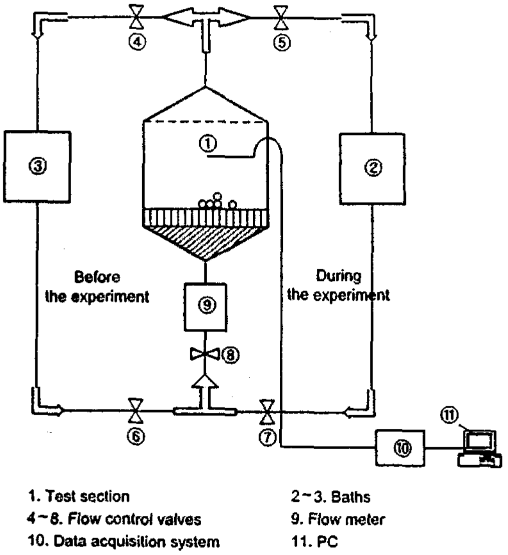

Fig.2 Schematic diagram of the experimental apparatus

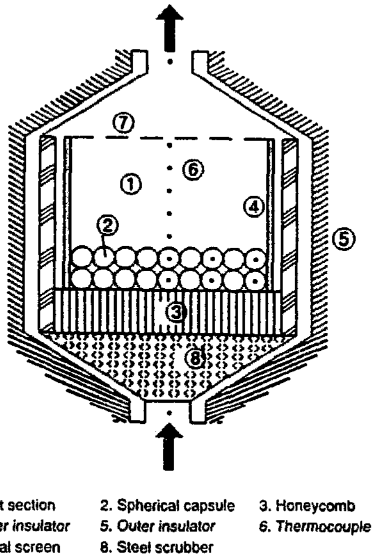

Fig.3 Detailed diagram of the test section

tank to the capsule was fixed at 8.8.

2.2 Experimental apparatus and procedure

The schematic of the experimental apparatus is shown in Fig.2. The detailed diagram of the test section is shown in Fig.3. The acryl thermal storage tank has the diameter of 220mm, wall thickness of 10mm and the height of 173mm. The spherical capsules in the storage tank were packed in-line with 7 stories and its porosity is 0.47.

The storage tank was insulated with glass wool. Inlet and outlet of the system were made by 1-mm-thick stainless steel funnel with the angle of 63.7°. Metal scrubber was put inside the inlet of the tank and the honeycomb was put behind the inlet of the tank to make the flow at the inlet of tank uniform. The spherical capsules with the diameter of 24.5mm and the thickness of 0.8mm were made of high density polyethylene. Paraffin or water was filled in the capsule by considering the volume change during the phase change. The initial temperature in the capsule and the inlet temperature of the storage tank were controlled by a constant temperature bath which circulates ethylene glycol 40% aqueous solution. The flow rate was controlled by the flow control valves and measured by the rotameter calibrated within ±1% accuracy. The temperature values inside and at the surface of capsules and working fluid temperature were measured by copper-constantan thermocouples with the diameter of 0.127mm calibrated within ±0.15℃ using a standard RTD. Measured temperatures were recorded by a 60 channel data acquisition system.

The experimental procedures were as follow. Before the charging, temperature inside the storage tank was set at 10℃ by constant temperature bath (part #3 in Fig.2) and the other bath (part #2 in Fig.2) was set at the inlet temperature. Charging process started with connecting the bath (part #2 in Fig.2) to the test section and turning off the bath (part #3 in Fig.2). Charging process was done by controlling the valves and inlet temperature. Discharging process was done in the reversed order from charging process.

3. Results and Discussions

3.1 Local temperature variation and charging and discharging time in the storage tank

Typical temperature variations inside and at the surface of capsules, located along the centerline of the storage tank, are shown for n-Tetradecane in Fig.4 (charging process) and Fig.5 (discharging process). The inlet temperature was -4℃ and Reynolds number was 16. Temperature at the surface of the capsule was always lower than temperatures inside the capsule during charging process. The reason is that heat transfer occurred from the inside of the capsule to the coolant through the surface of the capsule. Center of the capsule showed relatively constant phase change temperature, but temperatures at different locations except the center of the capsule decreased during charging process since the heat removal amount was larger than the solidification energy. Grodzka[14] reported that temperature may decrease during phase change process by the larger heat removal amount than the solidification energy when the solidification process is slow and the temperature gradient gets larger as the purity of the material is lower.

Time to reach to the inlet temperature of -4℃ was 50min for the 1st story, 60min for the 4th story, 70min for the 7th story during charging process along the centerline of the storage tank. Time to reach to the inlet temperature of 10℃ was 80min for the 1st story,

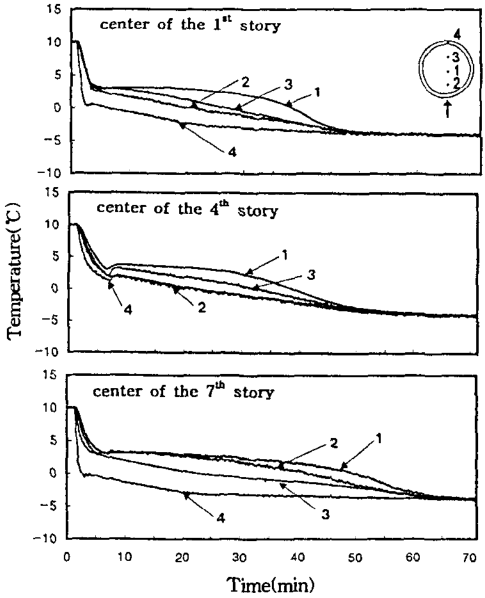

Fig.4 Temperature variations inside and at the surface of capsules with n-Tetradecane along the centerline of the tank during charging process(T_{fi}=-4℃, Re=16)

85min for the 4th and 7th stories during discharging process along the centerline of the storage tank.

Temperatures were measured at the center of the capsule in the middle and at the edge of the 1st and the 7th story in the storage tank in order to investigate the temperature variations in the axial and radial direction of the storage tank. The typical temperature variations at the center of the capsule with n-Tetradecane and working fluid temperature around the capsule are shown in Fig.6. The inlet temperature was -4℃ and the Reynolds number was 16. The temperature gradient in the liquid sensible heat section was larger than that in the solid sensible heat section. The reason is that the thermal diffusivity of liquid phase is larger by 26% than that of solid phase.

Charging or discharging time was defined as the time period from starting to ending of phase change when the temperature difference is within ±0.2℃. The charging time was 53min at the center and the edge of the 1st story and 70min at the center and the edge of the 7th story. The discharging time was 53min at the center of the 1st story, 39min at the edge of the 1st story, 64min at the center of the 7th story, and 51min at the edge of the 7th story. Charging and discharging processes were performed faster at the 1st story than at the 7th story and faster at the edge than at the center. The reason is that the local porosity at the center of the tank is smaller than that at the edge of the tank as shown by Benenati and Brosilow[6]. The difference between the 1st and the 7th story for charging time was larger than that for discharging time. The difference between the center and edge for charging time was

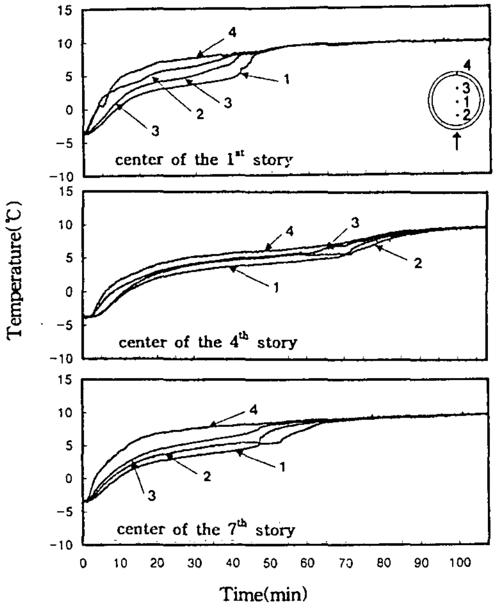

Fig.5 Temperature variations inside and at the surface of capsules with n-Tetradecane along the centerline of the tank during

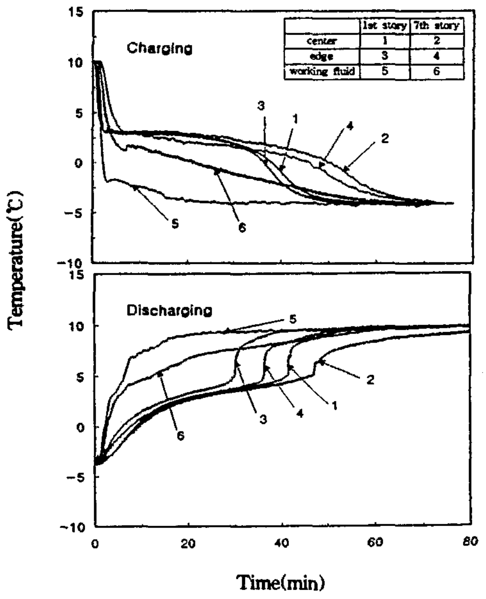

Fig.6 Temperature variations at the center of a capsule with n-Tetradecane and of working fluid around the capsule (T_{fi}=-4℃, Re=16)

larger than that for discharging time. The effects of the inlet temperature and the Reynolds number on charging and discharging time are shown in Fig.7 for the capsule filled with n-Tetradecane at the center of the 4th story of the tank. Charging and discharging times were decreased as the Reynolds number increased and the inlet temperature decreased. As the inlet temperature increased from -7 to -1℃, charging and discharging times were increased by 88% and 7% for the Reynolds number of 8 and by 53% and 11% for the Reynolds number of 16, respectively. The dotted line in Fig.7 shows the charging time subtracted by the supercooling time when the inlet temperature was -1℃. The supercooling time was 11min and 4min for Reynolds number of 8 and 16, respectively. The effect of the inlet temperature on the charging time was larger than that on the discharging time.

The effect of the storage materials on the charging and discharging time is shown in Fig.8. The difference between the inlet temperature and phase change temperature was approximately 8℃. The time was measured at the center of the capsule filled with n-Tetradecane in the middle of the 4th story. The supercooling time for capsule with water was 76min for the Reynolds number of 8. The dotted line shows the charging time subtracted by the supercooling time. The charging time for water was larger by 16~72% than that for paraffin mixture. The difference of discharging time with respect to storage materials was smaller than that of charging time.

3.2 Dimensionless thermal storage amount(Q^+)

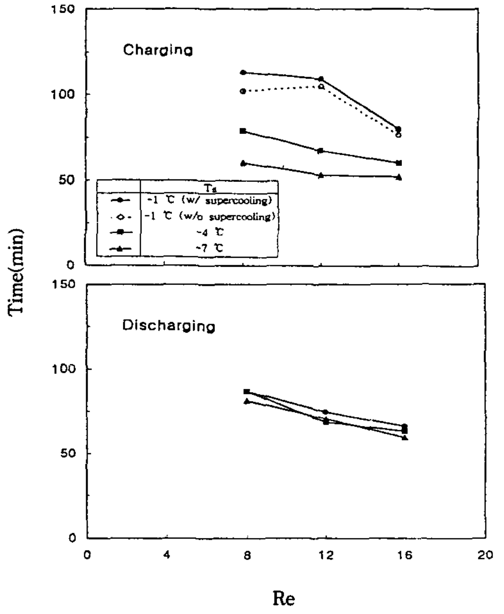

Fig.7 Charging and discharging time at a center of a capsule with n-Tetradecane at the center of the 4th story of the tank

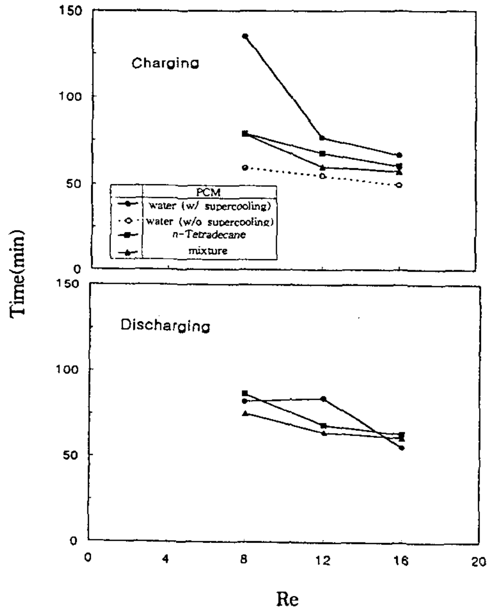

Fig.8 Charging and discharging time at a center of a capsule at the center of the 4th story of the tank w.r.t the thermal storage($T_m - T_{fi} \fallingdotseq 8$℃)

Total thermal storage amount in the storage tank can be obtained by :

$$Q_{tot}=\int_{0}^{t_1} q\,dt+\int_{t_1}^{t_2} q\,dt+\cdots+\int_{t_{n-1}}^{t_n} q\,dt \qquad (1)$$

Since the total thermal storage amount changes with respect to storage materials and experimental parameters, dimensionless thermal storage amount defined by equation (2) is used to investigate the effect of materials and parameters.

$$Q^{+}=\frac{\int_{0}^{t} q\,dt}{Q_{tot}} \qquad (2)$$

The effects of the inlet temperature and Reynolds number on the dimensionless thermal storage amount are shown in Fig.9 for n-Tetradecane. The time to reach to the dimensionless thermal storage amount of 1 was smaller by 47% for the inlet temperature of -7℃ than for the inlet temperature of -1℃ during charging process, but there is little difference in the time with respect to the change of inlet temperature during discharging process. The time to reach to the dimensionless thermal storage amount of 1 when the Reynolds number is 16 was shorter by 30% than that when the Reynolds number is 8 during charging and discharging processes.

The effect of storage materials on the dimensionless thermal storage amount is shown in Fig.10 where the difference between the inlet temperature and the phase change temperature was approximately 8℃ and the Reynolds number was 16. The time to reach to the dimensionless thermal storage amount of 1 for water was longer by 50% than that for paraffins during charging process, but that was differed little during discharging process.

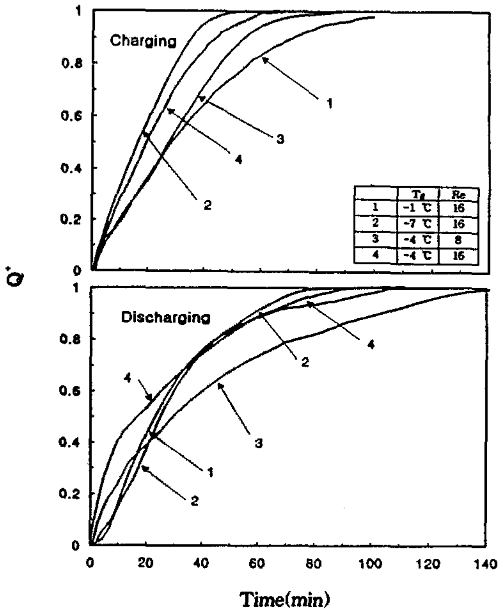

Fig.9 Dimensionless thermal storage amount for the capsules with n-Tetradecane in the tank w.r.t the experimental parameters

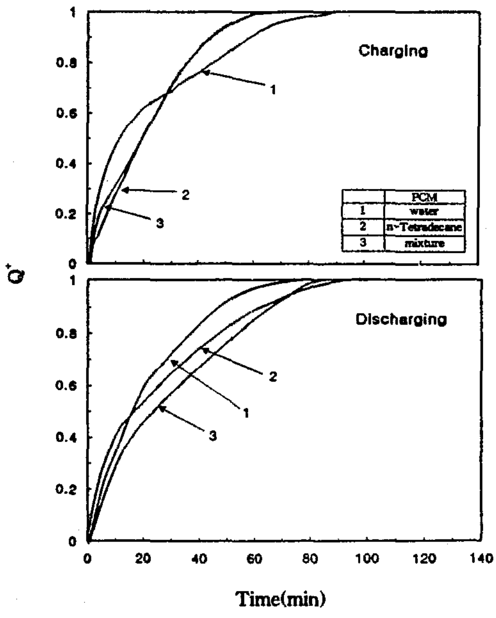

Fig.10 Dimensionless thermal storage amount for the capsules in the tank w.r.t. the thermal storage material(T_m-T_{fi}≒8℃, Re=16)

The rate of time variation of the dimensionless thermal storage amount for paraffin was faster during charging process and slower during discharging process than that for water.

3.3 Average heat transfer coefficient(h_o)

The local heat transfer coefficient between the capsule and working fluid is difficult to obtain since the temperature difference between the capsule and surrounding fluid was within ±0.15℃. Thus, the average heat transfer coefficients obtained by :

$$h_o = \frac{q}{nA \cdot \Delta T} \tag{3}$$

The ΔT in equation (3) is the temperature difference between the average surface temperature of capsules at the 1^{st} and 7^{th} story and the average working fluid temperature around capsules at the 1^{st} and 7^{th} story. The q in equation (3) was obtained by using the average temperature of working fluid around the capsules at the 1^{st} and 7^{th} story and inlet flow rate of working fluid.

Since the average heat transfer coefficients were changed with time during sensible heat period, the average heat transfer coefficients during phase change period are used for comparison. The effects of inlet temperature and Reynolds number on the average heat transfer coefficients are shown in Fig.11 for n-Tetradecane. The average heat transfer coefficients increased by 10~25% during charging process and by 60~220% during discharging process, when the inlet temperature was decreased from -1 to -7℃. The average heat transfer coefficients were increased by 30% during charging process and by 70~250% during discharging process, when the Reynolds number was increased from 8 to 16. The effects of inlet temperature and Reynolds number were larger during discharging process than during charging process since the surface temperature of the capsule was higher than the inside temperature of the capsule and it caused natural convection effect during discharging process.

The effect of storage materials on the average heat transfer coefficients is shown in Fig.12 where the difference between the inlet temperature and the phase change temperature is approximately 8℃. The average heat transfer coefficients were larger in the order of n-Tetradecane, mixture and water during charging process and in the order of mixture, n-Tetradecane and water during discharging process. The average heat transfer coefficients for n-Tetradecane were smaller than those for water exceptionally, when the Reynolds number is 8.

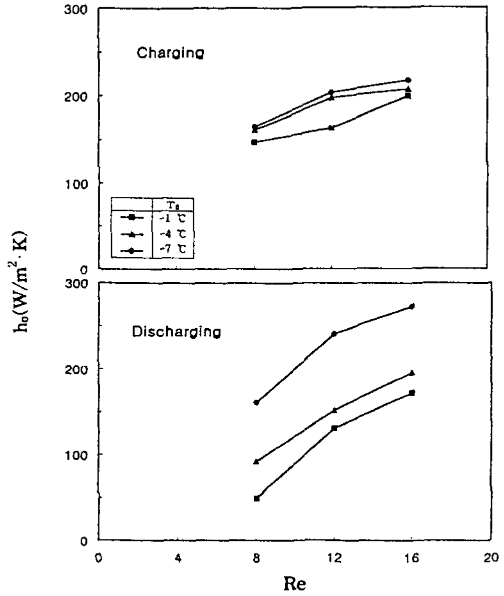

Fig.11 Average heat transfer coefficients for the capsules with n-Tetradecane

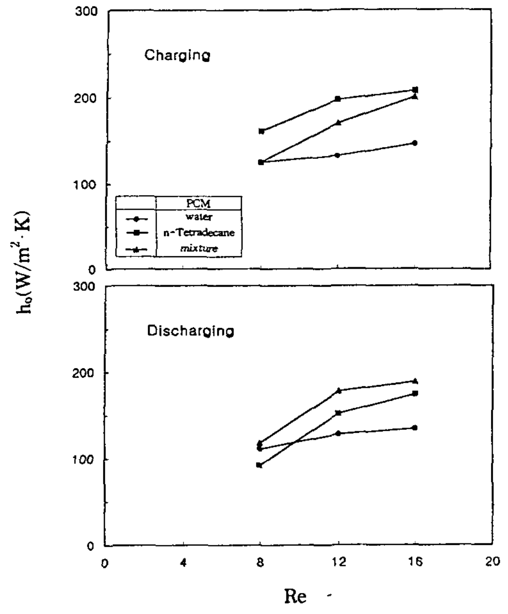

Fig.12 Average heat transfer coefficients for the capsules w.r.t the thermal storage material(T_m-T_{fi}≒8℃)

4. Conclusions and Summary

1) Local temperatures inside the capsule were not constant due to the difference between heat removal amount and solidification energy.

2) Charging and discharging times at the edge of the storage tank were shorter than those at the center of the tank due to the different porosity at the center and edge of the tank.

3) Charging time for paraffins was shorter by 11~72% than that for water and discharging time showed little difference among storage materials. Water showed long supercooling time, but paraffins showed short supercooling time.

4) The effect of Reynolds number on the dimensionless thermal storage amount was smaller than that of inlet temperature during charging process and it was in the reverse order during discharging process.

5) The effects of inlet temperature and Reynolds number on the average heat transfer coefficient during discharging process were smaller than those during charging process due to the natural convection effect.

6) The average heat transfer coefficients were larger in the order of n-Tetradecane, mixture and water during charging process and they were larger in the order of mixture, n-Tetradecane and water during discharging process. The average heat transfer coefficients of paraffins were generally larger by 40% maximum than those of water during charging and discharging processes.

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