[논문] 태양에너지
Solar Energy
Vol.18. No.1, 1998

An Experimental Study on Minimization of Storage Tank for Solar Thermal Energy

Yoon S. Yang*, Chang W. Sohn, C. Lenotre*** K. Kanari******

* *Active Solar Thermal Energy Lab.,Korea Institute of Energy Research*
** *U.S. Army Construction Engineering Research Laboratories*
*** *CRISTOPIA Energy System, France*
**** *Electrotechnical Laboratory, Japan*

요 약

태양열이나 심야전력과 같이 에너지의 공급과 수요가 시차적으로 다를 경우 축열저장이 필수적이다. 축열조는 부하에 따라 그 부피가 커지게 되고 부피는 곧 경제성과 밀접한 관계를 갖고 있다. 따라서 이 연구는 축열조의 소형화에 관한 연구로 이번 실험에서 수행된 Nodule S-64(PCM-NaOH)인 구형 볼타잎을 사용하였고, 260Lit 용량의 축열조를 설계 제작하여 수학적 모델링과 실험을 병행하였다. 실험에 사용한 S-64는 이번 실험을 위해 제작한 것으로 축열결과 현열인 물의 경우보다 축열량이 두배로 증가하였다. 따라서 기존 축열조 부피를 절반정도 축소가 가능하며, 운전조건에 따라 더이상 줄일 수도 있어 태양열이나 심야전력용 축열조로 매우 적합함을 알 수 있었다.

Nomenclature

as = Surface area of Nodule-64[m^2]
Ac = Surface area of heat storage system [m^2]
As = Total surface area of ball in storage system[=N.as][m^2]
Cp = Specific heat [J/kg.k]
D = Diameter of Nodule 64 (m)
h = Heat transfer coefficient of Nodule-64 surface[(w/m^2 k]
l = Position coordinate along the axial direction of heat storage system = Heat flow rate through the cross section of heat storage system [kg/hr]
k = heat conductivity coefficient[w/mk]
L = Depth of heat storage system [m]
m = Flow rate of city water[g]
Mpcm,ball = Mass of phase change material in each ball[g/ball]
N = Total number of Nodule 64 in heat storage system
Nu = Nusselt number[hD/k]
Pr = Prandtl number[(μCp/k)]
Qcov = Energy flow rate by convection[kwh]
Qlat = Latent heat of material[kwh]
QL/ball = Latent heat of ball[J/ball]
Qs,sol,ball = Sensible heat of solid-state ball[J/ball oC]
Qs,loq,ball = Sensible heat of thermal conduction of liquid-state ball[J/ball oC]
Qs,H2o,tank = Thermal mass of water[J/tankoC]
ql = latent heat[cal/g]
qs,sol = sensible heat of solid-state[cal/g]
qs = sensible heate of liquid-state[cal/g]
q = Quantity of latent heat in limit volume [J/m^3]
Re = Reynolds number (ρUD/μ)
Tin = Inlet temperature of heat storage system
T = Water temperature in heat storage system [K]
Tbs = Surface temperature of Nodule 64 [K]
Vpcm,ball = Volume of phase change material in each ball[cc]
VHDPE = Total volume of HDPE[cc]
μ = Viscosity [Kg/m.sec]
ρ = Density [Kg/m3]

1. INTRODUCTION

The most common heat storage system is a hot water tank. It relies on the sensible heat of water. The favorable characteristics of water include high specific heat, environmental safety and relative economies as a storage medium. The water storage, however, has a number of shortfalls. The water storage cannot operate at a temperature above 100 deg C under normal pressure. The volume of water for heat storage is also a concern where the space is at premium such as under densely populated environment. A solution to the above problems is utilization of latent heat as the heat storage mechanism. The operational temperature can be raised depending on the phase change temperature of a storage medium. Latent heat is typically many folds larger than the sensible heat per unit mass of medium for a typical temperature range of storage operation. A compact heat storage device can be made utilizing the latent heat of storage material. An experimental latent heat storage system was assembled in the laboratory. Operational characteristic of the system was studied experimentally in this project.

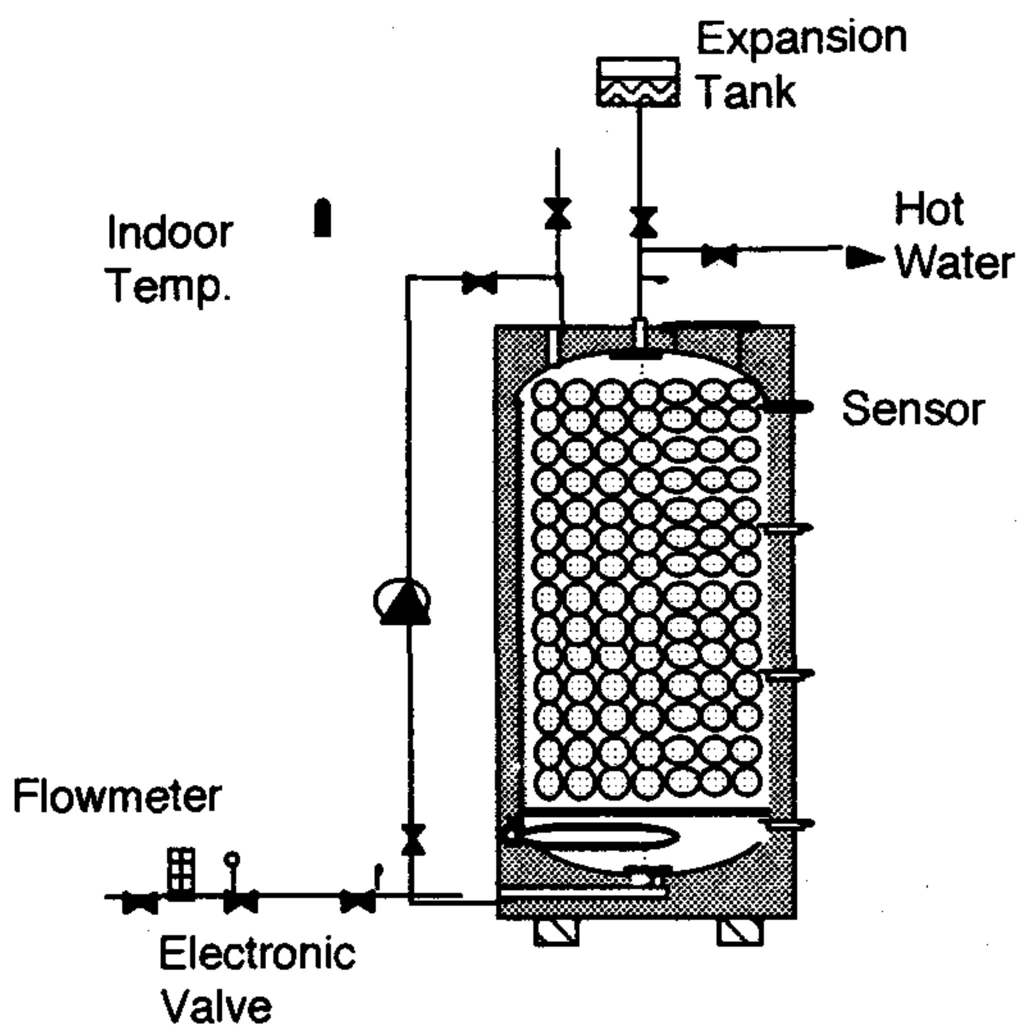

Fig. 1 Description of Storage Tank

2. EXPERIMENTAL FACILITY AND PROCEDURES

2.1 Test facilities

A schematic description of the storage tank is shown in Figure 1. The tank is a cylindrical vessel of storage capacity of 260 liter. The tank was filled with spherical storage balls. The major component of storage medium is sodium hydro-oxide (NaOH) which is encapsulated with the high density polyethylene covering. The characteristics of storage ball is given in Table 1.

Latent Heat	68(Kwh/m2 of tank
Sensible Heat,Solid	1.07(Kwh/oC)
Thermal conduction, liquid	1.07(Kwh/oC)
Thermal conduction, Crystalization	1.6(Kwh/oC)
Thermal conduction, fusion	2.2(Kwh/oC)
Volume of Nodule 64	avg 2550(balls/m2 of tank)
Diameter of Nodule 64	77.2mm
Thickness of capsule	2mm.avg

Table 1. Specification of Nodule S-64(Ref 4)

Temperatures inside the storage tank and along the distribution line were measured by T-type thermocouples. Flowrates during charge and discharge were measured by a turbine type flowmeter [Oval FLOW-ET-N X, model LS5277-20]. Charge and discharge periods were controlled by a timer. A data logger was employed to collect and record the temperatures, Flowrates, charge inputs and cycle periods.

2.2 One-Dimensional Modeling

An analysis of energy balance within the control volume of the storage tank was made to identify important parameters in system design and operation. A schematic description of the control volume is shown in Figure 2. As discussed in the later section, the discharge process is more critical than the charge process in system design and operation. During the discharge process as shown in Figure 2,

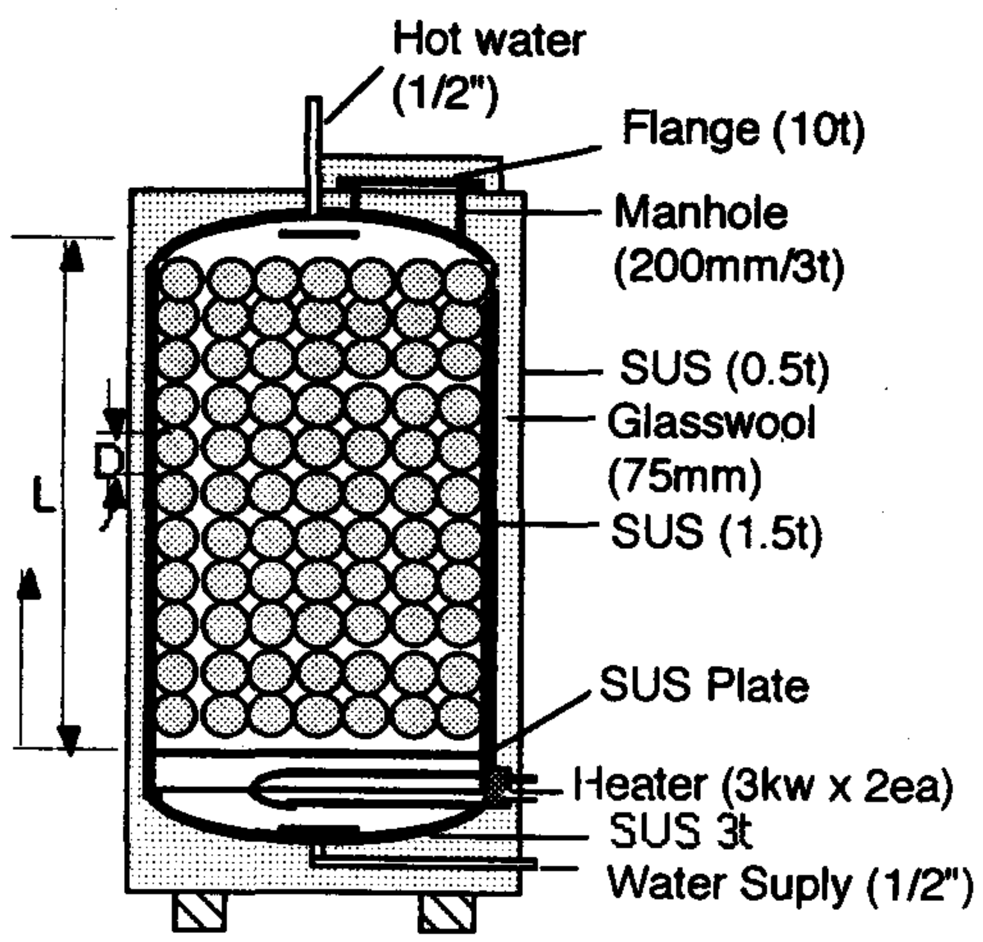

Fig. 2 Control Volume of Thermal storage Tank

Q_{conv} = discharge energy flow rate of latent heat material (Q_{lat}) (1)

$$Q_{conv} = \dot{m}C_p(T + \Delta T) - \dot{m}C_pT \text{ ---(2)}$$

$$Q_{lat} = (\tfrac{\Delta l}{L})A_s[T_{bs} - (T + \tfrac{\Delta T}{2})] \bullet h \text{ ---(3)}$$

We assumed that the latent heat of storage medium is dissipated through the surface of the storage balls, whose temperature remains constant at the phase change temperature of the storage medium.

The axial variation of temperatures inside the storage tank is given by,

$$\frac{dT}{dt} = \frac{A_s \bullet h}{L \bullet \dot{m}C_p}(T_{bs} - T) \text{ ---(4)}$$

After normalization with

$$T^* = \frac{T_{bs} - T}{T_{bs} - T_{in}}, and\ l^* = \frac{l}{L},$$

$$\frac{dT^*}{dl^*} - CT^* = 0 \text{ ---(5)}$$

$$C = \frac{A_s \bullet h}{\dot{m}C_p} \text{ ---(6)}$$

Note that the constant C is an important parameter in design and operation of a storage device. The implication of C is discussed more in detail later.

In a dimensional form, the axial temperature distribution is given by

$$T = T_{bs} - (T_{bs} - T_{in})$$
$$\exp[(-A_s \bullet h / \dot{m}C_p)(l / L) \text{ ---(7)}$$

Let's take a close look at the quantities comprising the constant C in Eq (6). The specific heat of water (Cp) is a fixed and relatively constant quantity. The heat transfer coefficient from the ball surface (h) is also relatively constant as shown in Eq (8).

$$N_{ud}(=hD/k)=2+(0.4\mathrm{Re}_d^{1/2}+0.06\mathrm{Re}_d^{2/3})\mathrm{Pr}^{0.4}(\mu_\infty/\mu_w)^{1/4}\quad---(8)$$

The heat transfer coefficient is a weak function of the flowrate through the Reynolds number in Eq (8), where Re is a function of flowrate ($\dot{m}$) through the tank. The Prandtl number and the viscosities are material properties of water, that is independent of system design and operation. The most critical parameters in EQ (6) are the effective heat transfer surface area (As) and the flowrate ($\dot{m}$). Note that the former is more related to the design and the latter is more related to the operating condition of a storage system. Note again that the flowrate is the only parameter affecting the performance of a heat storage system once the system is designed and built.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Heat Capacity of Experimental Apparatus

Thermal mass of each component of the experimental system has been calculated as following:

A. Heat Storage Ball

The number of balls charged inside the storage tank is 490. According to the characteristics of the Ball (in Table 1),

$$Q_{L/ball}=68/2550(kwH/ball)=26.67(WH/ball)=96{,}000J/ball(=22944.6cal/ball)$$

$$Q_{s,sol,ball}=1425.9J/ball^{o}C(=340.8cal/ball^{o}C)$$

$$Q_{s,lig,ball}=1510.6J/ball^{o}C(=361.0cal/ball^{o}C)$$

The volume of a Ball is

$$V_{pcm,ball}=\frac{4}{3}\pi\left(\frac{7.32}{2}\right)^3=205.4(cc)$$

With a specific gravity of 2.13, the mass of the phase change material in each ball is

$$m_{PCM,ball}=205.4\times2.13=437.5(g/ball)$$

Therefore,

$$q_l=52.4cal/gr$$
$$q_{s,sol}=0.87cal/gr$$
$$q_{s,liq}=0.83cal/gr$$

For all the 490 balls inside the tank, the total mass of phase change material is 214,375 gr. The total thermal mass is,

$$Q_{L,\tan k}=46{,}991{,}000J/\tan k=13.05Kwh/\tan k\quad---(9)$$

$$Q_{S,sol,\tan k}=698{,}862J/\tan k\ ^{o}C=0.194Kwh/\tan k\ ^{o}C\quad---(10)$$

$$Q_{s,liq,\tan k}=743{,}881J/\tan k\ ^{o}C=0.207Kwh/\tan k\ ^{o}C\quad---(11)$$

B. Water in the Storage Tank

The capacity of the storage tank is 260 liters. The total volume of the 490 balls is calculated to be 118 liters. Therefore, the amount of water in the tank is 142 liters. Considering the dead space in the tank not filled with the balls, the actual volume of water in close contact with the storage balls is estimated to be 100 liters. The thermal mass of water is,

$$Q_{S,H2O.\tan k} = 418{,}000 J/\tan k\ ^{o}C$$
$$= 0.116 Kwh/\tan k\ ^{o}C --- (12)$$

C. Shell of Heat Storage Balls

The heat storage material is enclosed in a ball of 7.72 Cm diameter and the wall thickness of 2mm. The wall is made of high density polyethylene (HDPE). With the specific heat (1600 J/Kg) and the specific gravity (0.95) of HDPE in the standard table, the thermal mass of the shell material is calculated to be 0.007 kWH/tank deg C.

$$V_{HDPE.\tan k} = 490 \times \frac{4}{3}\pi[(\frac{7.72}{2})^3 - (\frac{7.32}{2})^3$$
$$= 17.395(cc) --- (13)$$

D. Storage Tank and Piping Inside

The mass of the tank and the piping inside is measured to be about 50 Kg. With the specific of steel (0.465 J/g deg C), the thermal mass of the tank is calculated to be 0.006 kWH/tank deg C.

$$Q_{S,steel} = 0.006 Kwh/\tan k\ ^{o}C --- (14)$$

Based on the thermal mass of each component in (9)-(14), the latent heat of the storage material accounts for 96.1% of the total thermal mass of the storage system.

3.2 Data Analysis during Charge Process

The charging process is divided into three stages as following: (i) Heating up to melting temperature of the phase change storage material as observed by the linearly increasing temperature, (ii) Continuous heating during the melting of PCM as observed by a temperature plateau, and (iii) Continuous heating until the prescribed system temperature as observed by a resumption of linear rise of temperature.

Figures 3 and 4 show typical charging histories. The initial tank temperature for Figure 3 is 12 deg C, and that for Figure 4 is 17 deg c. It is noted that the Figure 3 and 4 collapses each other if the time axis of Figure 3 is shifted about 20 minutes. This confirms the charging process is repeating same thermal cycles. During the stage (i), the heat supplied to the system is stored as sensible heat raising the temperature of the storage system.

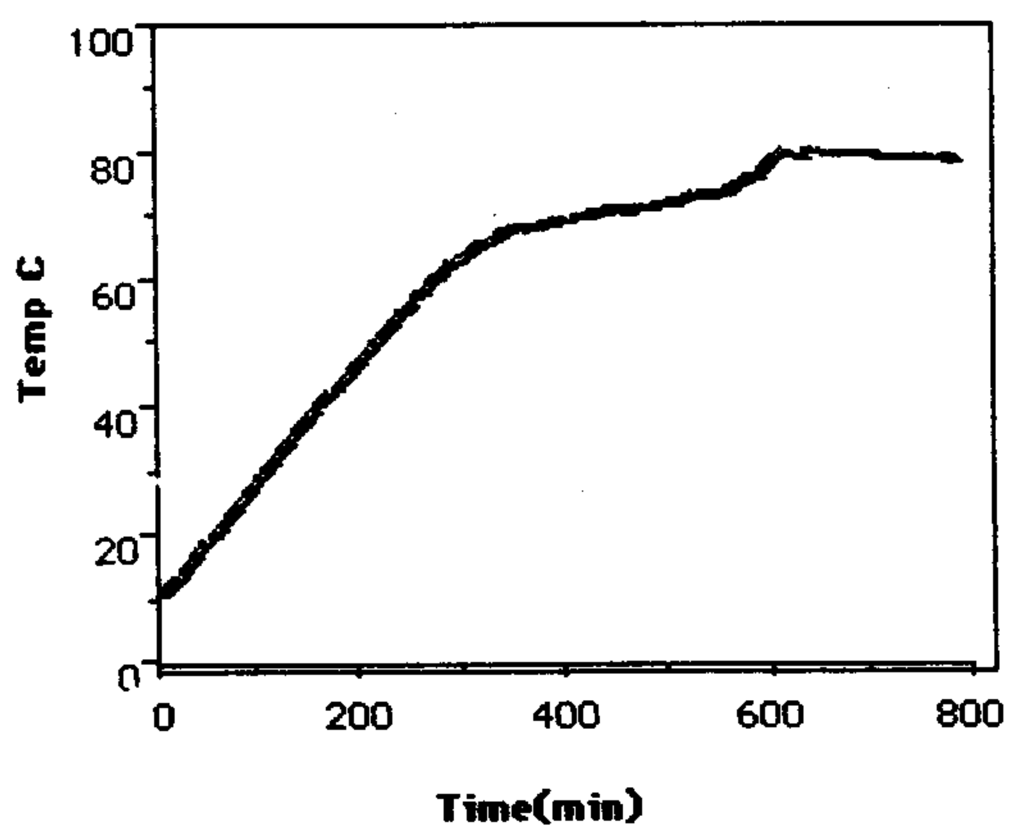

Fig. 3 Temperature variation in the thermal storage tank of thermal charge pro cess(the initial temperature in the Tank:12℃)

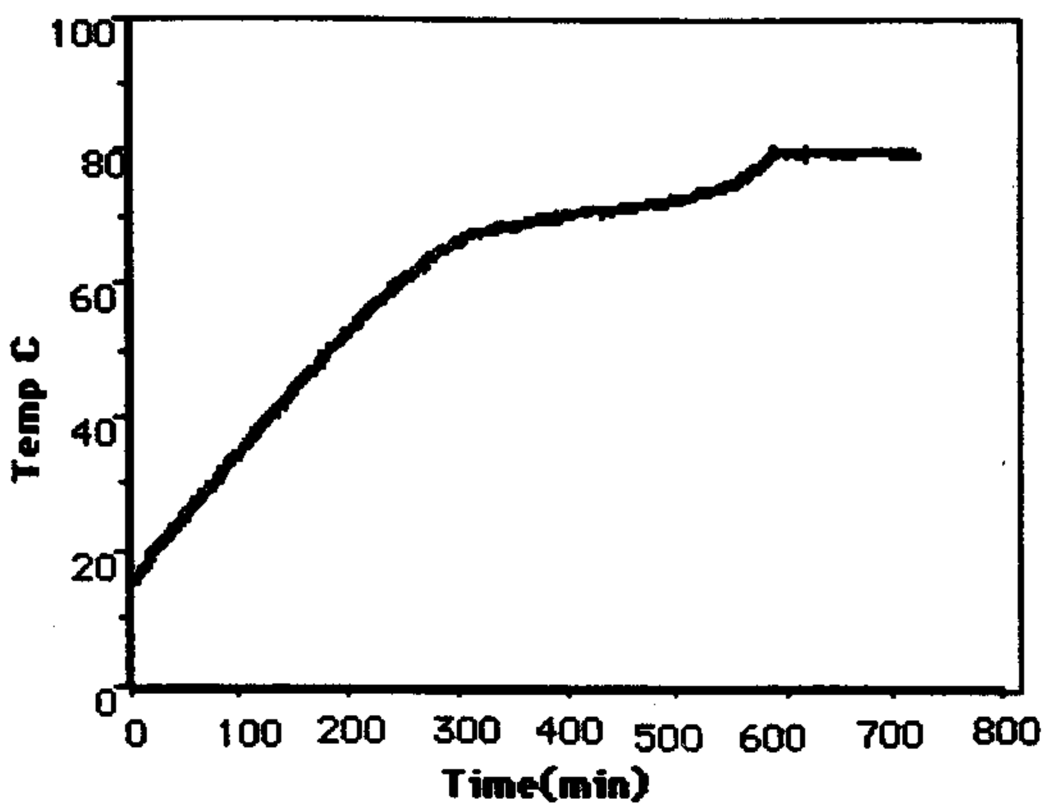

Fig. 4 Temperature variation in the thermal storage tank of thermal charge pro cess(the initial temperature in the Tank:17℃)

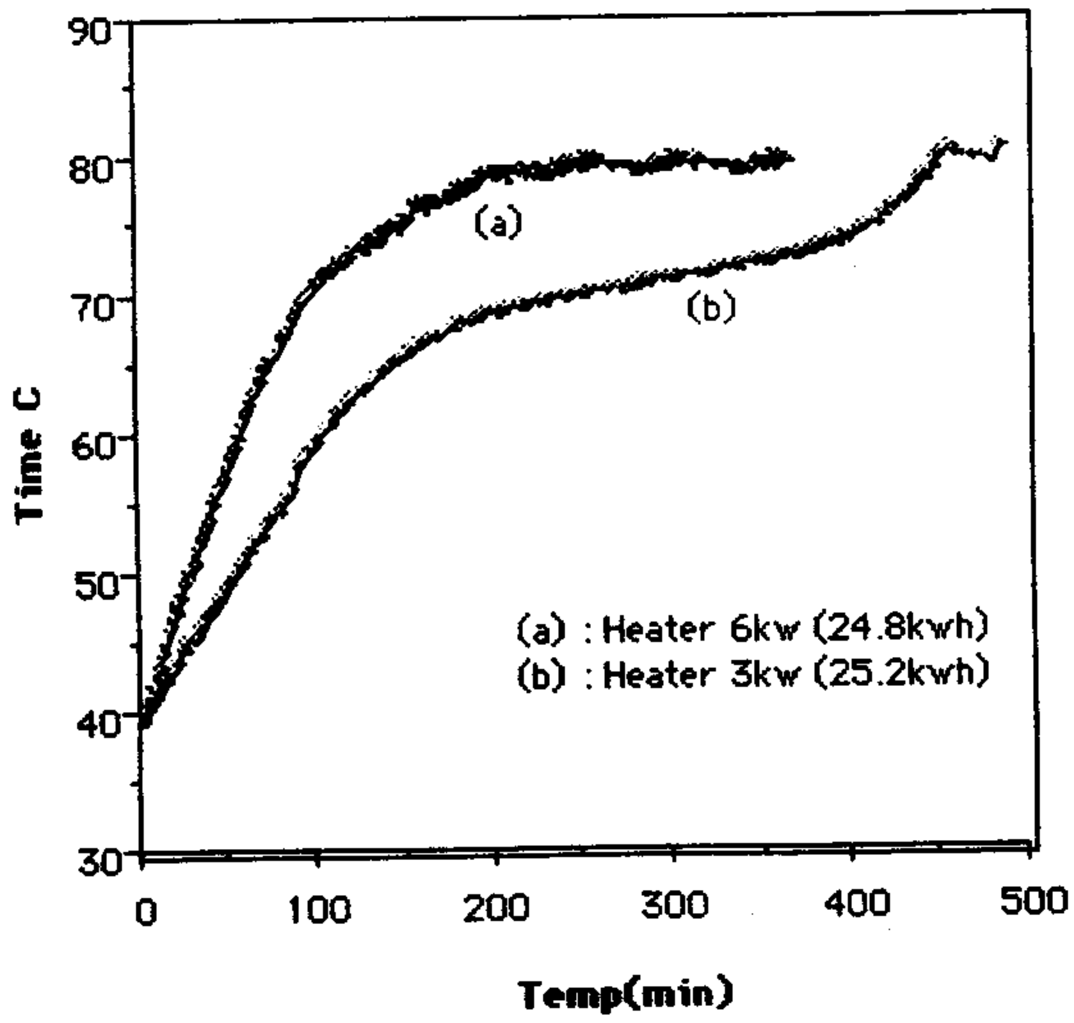

Fig. 5 Temperature variation in the storage of tank of the thermal charge process at various heater capacities

$$Q_{heater}\,\Delta t\,/(Mcp)\tan k\Delta T\;---(15)$$

(MCp)tank is given by a sum of (10) and (12)-(14), which is 0.32 kWH/tank deg C. The slope of (delta T/delta t) based on the measured heat input (3 kW) and the estimated thermal masses (10)-(14) is,

$$\Delta T\,/\,\Delta t = Q_{heater}\,/(Mcp)_{\tan k}$$
$$= 9.4(^{\circ}C\,/\,hr)\;---(16)$$

The linear slope during the stage (i) is calculated from the temperature data in Figure 3,

$$\Delta T\,/\,\Delta t = (50-12)\,/(200/60)$$
$$= 11.4^{\circ}C\;---(17)$$

A close agreement of (16) and (17), within 20%, is satisfactory, considering the errors in measurement of data as well as the estimate of thermal mass of each component in the storage system.

The stage (ii) is typified by the change of slope in the time history of temperature. Denoting (Qlat) be the total instantaneous heat transfer rate through the surface of the storage balls and (Qheater) be the charging rate of the heater, the temperature slope will be zero when Qlat>=Qheater. It's because the melting will continue at a fixed temperature of the melting point of the storage material. If Qheater>Qlat, the excess heat flux of the heater will be used for raising the sensible heat of the water as observed by a positive temperature slope. Figure 5 shows the effect of variation of Qheater. According to the experimental data, the melting point of the storage material is about 65 deg C. At a= higher rate of charging (6 kW), the storage temperature rose to the prescribed cutoff temperature of 80 deg C with little changes in the slope. The melting proceeded at close to the cutoff temperature. Even at a lower rate of charging (3kW), Qlat is observed to be less than Qheater. Charging at a higher temperature than the melting point (Qheater>=Qlat) may be dictated by design consideration (depending on the available charging window). The effect of charging rates on the thermal efficiency is considered to be minimal as long as the tank is adequately insulated. However, the imbalance in heat transfer rates during the discharge process would cause a serious concern in actual operation as discussed in the following section.

3.3 Data Analysis during the Discharge Process

Figures 6 and 7 show discharge characteristics of the test system. The importance of the discharge rate from the storage balls to the hot water flow (energy recovery) is shown in the data. >From the fully charged state (at 80 deg C), warm water is recovered from the storage tank while the tank is replenished with tap water at 15 deg C at the same flowrate. In Figure 6, after 20 minutes of discharge, the water temperature in the mid-section of the tank drops to 30 deg C. It is not because the storage tank is fully drained of its stored energy but due to the limited heat transfer rate of the latent heat stored inside the balls transferring through the surface of the balls. While the discharge process is stopped after the first 20 minutes of discharge, in Figure 6, a rapid rise of water temperature in the tank indicates plenty of stored heat still left in the balls.

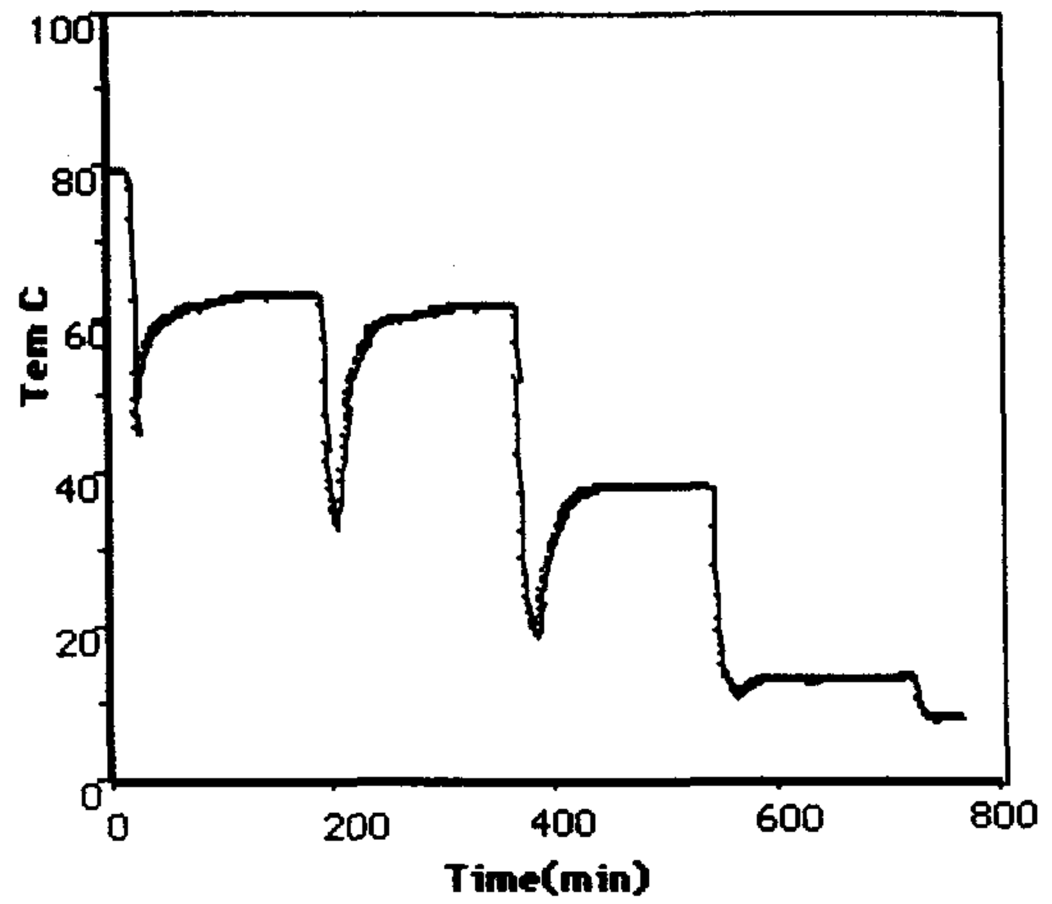

Fig. 6 Temperature variation storage tank of the thermal discharge process at an interval of 160 min

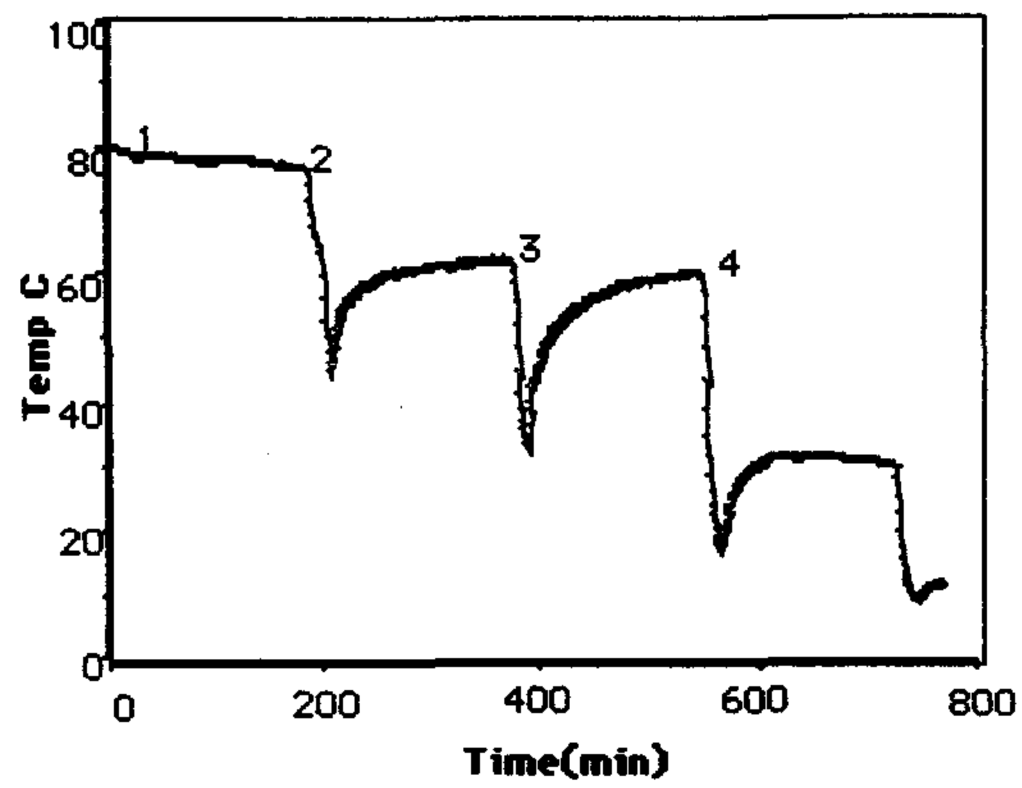

Fig. 8 Temperature variation in process of the thermal discharge on the top of storage tank

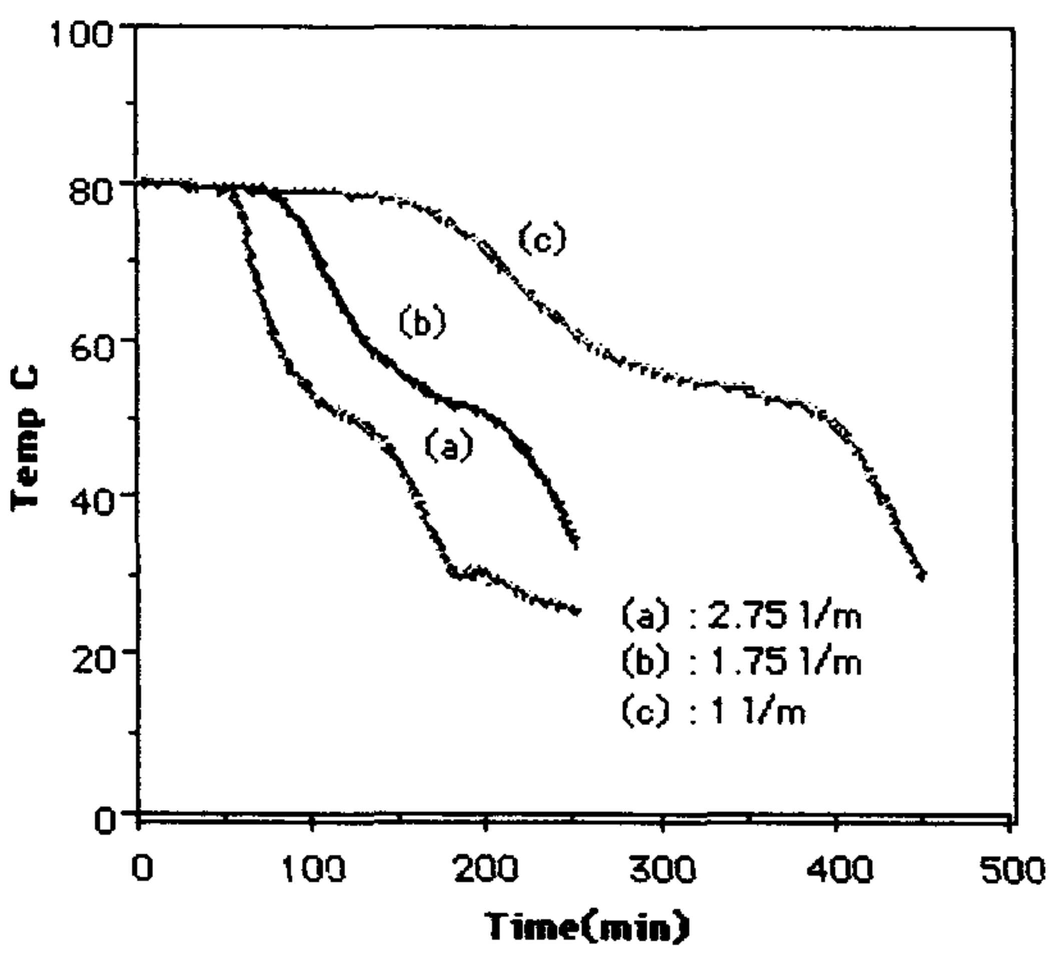

Fig. 7 Temperature variation in the storage tank of the thermal discharge process at various flow rate

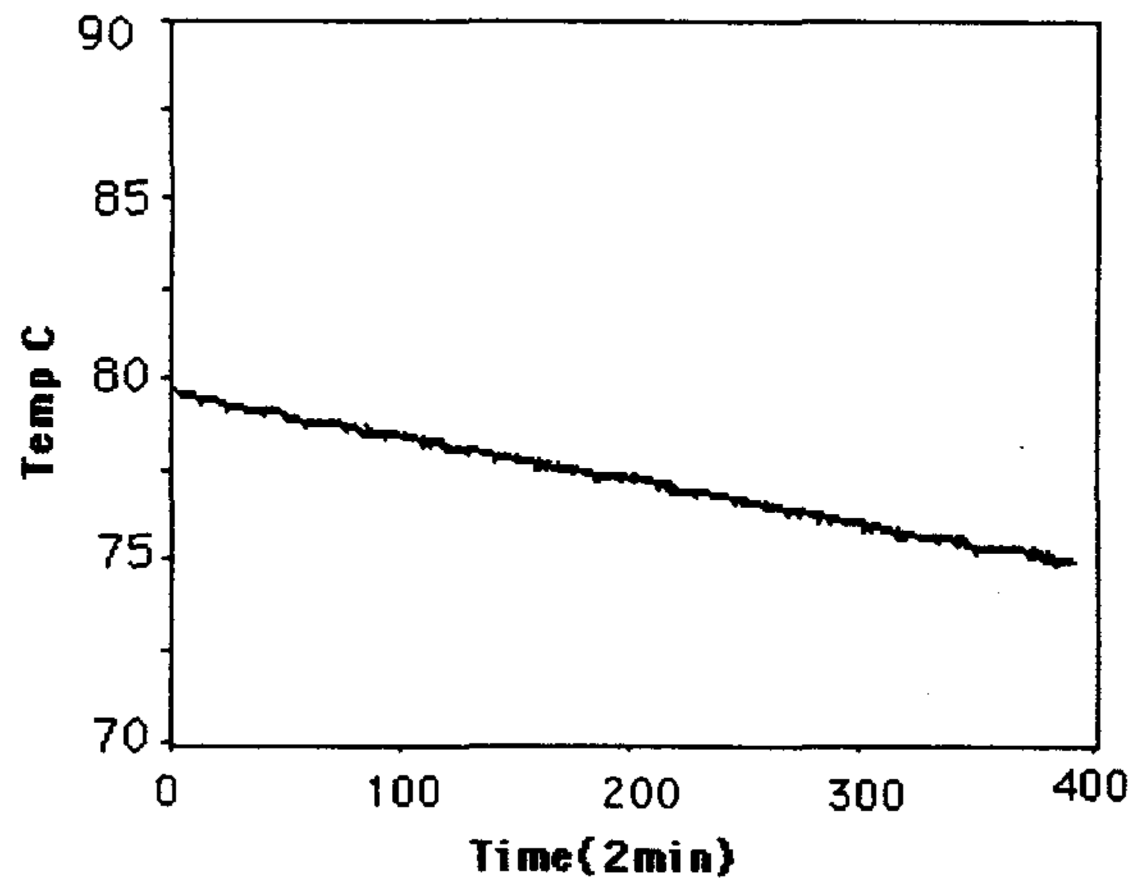

Fig. 9 Temperature variation of the insulation effect of the thermal storage tank

The impact of the discharge flow rates on the outlet water temperatures is shown in Figure 7. It should be noted that the discharge rate (As*h) must match the maximum expected discharge requirement. If the discharge rate falls short, a typical example of potential failures would be a sudden drop of water temperature in the middle of shower or laundry. Figure 8 shows the variation of temperatures at the top section of the tank during the discharge process. Figure 9 shows the insulation performance of the test storage tank. The tank was fully charged and left idle for a period of 8 hours. The temperature drop inside the tank during the idling period is

4.6 deg C, which exceeds the insulation performance requirements of electrical water heaters. The minimum performance requirements for the electrical water heaters are less than a 10 deg C drop in 13 hours for a storage capacity of 400 liters, less than 9 deg C for 900 liters and less than 8 deg C for a 2700 liters.

4. SUMMARY AND CONCLUSION

An experimental heat storage system with phase change material has been studied for the development of minimized storage tank. A factor of two increment in the storage capacity has been realized in the prototype system. Based on a simple one-dimensional model, a dimensionless group has been identified as an important parameter in design and operation of a PCM based heat storage system. The group is expressed as (As*h)/(m-dot*Cp). Note that the heat transfer coefficient and the specific heat of water are rather to be viewed as constant. The effective surface area and the discharge flowrate, however, are viewed as design factor (of PCM vessel) and system operation condition, respectively. Increment of As will be desired to increase the discharge rate of a system. A proper selection of maximum discharge flowrate is necessary to provide a satisfactory discharge performance.

The experimental data confirms the importance of the dimensionless group identified above. With a limited heat transfer rate from the storage medium to the discharge water stream, a premature drop in the discharge temperature is observed. A practical concern is a failure of delivery of required rate of hot water at a prescribed temperature. Based on the experimental study, the following conclusions are made: (i) The effective heat transfer area of the phase change material and the discharge flowrate are the most important factors in PCM storage design and operation, respectively. (ii) The discharge flowrates are dictated by the requirements of the user. Therefore, increment of the heat transfer area should be the target for the improvement of system performance. (iii) The increase in the heat transfer area could be accomplished by improvement in the packaging of the phase change material. For example, a sphere provides the least surface area for a given volume. A configuration other than a sphere would increase the surface area of PCM material of a given volume.

References

1. Heat Transfer, J. P.Hold Man
2. ASHRAE, Cool Thermal Strage Design Guide, 1993.

3. whitaker S. "Forted Convection Heat Transfer Correlations for Flow in Pipes, Past Flat plates, Single Cylinders, Single Spheres and Flow in Packed Bids and Bundles, " AICHE J . vol. 18, pp361, 1992.
4. Robert , L."RE:S 64/Cristopia Thermal Energy StorageNodulePCM 6 4℃." Personal Correspondence to C. Sohn, Aug. 3V 1995.
5. ASHRAE, 1984 System Handbook, chapter 34 Service water Heating, 1984.
6. Masuda, T. Semiar "TEC and AMTEC Activites at the Electrotechnical Laboratory in Japan, " presented to the Korea Institutes of Energy Reseach . Dec. 12. 1995.

An Experimental Study on Minimization of Storage Tank for Solar Thermal Energy

Yoon S. Yang*, Chang W. Sohn, C. Lenotre*** K. Kanari******

* *Active Solar Thermal Energy Lab.,Korea Institute of Energy Research*

** *U.S. Army Construction Engineering Research Laboratories*

*** *CRISTOPIA Energy System, France*

**** *Electrotechnical Laboratory, Japan*