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# 열성층 온수저장시스템의 효율적 이용에 관한 실험적 연구

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# Experimental Study on the Effective Use of Thermally Stratified Hot Water Storage System

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## 요 약

현열저장에서 열성층의 이점을 태양열 주택에 적용해보았다. 성층으로 인하여 에너지 입력의 열이용 효율이 증가되는 효과가 논의되었고, 실험과 시뮤레이션을 통하여 설명되었다. 성층을 촉진시키기 위하여 Distributor를 사용하였으며, 본 실험에서 Q=8 liter/min, △T=40℃일 때, 최대 90%의 열이용 효율을 얻을 수 있었다. 한편 성층을 촉진시키기 위하여 Distributor의 적은 구멍에서 나오는 유동(속도와 압력)이 같게 제작할 수만 있다면 그 이상의 열이용효율도 얻을 수 있음이 입증되었다.

## ABSTRACT

The benefits of thermal stratification in sensible heat storage were investigated for residential solar applications. The effect of increased thermal useful efficiency of hot water stored in an actual storage tank due to stratification has been discussed and illustrated through experimental data and computer simulation, which were taken by changing dynamic and geometric parameters. When the flow rate was 8 liter/min and △T was 40℃, the useful efficiency($\eta_u$) was about 90% in case of using a distributor, but not using a distributor the useful efficiency($\eta_u$) was about 82%. So these kinds of distributor would be recommendable for a hot water storage system and residential solar energy application to increase useful efficiency($\eta_u$). In the case of the uniform circular distributor, when the flow rate was 8 liter/min partial mixing was decreased and a stable stratification was obtained. Furthermore, if the distrbutor was manufactured so that the flow is to be the same from all perforations in order to enhance stratification, it might be predicted that further stable stratification and higher useful efficiency($\eta_u$) are obtainable.

**KEY WORLDS :** Thermal stratification, Distributor, Perforation, Useful efficiency

## INTRODUCTION

Solar energy system which employ sensible heat storage may benefit in two ways if the collected energy is not degraded by mixing during storage. First, the effectiveness with which the energy can be used will be improved if it is supplied to the load at the temperature at which it was collected rather than at a lower mixed-storage temperature, Second, the amount of energy collected may be increased if the collector inlet fluid temperature is lower than the mixed-storage temperature. The absolute and relative importnace of these effects depends on the details of the solar system design and application.

The advantages of stratification were qualitatively illustrated in the results presented by Brumleve(1) of calculations comparing stratified and mixed storage under conditions of fixed return temperatures from the load and from the collector. A quantitative comparison is reported by Duffie and Beckman(2), who simulated the operation of a solar water heating system over a one week period. They found a 9% increase in the fraction of the total load carried by solar when a three-segment stratified storage tank was substituted for mixed storage. Although this increase is certainly significant, the single-point comparison provides no information on the sensitivity to design variables of the advantage of stratification. The problem of thermal stratification in solar energy storage systems has been considered by several investigators(3)-(11). For example, Davis and Barera(12) observed from experiments that improvement in the performance of solar water heating systems due to stratification is of the order of 10 percent. Sharp and Loehrke(13) conducted detailed investigations of the system performance when stratified water storage is employed. Pak and Chio(14) conducted an experiment involving flow anaysis of buoyant jets into a storage tank through variable nozzles and Pak, Hwang and Cho(15) also conducted an experimental study of the thermal storage efficiency through variable porous manifolds in a test storage tank. Recently, Pak conducted the experiments on thermally stratified hot water storage and exctraction, and a simulation for the stratified thermal storage system(16)-(18). The effect of an increased energy input rate due to stratification has been discussed and illustrated experimentally.

The major objectives of the study were to decide the optimum design condition of dynamic factors and geometric factors by measuring temperature for the vertical temperature profile and pressure distribution in the outlet of a distributor.

## EXPERIMENTS

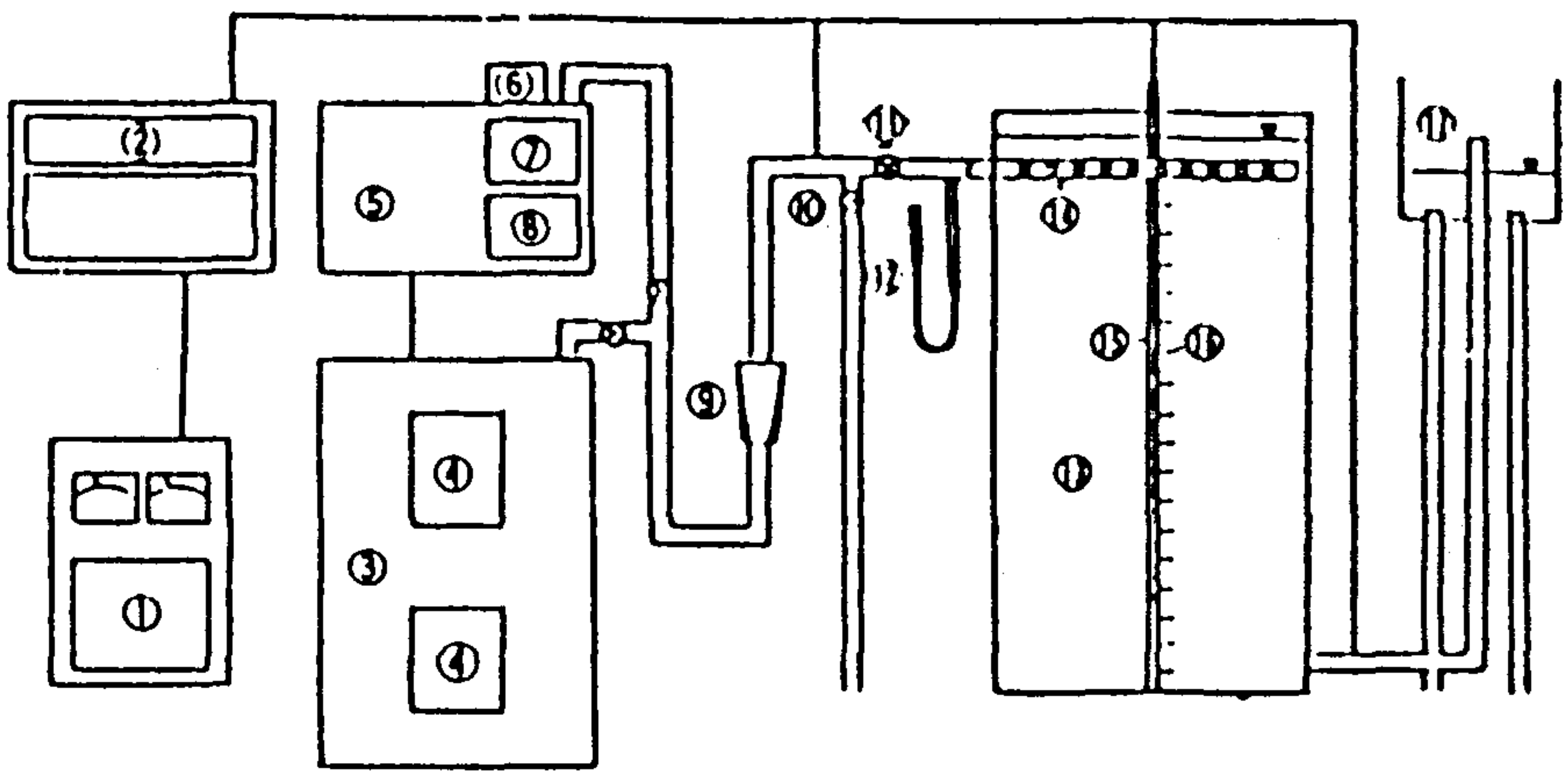
The experimental apparatus consisted of a charging loop, an experimental tank, interchangeable inlets and distributor, and an outlet kept stationary at the bottom of the tank, A data gathering system was involved in the apparatus. A schematic diagram of the experimental apparatus is shown in Fig. 1.

### Experimental Tank and Distributor

The experimental tank is cylinderical, 1680 mm tall and 516mm in diameter(H/D=3 in this case). The tank, containing 350 liters of water, is made of transparent fiberglass in order to enable picture taking and is insulated with 100 mm of batt insulator. Tank inlet(including distributor) and outlet position are also shown Fig. 1. The inlets were constructed of 20mm thickness and screwed into the inlet port. The distributor perforated with the same diameter holes was also constructed of the same material and diameter as the inlet tubes and the total area of perforation to cross section area of the distributor was 2($\alpha = A_b/A_L = 2$).

### Data Gathering System

The data gathering system consisted of temperature sensor of thermocouple probe, flow sensor of flow meter, a manometer recording. The inlet temperature, outlet temperature and vertical temperature profile were measured using T-type thermocouples. The vertical temperature profile was taken with 26 probes for the case of H/D=3 in a 10mm diameter polycarbonate tube located along the centerline of the tank. It was assumed that the vertical temperature profile was one dimensional. The accuracy of



1. Automatic Voltage Regulator
2. Hybrid Recorder
3. Hot Water Supply Davice
4. Temp. Controller and Heater
5. High-Temp Bath
7. Pump Speed Controller
8. Temp Controller
9. Flowmeter
10. Bypass Valve
11. Main Valve.
13. Testing Tank
14. Distributor
15. Acril Bar
16. Thermocouple Probe
17.Exit Port

Fig. 1 Schematic diagram of experimental apparatus the temperature measurement was ±0.05℃. The flow measurements were made using a Rotameter with an accuracy of 0.5% of measurement. The pressure measurements at the inlets were made using a manometer with Carbon-tetrochioride($CCl_4$).

## Experimental Procedure

The experimental procedure performed were described in Ref. 16 & 17 in details. In order to decide the optimum condition, inflow rate(Q) and temperature difference between the inflow water into the tank and the water which existed in the tank(△T) were defined as the range of parameters. These ranges were respectively, 8 liter/min to 12 liter/min(Q=8, 10, 12 liter/min) and 25℃ to 40℃(△T=25, 30, 40℃).

The above experiments were conducted in two cases with city supply water and without city supply water, The ratio of height to diameter of the storage tank(H/D) was fixed to 3 in accordance with the past studies.

## COMPUTER SIMULATION

There are a number of system parameters which must be set before a sumulation can be made, and each of these may influence the relative advantage of stratified over mixed thermal storage. A major portion of this study was devoted to an assessment of the influence of these parameters. In order to accomplish this task without an excessive expenditure of computer time, simplified systems and models were used. Schematic diagrams of the three basic solar systems studied are shown in Fig. 2.

The coupled set of algebraic and ordinary differential equations describing the temperatures at various locations in any one of these systems was solved numerically on a digital computer. This initial value problem was solved using an explicit marching procedure in time.

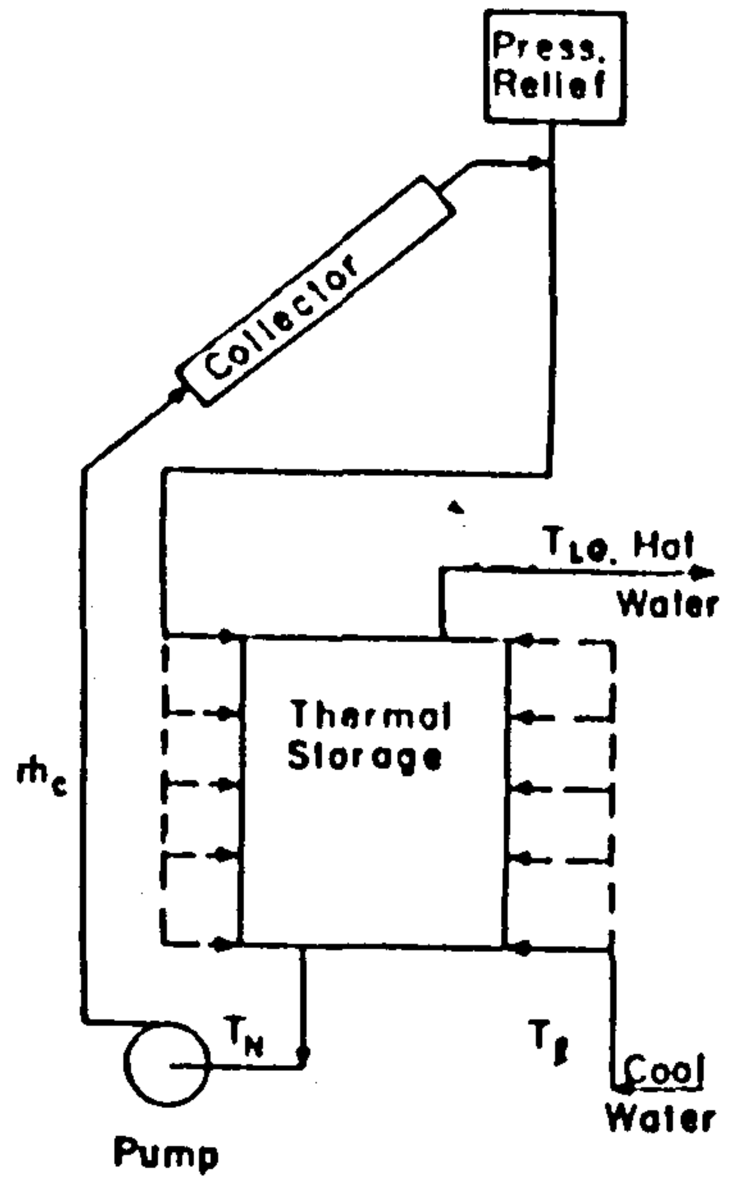


Fig. 2 System schematics

Hourly measured insolation and air tempararture data in January, April, July and October, 1988 in Seoul. The predictions of the models for the stratified tank have been compared with the results of experiments and described in Ref. 18.

## RESULTS AND DISCUSSION

The results of the experimental study on solar energy application show that improved performance of the application will be realized if stratification can be maintained in the storage tank. The results taken by computer simulation coincided well with the results through the experimental study.

1. In case without a city supply water to storage tank, using a distributor was better than using inlet port to increse the useful efficiency ($\eta_u$) (see Fig. 3 & 4). When the flow rate was 8 liter/min and $\Delta$T was 40℃, in case of using a distributor the useful efficiency($\eta_u$) was about 88% but not using a distributor the useful efficiency($\eta_u$) was about 86%, On the other hand, when the flow rate was 12 liter/min and $\Delta$T was 25℃, in case of using a distributor the useful efficiency($\eta_u$) was about 87% but not using a distributor the useful efficiency($\eta_u$) was about 82% (see Fig. 7 & 9). The useful efficiency($\eta_u$) was defined as follows :

$$\eta_u = \frac{T_{L,o} - T_s}{T_{c,i} - T_s}$$

2. During the heat storage, when the flow rate was lower and the temperature difference was larger, the momentum exchange decreased. Especially, when the flow rate was 8 liter/min and the temperature difference was 40℃, the momentum exchange was minimized. Therefore, a stable stratification was obtained(see Fig. 3 & 6).

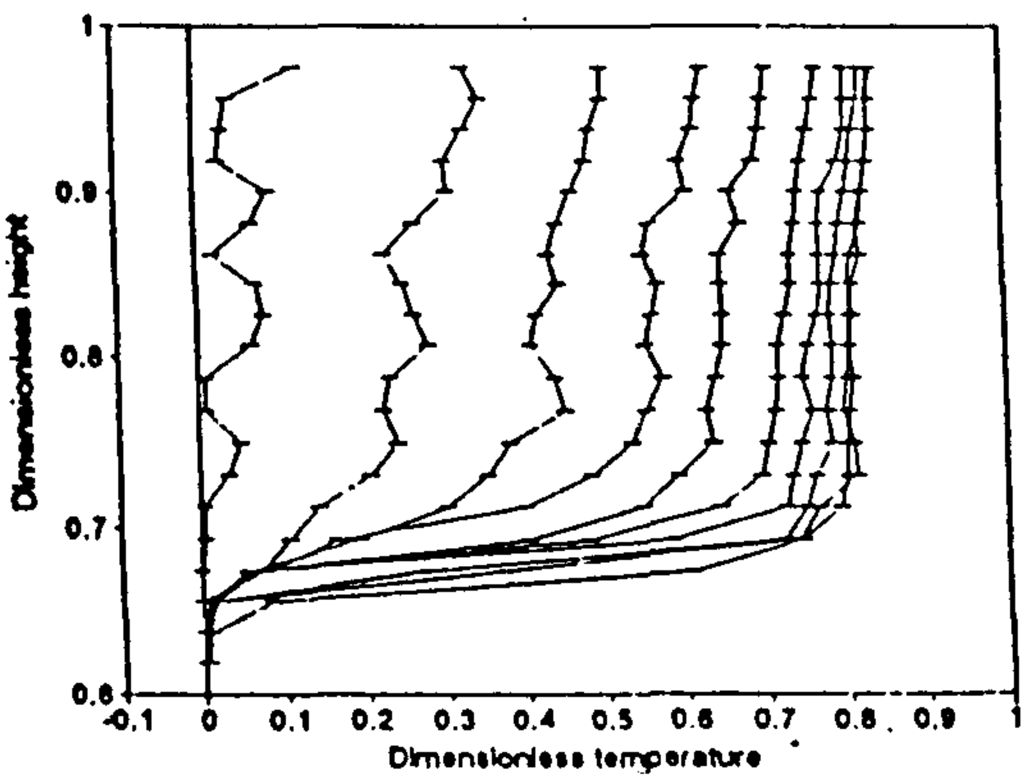



Fig. 3 Temperature profile in test tank(without Dietributor) (Q=12LPM, $\Delta$T−25℃, without city water supply)

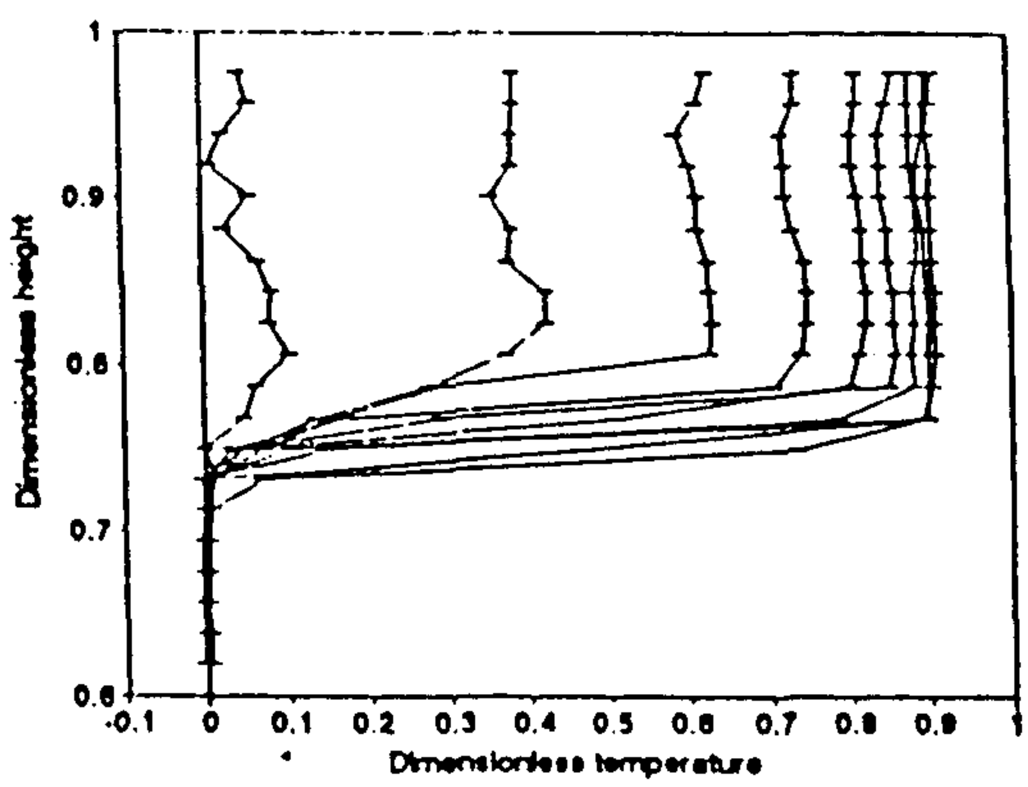



Fig. 5 Temperature profile in test tank(without Dietributor) (Q=12LPM, $\Delta$T−25℃, without city water supply)

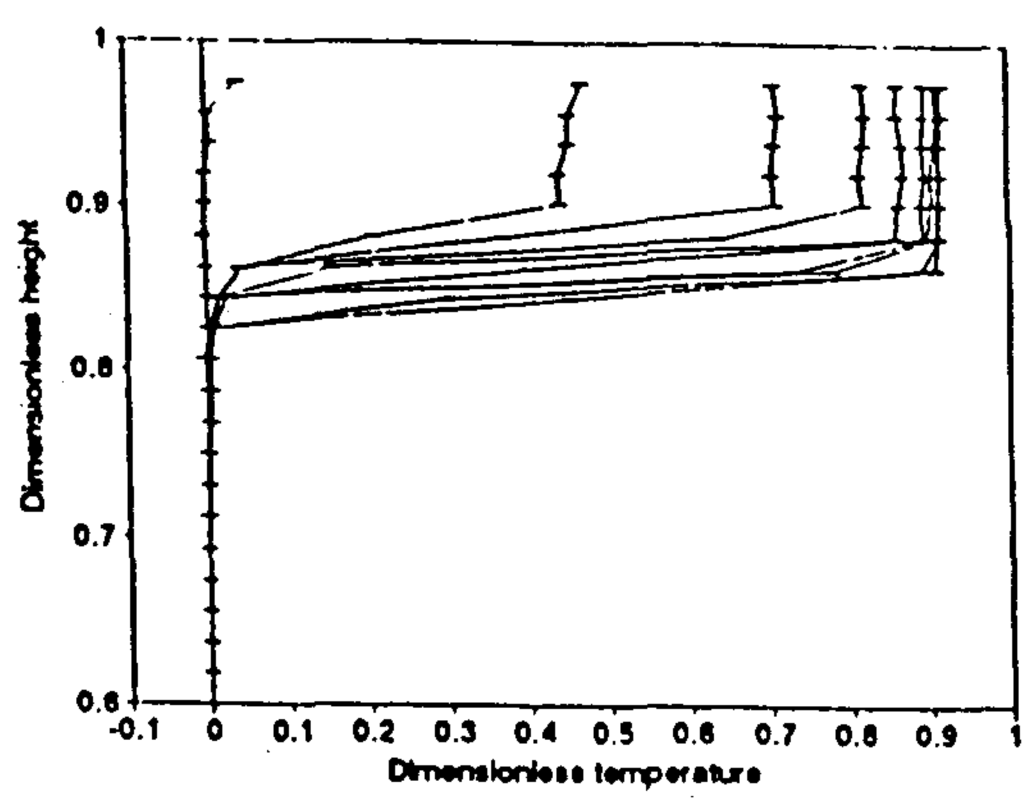



Fig. 4 Temperature profile in test tank(without Dietributor) (Q=8LPM, $\Delta$T−40℃, without city water supply)

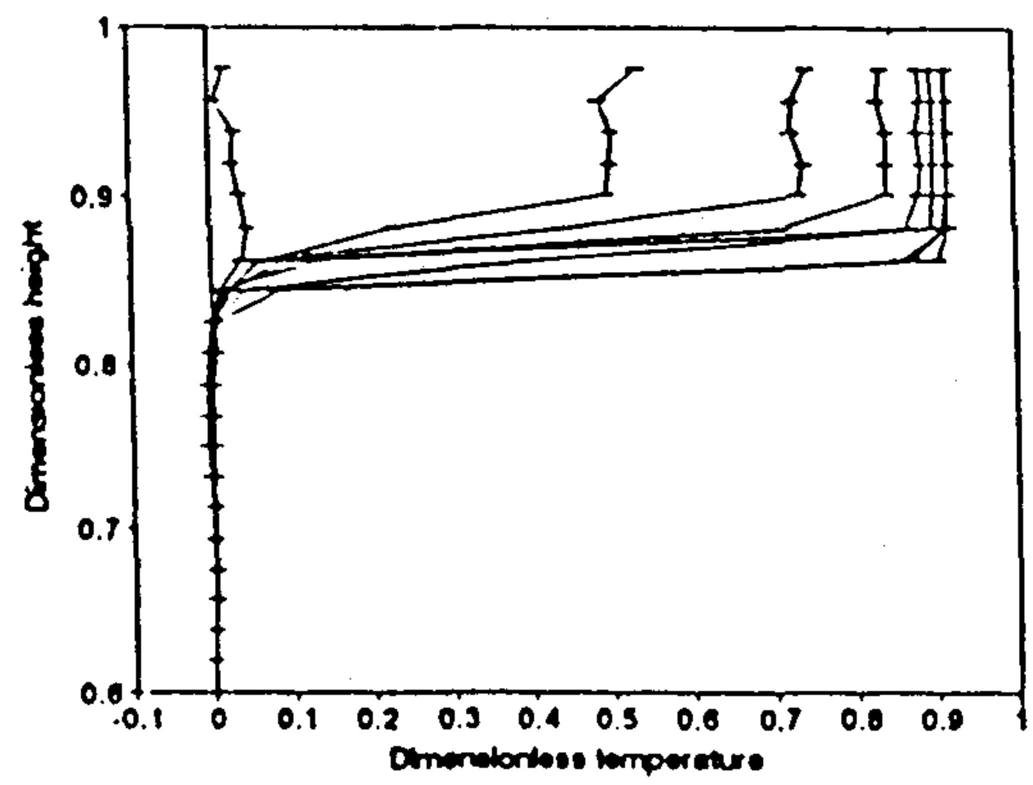



Fig. 6 Temperature profile in test tank(without Dietributor) (Q=8LPM, $\Delta$T−40℃, without city water supply)

3. In the case of the flow from city supply water or load to collector, temperature distribution of storage tank was not effective to temperature profile in the tank. Especially, in the case of low flow the natural convection would be helpful in maximizing the useful efficiency($\eta_u$) and keeping a stable thermal stratification too(see Fig. 5 & 6).

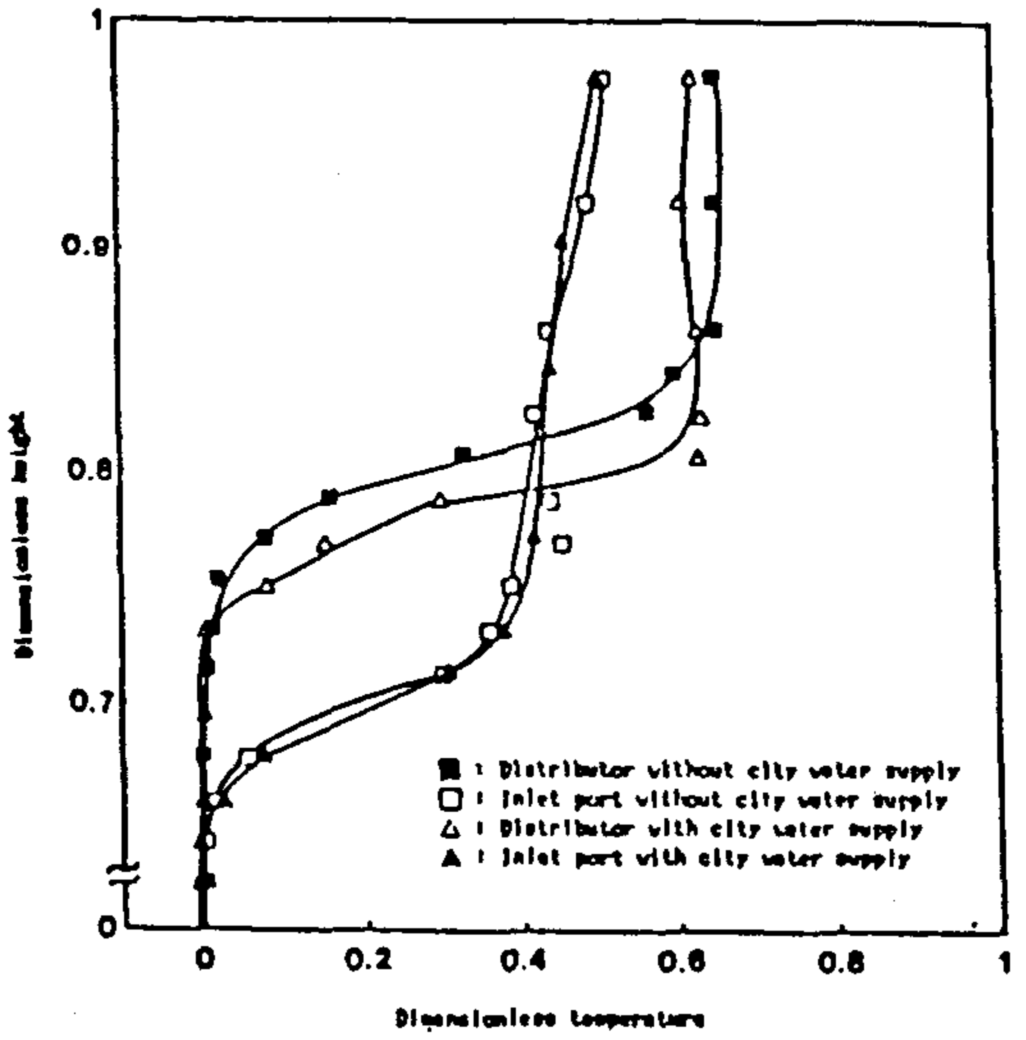



Fig. 7 Temperature variation with height in the tank at 6 min, from inflow(Q=12LPM, $\triangle$T−25℃)

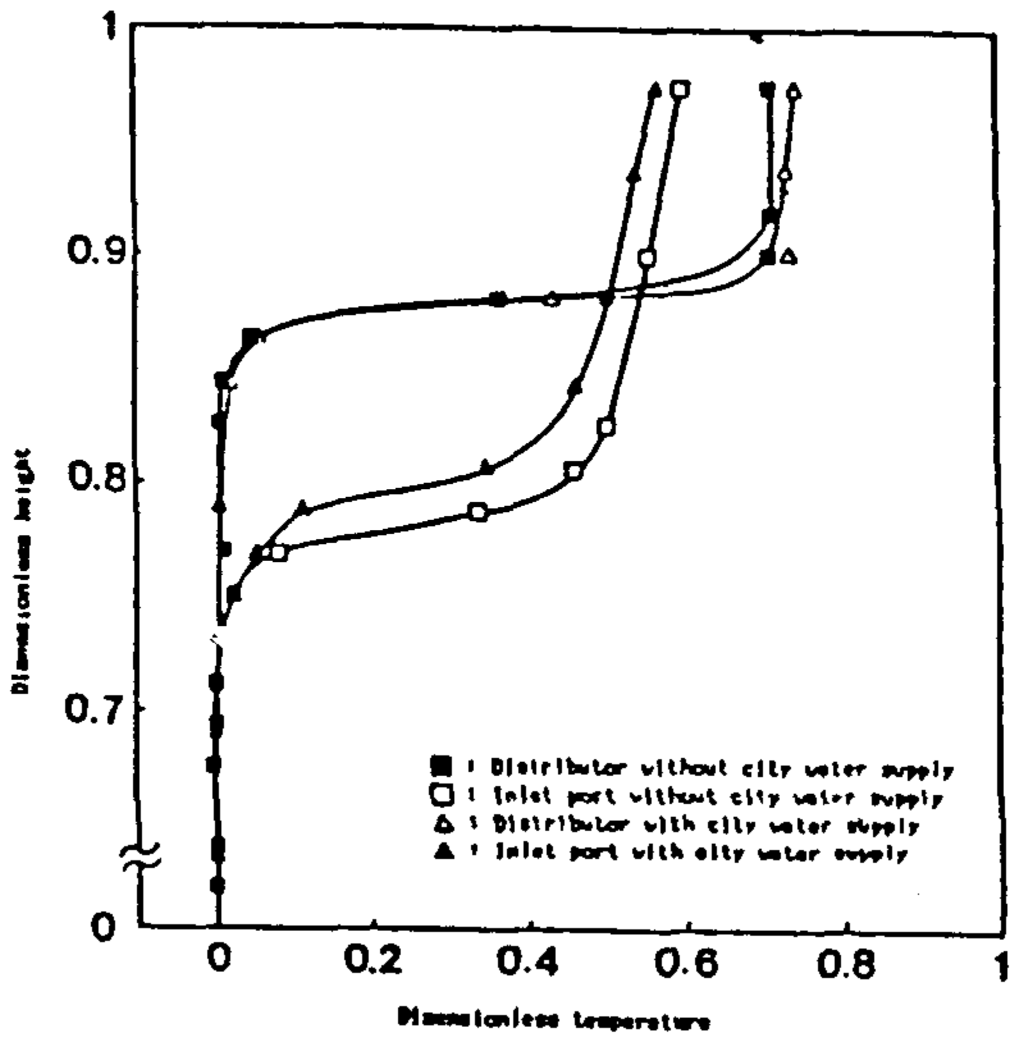



Fig. 8 Temperature variation with height in the tank at 6 min, from inflow(Q=8LPM, $\triangle$T−40℃)

When the flow rate was 8 liter/min and $\triangle$T was 40℃, the useful efficiency($\eta_u$) was about 90% in case of using a distributor, but the useful efficiency($\eta_u$) was about 88% in case of not using a distributor on the same parameters. So these kinds of distributor would be recommendable for a hot water storage system and residential solar energy application to get the maximum useful efficiency(see Fig. 8 & 10)

4. In the case of the uniform circular distributor (A=D=Constant), when the flow rate was 8 liter/min partial mixing was decreased and a stale stratification was obtained. Furthermore, if the distrbutor was manufactured following pressure distribution.

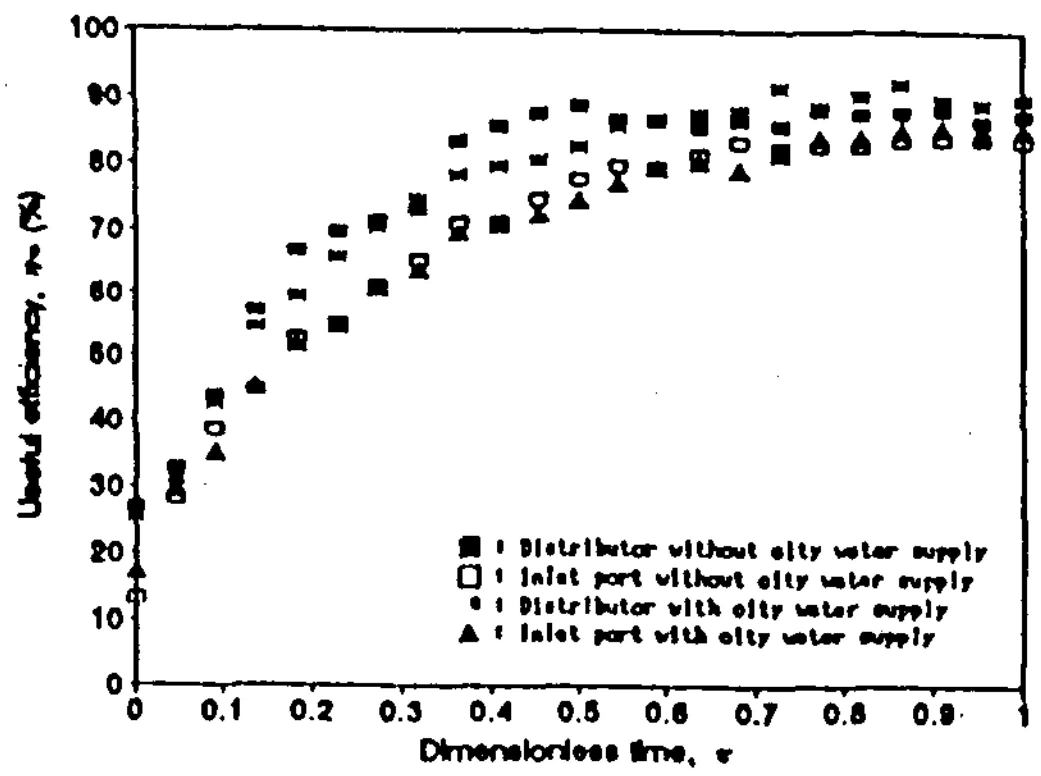



Fig. 9 Effect of time on useful efficiency(Q=12LPM, $\triangle$T−25℃)

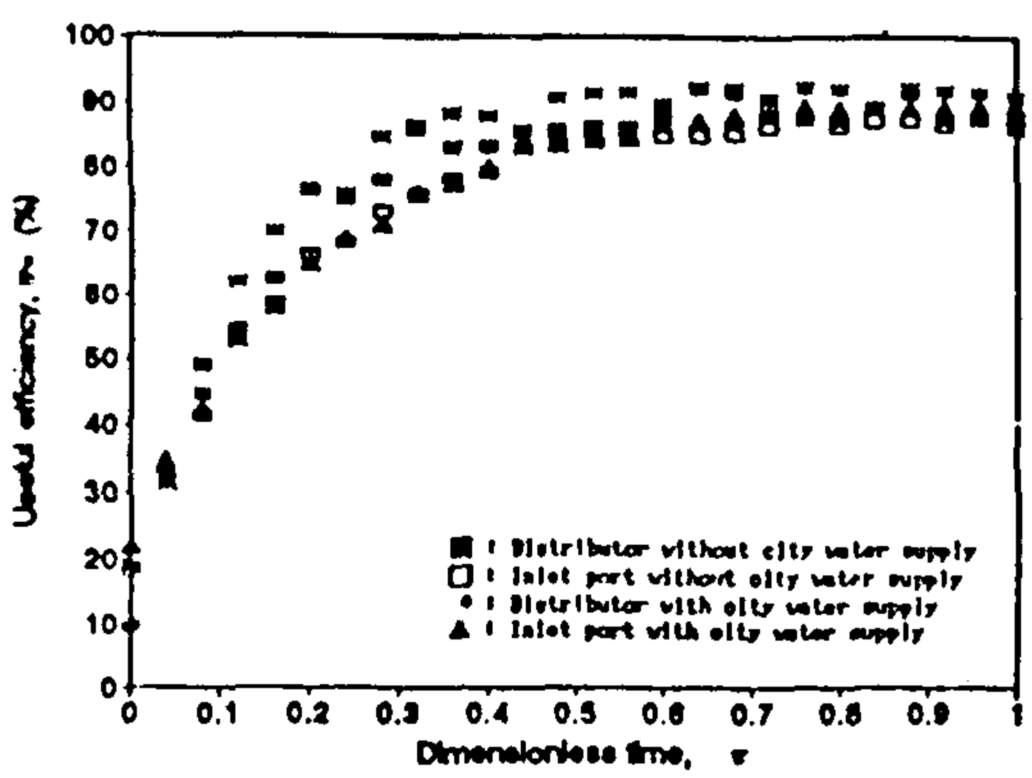



Fig. 10 Effect of time on useful efficiency(Q=8LFM, $\triangle$T−40℃)

$$\frac{dp}{dx}=\frac{1}{2}\rho(\frac{U_L A_L}{A})^2[\frac{4x}{DL^2}(\frac{dD}{dx})-\frac{2x}{L^2}+\frac{f x^2}{D_L L^2}]$$

it might be predicted that further stable stratification and higher useful efficiency($\eta_u$) are obtainable.

## CONCLUSIONS

The results of these experiments and simulations of solar water heating applications show that improved performance will be realized if stratification can be maintained in the storage tank.

When the flow rate was 8 liter/min and $\triangle T$ was 40℃, the useful efficiency($\eta^u$) was about 90% in case of using a distributor, but not using a distributor the useful efficiency($\eta_u$) was about 82%. So these kinds of distributor would be recommendable for a hot water storage system and residential solar energy application to get the maximum useful efficiency.

In the case of the uniform circular distributor, when the flow rate was 8 liter/min partial mixing was dicreased and a stable stratification was obtained. Furthermore, if the distrbutor was manufactured so that the flow is to be the same(velocity and pressure) from all perforations in order to enhance stratification, it might be predicted that further stable stratification and higher useful efficiency are obtainable.

## NOMENCLATURE

$A_b$ : Total perforation area of the distributor($cm^2$)

$A_L$ : Cross section area of the distributor($cm^2$)

$D$ : Diameter of the tank(cm)

D : Diameter of the distributor(cm)

$D_L$ : Diameter of the distributor at dead end(cm)

f : Friction factor

H : Height of the tank(cm)

L : Length of the distributor(cm)

$m_c$ : Mass flow rate from collector(kgm/sec)

P : Pressure($kg/cm^2$)

T : Temperature(℃)

$T_1$ : Temperature of water returning to tank from load(℃)

$T_{L,o}$: Temperature of water supplying to load from storage tank(℃)

$T_{c,i}$ : Temperature of water storing to storage tank from collector(℃)

$T_N$ : Tank bottom temperature(℃)

$T_s$ : 5Temperature of initially water stored(℃)

$U_L$ : Velocity of hot water at inlet of the distributor(cm/sec)

x : Distance from the dead end of the distributor(cm)

α : The ratio of cross section area of the distributor to total perforation area($=A_b/A_L$)

ρ : Density of the water($kg/cm^3$)

$\eta_u$ : Useful efficiency

## REFERENCE


1. Brumleve, T. D., "Sensible Heat Storage in Liquids," Sandia Laboratories Energy Report, SLL-73-0263, 1974.
2. Duffie, J. A. and Beckman, W. A., Solar Energy Thermal Processes, Wiley, New York, 1974
3. Lavan, Z. and Thompson, J., "Experimental Study of Termally Stratified Hot Water Storage Tanks", Solar Energy 19, pp. 519-524, 1977.
4. Sliwinski, B. J., "Stratification in Thermal Storage during Charging", 6th International Heat Transfer Conference, Toronto, Vol. 4, pp. 149-154, 1978.
5. Loehrke, R. I., Holzer, R. I., Gari J. C. and Sharp, M. K., "Stratification Enhancement in Liquid

Thermal Storage Tanks", J. of Energy, Vol. 3, No. 3, pp. 129-130, 1979.

6. Juzar, A. Lokhandwala and Richard B. Bannerot, "Improving Extraction Efficiency of a Horizontal Tank Thermal Storage System", Heat Transfer Pittsburgh, Aiche Symposium Series, Vol. 83, No. 257, pp. 171-176, 1987.
7. Jaluria, Y. and O'Mara, B. T., "Thermal Field in a Water Body for Solar Energy Storage and Extraction Due to a Bouyant Two Dimensional Surface Water Jet", Solar Energy 43, pp. 129-138.
8. Gari, H. N. and Loehrke, R.I., "A Controlled Buoyant Jet for Enhancing Stratification in a Liquid Storage Tank", J. of Fluids Engineering Vol. 104, pp. 475-481, 1982.
9. Shyu, R. J., Lin, J.Y., and Fang, L. J., "Thermal Analysis of Stratified Storage Tanks", J. of Solar Energy Engineering, Vol. 111, pp. 54-61, 1989.
10. Jaluria, Y. and Gupta, S. K., "Decay of Thermal Stratification in a Water Body for Solar Energy Storage", Solar Energy, Vol. 28, No. 2, pp. 137-143, 1982.
11. Guo, K. L. and Wu, S. T., "Numerical Study of Flow and Temperature Stratification in a Liquid Thermal Storage Tank", J. of Solar Energy Engineering, Vol. 107, pp. 15-20, 1985.
12. Davis, E. S. and Barera, R., "Stratification in solar water heater storage tank," Proc. Workshop on Solar Energy Storage Sobsystem for the Heating and Cooling of Bulding. Charlottesuile, Virginia, pp. 38-42. April 1975.
13. Sharp, M. K. and Loehrke, R. I. "Stratified Versus Well Mixed Sensible Heat Storage in a Solar Space Heating Application," Paper No. 78-HT-49, Presented
14. Pak, E. T. and Cho, W., "Flow Analysis of Buoyant Jets into Storage Tank through Variable Nozzles," J. of Solar Energy Society of Korea, Vol. 9, No.2, pp. 42-50, 1989.
15. Pak, E. T., Hwang, S. I. and Choi, Y. I., "Experimental Study on the Thermal Storage Efficiency Through Variable Porous Manifolds in a Test Storage Tank," J. of Korea Solar Energy Society, Vol. 9, No. 2, pp. 37-43, 1989.
16. Pak, E. T., "Thermally Stratified Hot Water Storage", Solar Energy, Vol. 10, No. 3, pp. 3-12, 1990.
17. Pak, E. T., "Thermally Stratified Hot Water Extraction", Solar Energy, Vol. 11, No. 2, pp. 34-40, 1991.
18. Pak, E. T., "A Simulation for the Stratified Thermal Storage System in Residential solar Energy Application", Solar Energy, Vol. 11, No. 3, pp. 44-52, 1991.

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The benefits of thermal stratification in sensible heat storage were investigated for residential solar applications. The effect of increased thermal useful efficiency of hot water stored in an actual storage tank due to stratification has been discussed and illustrated through experimental data and computer simulation, which were taken by changing dynamic and geometric parameters. When the flow rate was 8 liter/min and $\triangle T$ was 40℃, the useful efficiency($\eta_u$) was about 90% in case of using a distributor, but not using a distributor the useful efficiency($\eta_u$) was about 82%. So these kinds of distributor would be recommendable for a hot water storage system and residential solar energy application to increase useful efficiency($\eta_u$). In the case of the uniform circular distributor, when the flow rate was 8 liter/min partial mixing was decreased and a stable stratification was obtained. Furthermore, if the distrbutor was manufactured so that the flow is to be the same from all perforations in order to enhance stratification, it might be predicted that further stable stratification and higher useful efficiency($\eta_u$) are obtainable.

## A study of heat transfer with Phase Change Material in heat storage system
## −Inward freezing in the vertical cylinder−

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*Yuhan Junior Collage*
**Inha University*
***University of British Columbia*

This study investigated heat transfer phenomena during the freezing of an initially superheated or non-superheated liquid in a cooled cylinder tube. Numerical and experimental method were performed to obtatin the temperature and velocity distribution, the shape of interface. Natural convection effects in the superheated liquid were confined and moderated a short freezing time. After natural convection ceases, heat conduction dominated in the whole paraffin, so Caystal and much-Zone were found out in PCM.

Initial superheating of liquid tended to morderatly diminish the frozen layer thickness at short