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태양열의 성층축열과 주택이용에 관한 연구(성층축열)

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Thermally Stratified Hot Water Storage

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요 약

본 실험연구에서는 탱크의 직경에 대한 높이의 비(H/D)가 3이고 유입 유량이 8LPM, 유입수의 온도와 기존 저장수와의 온도차, △T=30℃일때, 운동량교환을 최소화하여 가장 좋은 성층을 얻었고 또한 실험에서 사용한 유입구(Inlet Port)의 경우 수정 Richardson수(Modified Richardson Number), Ri가 0.004(Q=10LPM, △T=30℃) 이하의 값에서는 완전 혼합(Fully Mixing)이 발생하고 H/D가 작아질수록 혼합층의 두께(H*/H)가 증가하여 성층 축열에는 바람직하지 못하였다. 그리고 성층은 성층을 촉진시키기 위하여 Distributor를 사용했을 때가, Distributor를 사용하지 않은 유입구(Inlet Port)의 경우 보다 잘 형성되어 저장효율이 Distributor를 사용한 경우(Q=8LPM, △T=30℃, H/D=3)에 Distributor를 사용하지 않은 유입구(Inlet Port)의 최저효율 63%(Q=12LPM, △T=30℃, H/D=3인 경우)보다는 31% 정도, 최대효율 84%(Q=8LPM, △T=30℃, H/D=3인 경우)보다는 11% 정도 높은 95%까지 저장 효율을 증가시킬 수 있었다. 더 나아가서 단면이 균일한 원형 Distributor(A=D=Constant)의 경우에, 유량이 8LPM인 경우에 관내의 압력차가 작아 부분혼합(Partial Mixing)이 감소하여 안정된 성층을 얻을 수 있었다.

그리고, Distributor의 직경을 다음식과 같이

$$\frac{D}{D_{\mathrm{L}}}=\left(\frac{x}{\mathrm{L}}\right)^{1/2}\left(1+\frac{\mathrm{fL}}{2D}\right)-\frac{\mathrm{f}x}{2D_{\mathrm{L}}}$$

길이에 대하여 변화시켜 Distributor를 제작함으로써, 보다 안정된 열 성층과 높은 열저장 효율을 얻을 수 있을 것으로 예상한다.

ABSTRACT

This paper deals with experimental research to increase thermal storage efficiency of hot water stored in an actual storage tank for solar application. The effect of increased energy input rate due to stratification has been discussed and illustrated through experimental data, which was taken by changing dynamic and geometric parameters. Ranges of the parameters were defined for flow rate, the ratio of diameter to height of the tank and inlet–exit water temperature difference. During the heat storage, when the flow was lower, the temperature difference was larger and the ratio of diameter to height of the tank was higher, the momentum exchange decreased. As for this experiment, when the flow rate was 8 liter/min, the temperature difference was 30℃ and the ratio of diameter to height of the tank was 3, the momentum exchange was minimized resulting in a good thermocline and a stable stratification. In the case of using inlet ports, if the modified Richardson number was less than 0.004, full mixing occured and so unstable stratification occured, which mean that this could not be recommended as storage through thermal stratification. Using a distributor was better than using inlet ports to form a sharp thermocline and to enhance the stratification. It was possible to get storage efficiency of 95% by using the distributor, which was higher than a storage efficiency of 85% obtained by using inlet ports in same operation condition. Furthermore, if the distributor was manufactured so that the mainpipe decreases in diameter toward the dead end to maintain constant static pressure, it might be predicted that further stable stratification and higher storage efficiency are obtainable(ie:more than 95%).

INTRODUCTION

Energy storage is employed in a solar thermal energy system to shift excess energy produced during times of high solar availability to times of low solar availability. Storage can also be used to provide energy during events such as cloudy days. Thermal energy may be stored as sensible heat or latent heat.(3) Sensible heat storage of thermal energy is perhaps, conceptually, the simplest form of storing thermal energy.(4) In many analyses, the temperature of the storage has been assumed to be uniform after storage, but in real situations liquid temperature in the tank will not be uniform after storage, especially in the vertical dimension. The warmer, lighter liquid is stored on top of the colder, heavier liquid resulting in thermal stratification. In practice, perfect stratification is not possible since the water entering the tank will cause a certain amount of agitation and mixing. Having obtained good thermal stratification by eliminating mixing, it is equally important to maintain the temperature layers(6).

Many thermal storage devices consist simply of a tank of water which is assumed to be mixed. However, there are definite advantages to operating the storage in a stratified mode, with the hot water separated from the cold water(6,7). The separation of the fluid may be accomplished by the use of simply a single tank operated to allow stratification to occur due to buoyant forces. The problem of thermal stratification in solar energy storage systems has been considered by several investigators. For example, Davis and Barera(8) 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(9) conducted detailed investigations of the system performance when stratified water storage is employed. Recently, Pak and Cho conducted an experiment involving flow analysis of buoyant jets into a storage tank through variable nozzles(10) and Pak, Hwang and Choi also conducted an experimental study of the thermal storage efficiency through variable porous manifolds in a test storage tank(11).

The purpose of this investigation was to experimentally determine what conditions produce optimum stratification during charging in thermal storage using water as a storage media. The investigation included a large number of parameters, such as inlet condition, mass flow rate, tank height to diameter ratio, and inlet–exit water temperature difference. Finally, it was intended to increase thermal storage efficiency of hot water stored in an actual size storage tank by stratification enhancement.

EXPERIMENTAL APPARATUS

The experimental apparatus consisted 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

The experimental tank is cylinderical, 1680mm 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 100mm of batt insulator. It was possible to interchange inlet and distributor inlet position on 3, 2 and 1 of tank height to diameter ratio(H/D).

Inlet Port and Distributor

Tank inlet(including distributor) and outlet position are also shown Fig. 1. The inlets were constructed of 20mm straight fiberglass tube with 2mm 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 $2(\alpha = A_b/A_L = 2)$.

Charging Loop

The charging loop consisted of a pump, a hot water supply device, a heater and an exit port. The hot water supply device was used to insure a constant supply temperature of hot water and the exit port to insure a constant flow. The maximum flow rate in the charging loop was 12 liter/min. which corresponds to a "turnover" time(total tank fluid mass divided by charging loop flow rate) of 29 minutes for the experimental system.

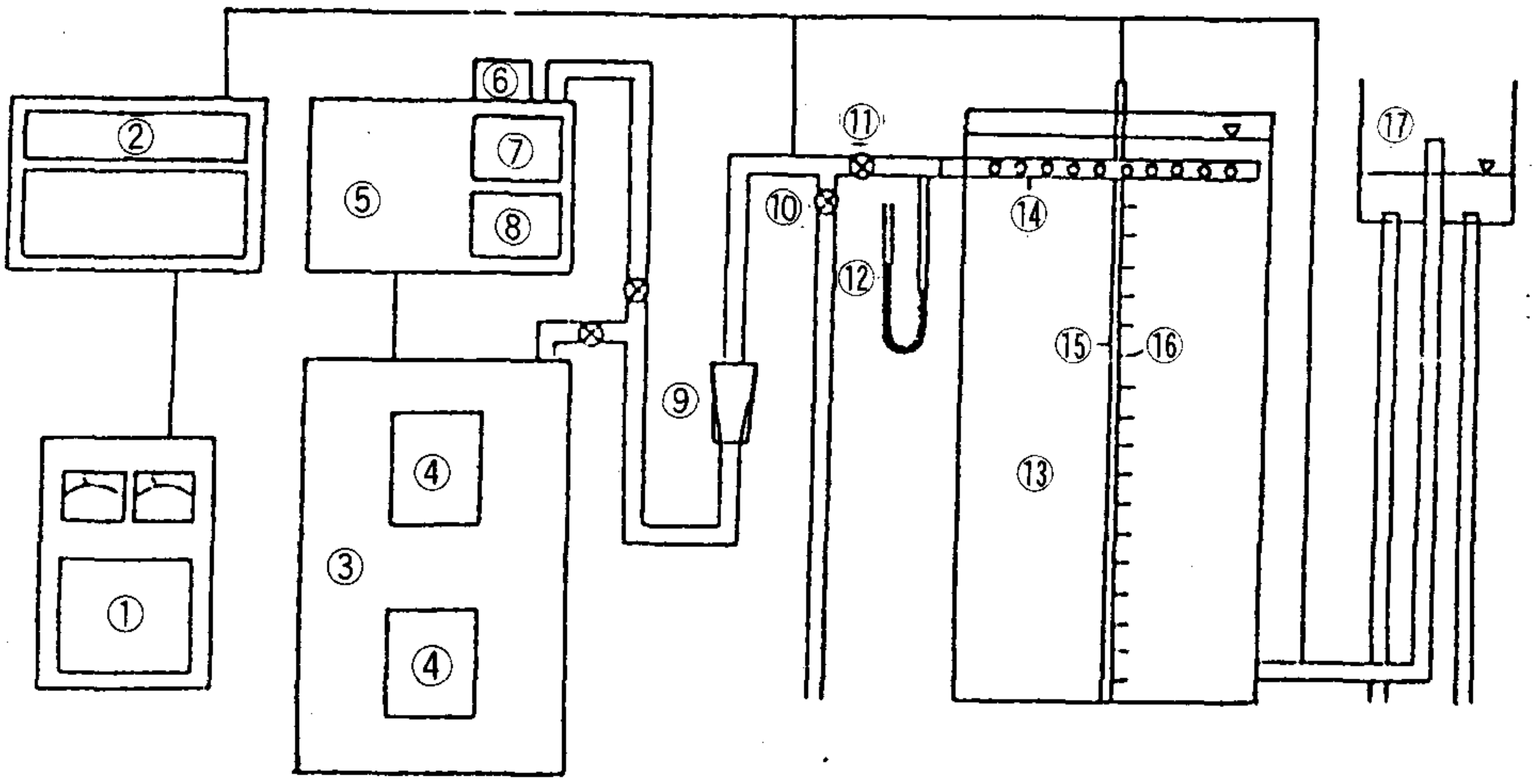
Data Gathering System

The data gathering system consisted of temperature sensor of thermocouple probe, flow sensor of flow meter, a manometer and a Hybride Recorder for temperature 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 $H/D=3$, 25 probes for $H/D=2$ and 21 probes for $H/D=1$ 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 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 following is a brief description of the experimental procedure performed:

1. Water was heated in the hot water supply device to the temperature wanted for the experiment.
2. Fresh water of 20℃ was supplied into the experimental tank to a level 3 cm higher than the inlet port and 7–8 minutes was allowed to pass for the fresh water supplied to become stable and steady.
3. The bypass valve was opened in order to remove bubbles generated from the hot water supply device.
4. The bypass valve was closed after removing all bubbles generated and the flow meter was set to charge the working fluid into the test tank.
5. The inflow valve was opened after operating the Hybrid Recorder and the working fluid was charged into the test tank. The temperature of the water in the test tank at intervals of 3 minutes for H/D=3 and 2 minutes for H/D=2 and 1 were then recorded.
6. The range of flow rate was defined to be 8,10, 12liter/min. in three steps and inlet–exit water temperature differences were defined to be 20, 25, 30℃ respectively for each flow rate.
7. The above procedure was repeated(item 1–7) for inlet port(without distrbutor) and for distributor using the test tank of H/D=1, 2, 3.
8. Pictures were taken using a food dye to analyze initial mixing phenomena and to compare the results of temperature profiles.



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

Fig.1 Schematic diagram of experimental apparatus

RESULTS AND DISCUSSION

Stratification through Temperature Profiles

The temperature profiles of each experiment were plotted in the form shown in Fig. 2, Each line represents a different point in time. The lines are plotted from $t=0$ until the end of the experiment. One of the most striking features of these graphs is the nearly parallel temperature profiles in case of using the distributor(see Fig. 5). From the graphs it can be observed that there is a region of nearly constant temperature gradient which moves down the tank as the tank is charged. This is the boundary or thermocline region.

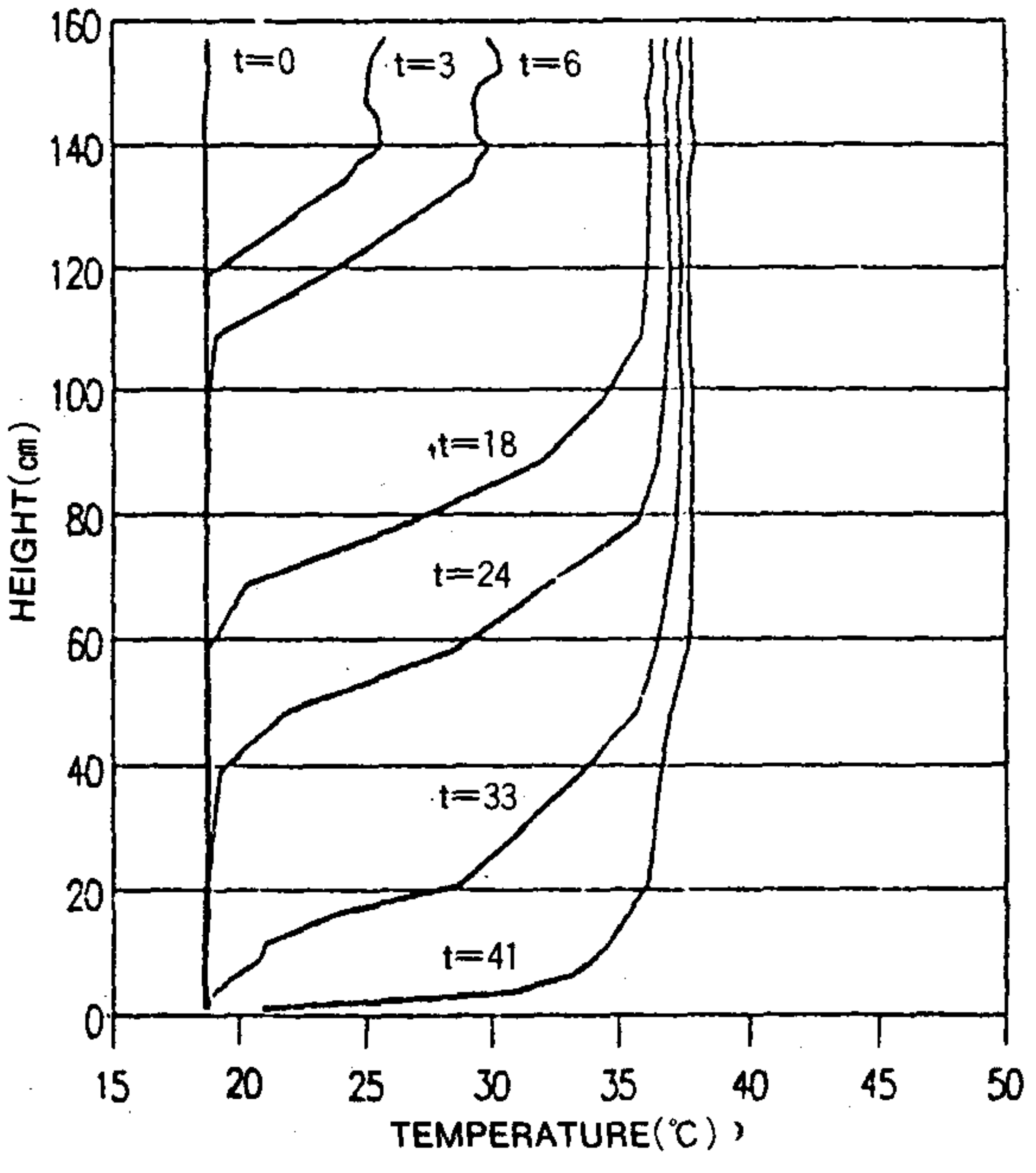


Fig.2 Temperature profile in test tank(Inlet port–without Distributor)(△T=20℃, H/D=3, Q=8 LPM, unit of time(t): minute)

When using only inlet ports(without distributor) for the heat storage, momentum exchange has increased in case of the larger flow rate, the lower inlet–exit water temperature difference and the smaller ratio of diameter to height

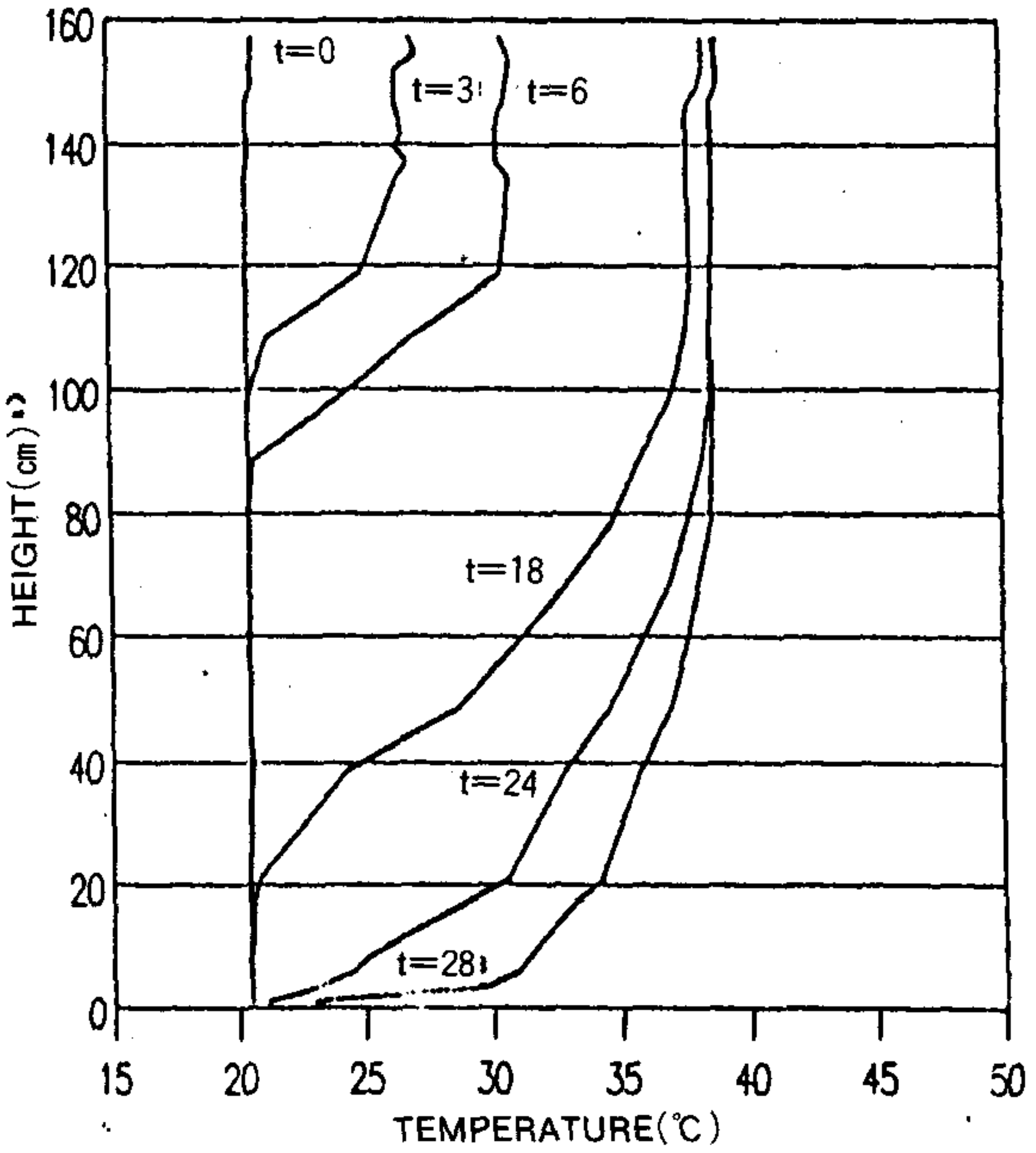


Fig.3 Temperature profile in test tank(Inlet port–without Distributor)(△T=20℃, H/D=3, Q=12 LPM, unit of time(t): minute)

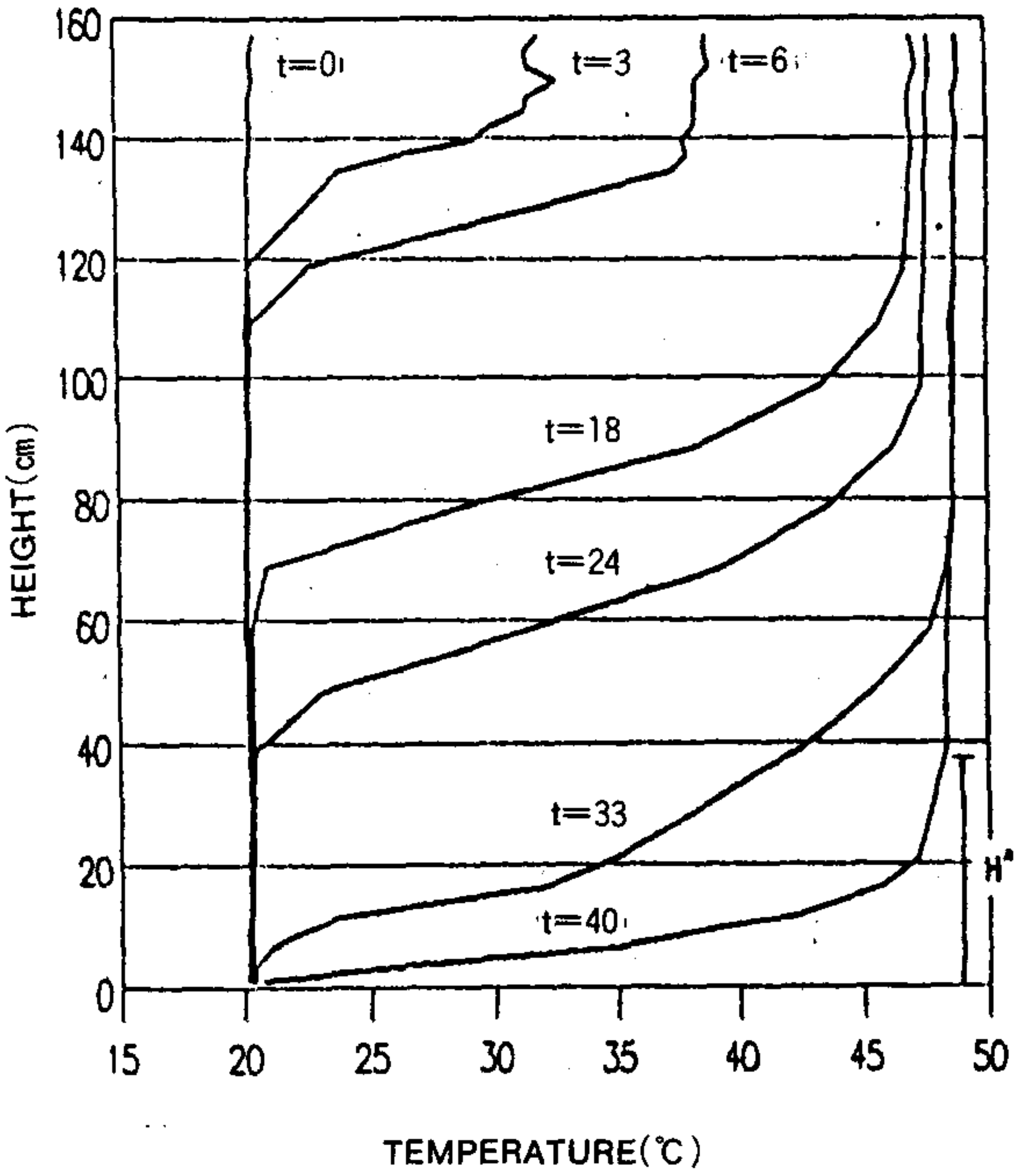


Fig.4 Temperature profile in test tank(Inlet port–without Distributor)(△T=30℃, H/D=3, Q= 8 LPM, unit of time(t): minute)

of the tank as indicated in the figures. Especially, when the flow rate was 8liter/min., the inlet-exit water temperature difference was 30℃ and the ratio of diameter to height of the tank was 3, the momentum exchange was minimized(see Fig. 3 and 4).

In the same operation condition, using the distributor was better than using the inlet ports only to form the stratification. Also, in the case of 8 liter/min, flow rate, 30℃ inlet-exit water temperature difference and 3 as the ratio of diameter to height of the tank, the stratification enhancement took place. It was also observed that the momentum exchange was minimized when the stratification enhancement took place(see Fig. 5).

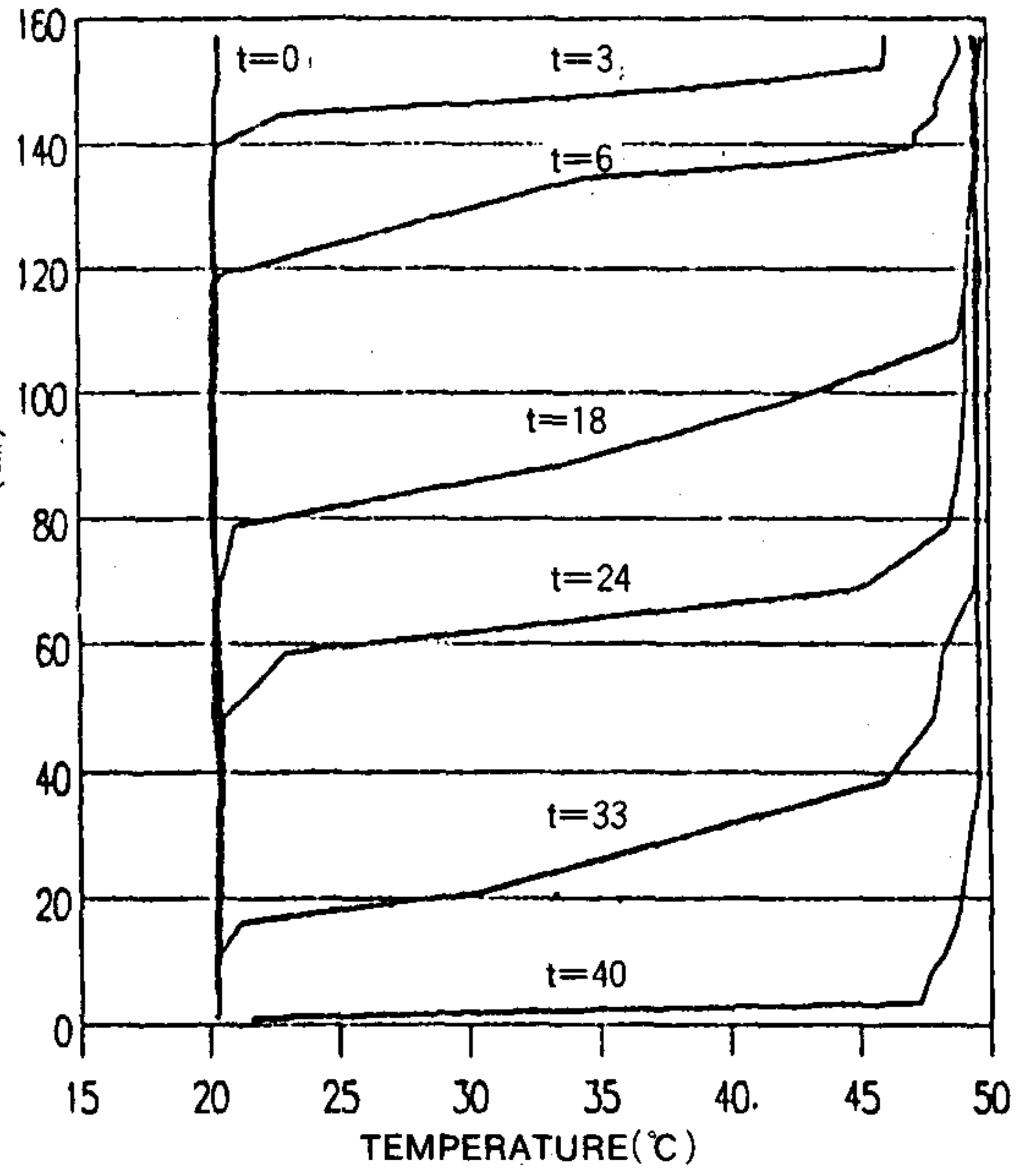


Fig.5 Temperature profile in test tank(with Distributor)($\Delta T=30$℃, H/D=3, Q=8 LPM, unit of time(t): minute)

Degree of stratification of the thermal storage is characterized by the magnitude of the temperature gradient in the boundary region. The magnitude of the gradient was observed to be a function of the Richardson Number. It was observed that the depth H^*, at which this boundary region first occurred in the tank varied from experiment to experiment and correlated well with the modified Richardson Number defined as:

$$R_i = \frac{g\ \beta\ \Delta T\ h}{U_i^2}$$

An example of the variation of H^* with Richardson Number can be seen by comparing Figures. The relationship between H^*/H and the modified Richardson Number is shown in Fig. 6.

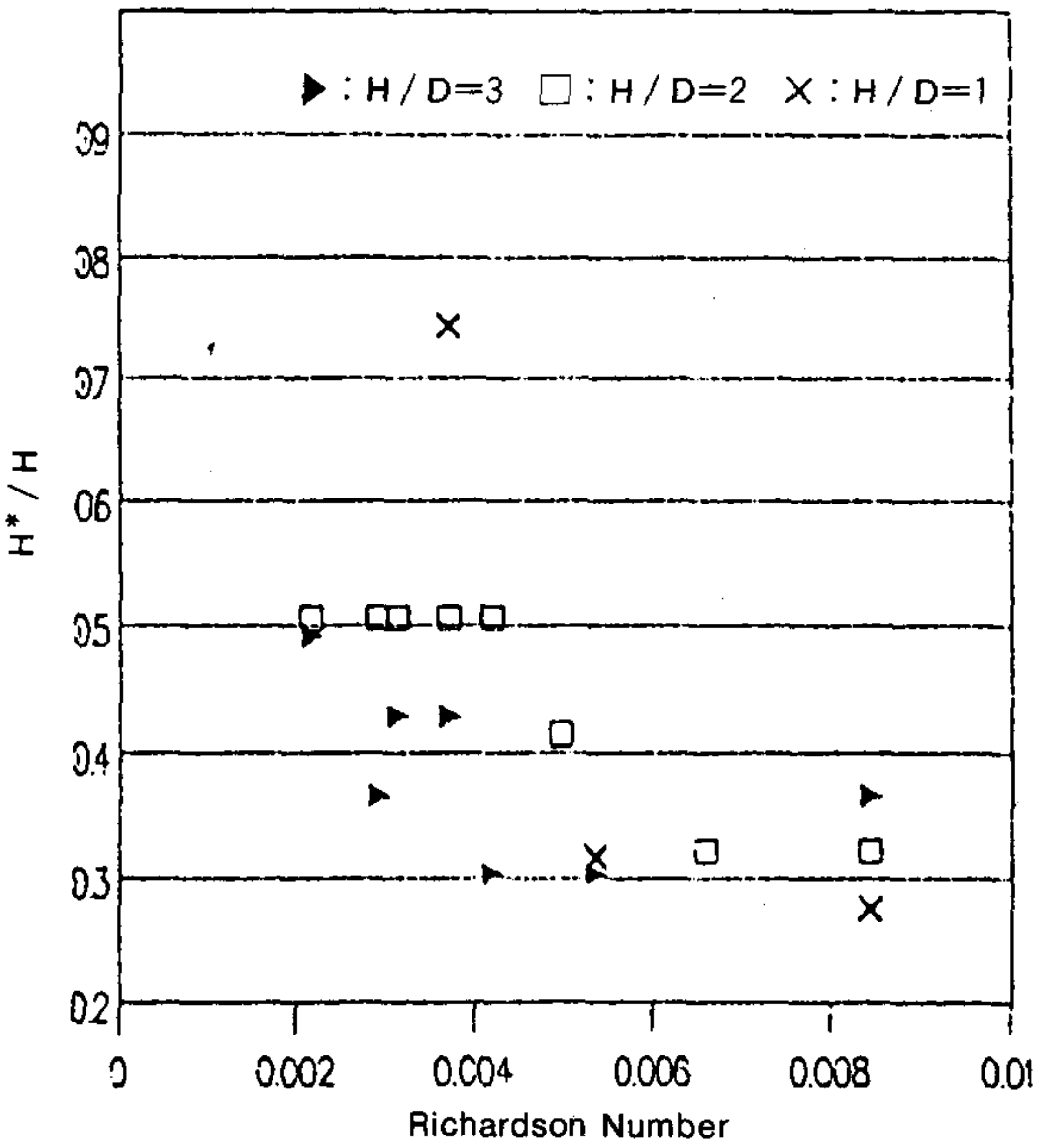


Fig.6 H*/H as function of Richardson number

It is important to note that the sharp out off in the graph is not at the point where the tank becomes fully mixed but only at the point where the tank no longer stratifies at the inlet. The point of complete mixing(i.e. $H^*/H=1$) corresponds to a Richardson Number of around 0.004.

Thermocline Energy Storage

The ultimate reduction in storage tank volume is achieved when the storage tank volume equals the storage fluid volume. An attempt to achieve this represent a thermocline system in which both the hot and cold storage fluids occupy the same tank.(12) Accordingly, thermocline energy storage system have received much attention because of their potential for low cost resulting from minimized tankage volume as mentioned above.

As can be seen in the above figures, when the flow rate was 8 liter/min the inlet-exit water temperature difference was 30℃ and the rate of diameter to height of the tank was 3, a sharp thermocline could be formed and the mixing of the hot and cold water layers was small. In comparing using the inlet ports(without distributor) with using a distributor, it could be seen that using the distributor resulted in a more sharply stable thermocline and a higher temperature of water in the tank than using inlet ports(see Fig. 7).

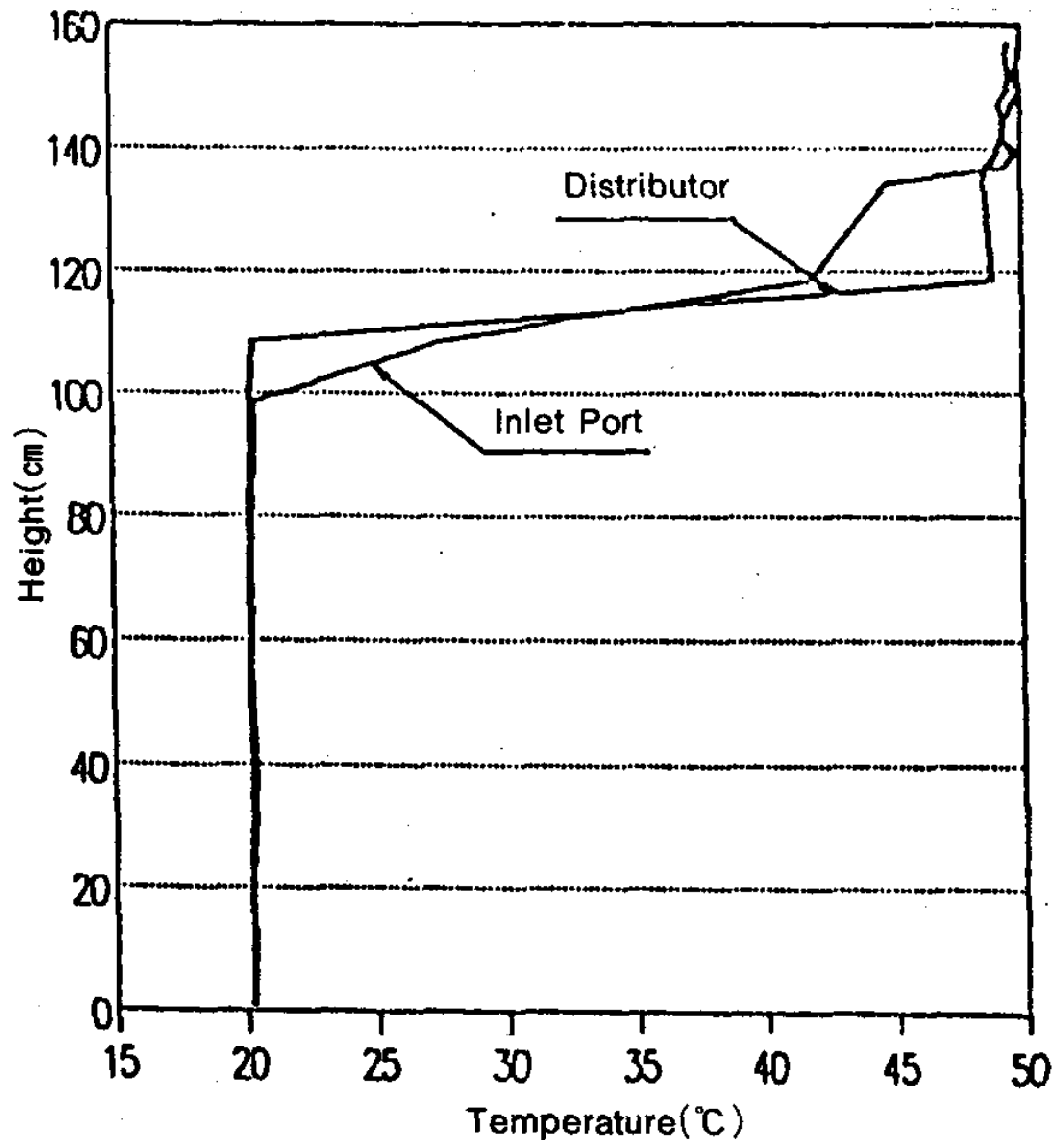


Fig.7 Temperature variation with height in the tank at 9 min, from charging for H/D=3, Q=8, △T=30℃

Effect of Stratification on Charging the Storage

Stratification of the thermal storage results in an increased rate of energy input. The equation for energy content as a function of time of a perfectly mixed tank with constant temperature input and constant mass flowrate is :

$$E = M_s\ C_p\ \triangle T \{1 - e^{-(Mi/Mm)t}\} \qquad (1)$$

The equation for the energy content of a perfectly stratified storage, with constant temperature input and constant flowrate is :

$$E = M_i\ C_p\ \triangle T\ t \qquad (2)$$

Equation 1 and 2 can be non–dimensionalized since storage efficiency is defined as the ratio of theoretical total energy to be stored to actual energy stored in the tank, so that for the perfectly mixed tank :

$$\eta_m = \frac{M_s\ C_p\ \triangle T \{1\text{-}e^{-(Mi/Mm)t}\}}{M_s\ C_p\ \triangle T} = 1\text{-}e^{-t^*} \qquad (3)$$

and for the perfectly stratified tank:

$$\eta_s = \frac{M_i\ C_p\ \triangle T\ t}{M_s\ C_p\ \triangle T} = t^* \qquad (4)$$

where $t^* = t / M_s / M_i$

Fig. 8 illustrates the charging rate of a perfectly mixed and perfectly stratified storage and the results of an actual stratified storage comparing the theoretical curve with experimental data.

As can be seen from Fig. 8, it is possible to increase storage efficiency to 95% by using the distributor in case of Q=8 liter/min., △T=30℃ and H/D=3.

It is also possible to get storage efficiency of 84% by using the inlet ports in the same operational conditions of geometric and dynamic parameters(Q, △T, H/D) as were applied 95% storage efficiency was obtained. Therefore, when the distributor was used, storage efficiency has increased by 11% to 95%.

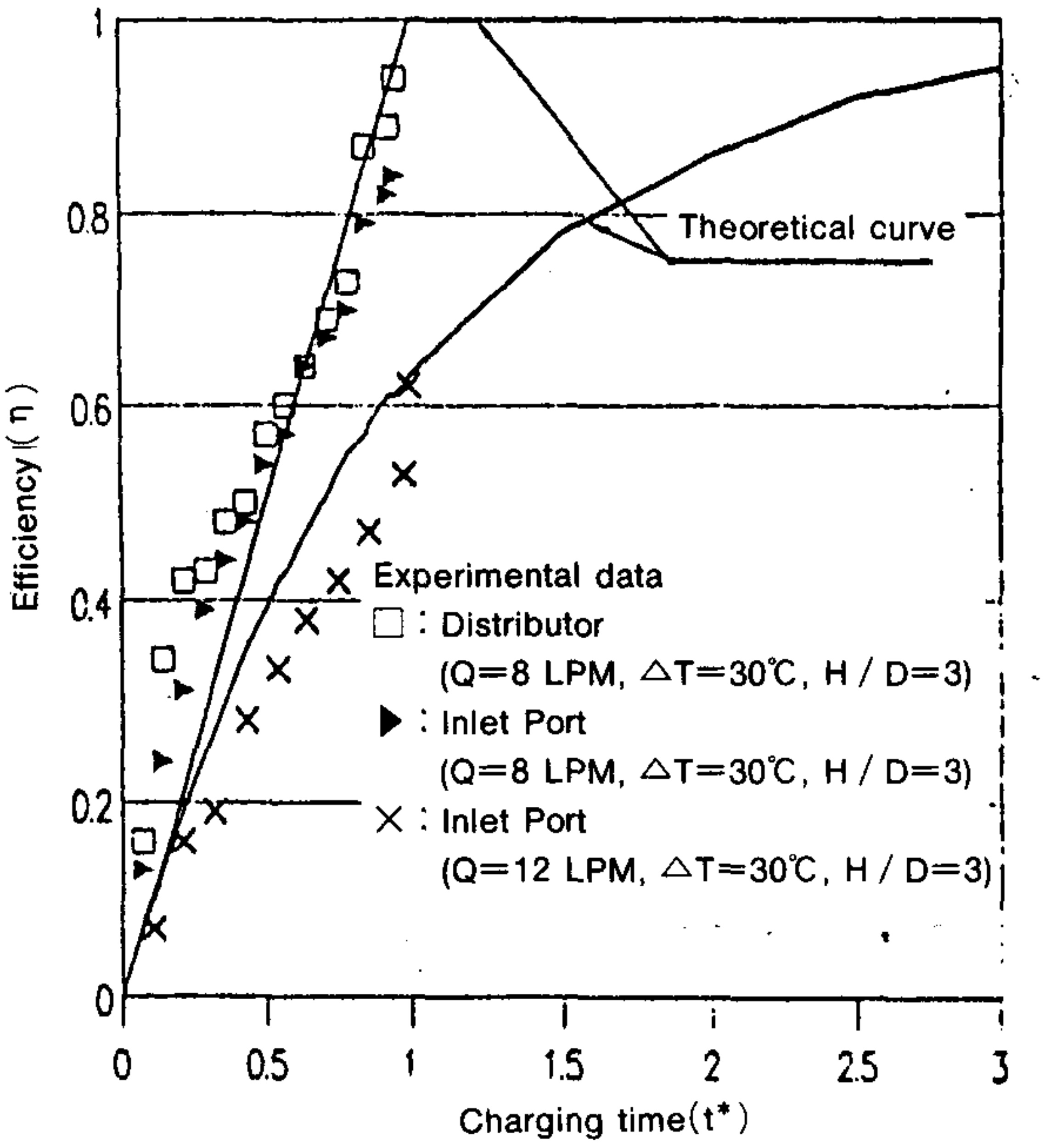


Fig.8 Effect of charging time on tank storage

Pressure Profiles on the Distributor

The hot water flow through the main pipe is distributed to a number of perforations. It is necessary for the flow to be the same(velocity and pressure) from all perforations in order to enhance stratification. The difference between the absolute static pressure of point 1 and 2 in the main pipe of Fig. 9 can be generalized to *yield the pressure change in the main pipe between* the 1 and i–1 perforations:

$$P_i-P_{i-1}=\frac{1}{2}\rho\ U^2_i\ K_i-\frac{1}{2}\rho(U_i^{\,2}-U^2_{i-1})$$
$$+\frac{1}{2}\rho\,U^2_{i-1}\ \frac{f_{i-1}\ \ell_{i-1}}{D_{i-1}}$$
$$+\rho g(Z_{i-1}-Z_i) \qquad (5)$$

Equation 5 can be *expressed in differential* form as

$$\frac{dp}{dx}=-\frac{1}{2}\rho\frac{dU^2}{dx}+\frac{1}{2}\rho\frac{U^2f}{D} \qquad (6)$$

x is the distance from the dead end of the distributor. The gravity term and the loss across the perforation junction have been neglected. Since the flow area is proportional to the diameter squared, A & D^2, equation 6 becomes:

$$\frac{dp}{dx}=\frac{1}{2}\rho\left(\frac{U_L\ A_L}{A}\right)^2\left[\frac{4x^2}{DL^2}\ \frac{dD}{dx}\right.$$
$$\left.-\frac{2x^2}{L^2}\ \frac{f}{D}\ \frac{x^2}{L^2}\right] \qquad (7)$$

This equation describes the static pressure gradient in incompressible fluid flow in a distributor with uniform flow. In this experiment, since the diameter of the distributor was uniform, A=D=constant, dD/dx=0. Equation 7 *can be easily integrated to yield the static* pressure along the main pipe:

$$p=p_L-\frac{\rho U^2{}_L}{2}\left[\frac{x^2}{L^2}-1+\frac{f\ L}{3D}\left(1-\frac{x^3}{L^3}\right)\right] \qquad (8)$$

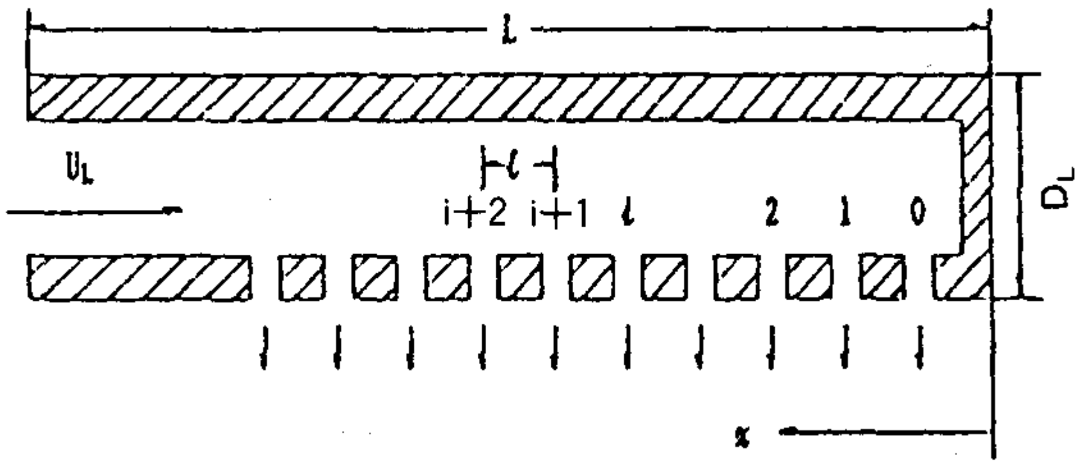


Fig.9 Co – ordinates of the Distributor

Fig. 10 is actual pressure distribution within the distributor in the experiment using f=0.08 and P_L measured by manometer.

It is necessary to achieve uniform perforation flow in the distributor in order to get fully perfect stratification in interface between hot and cold water in the tank. There are three methods of achieving equal flow through identical perforations can also be nearly equal if the area of the main pipe(distributor) varies so that *the static pressure is constant along the main* pipe.

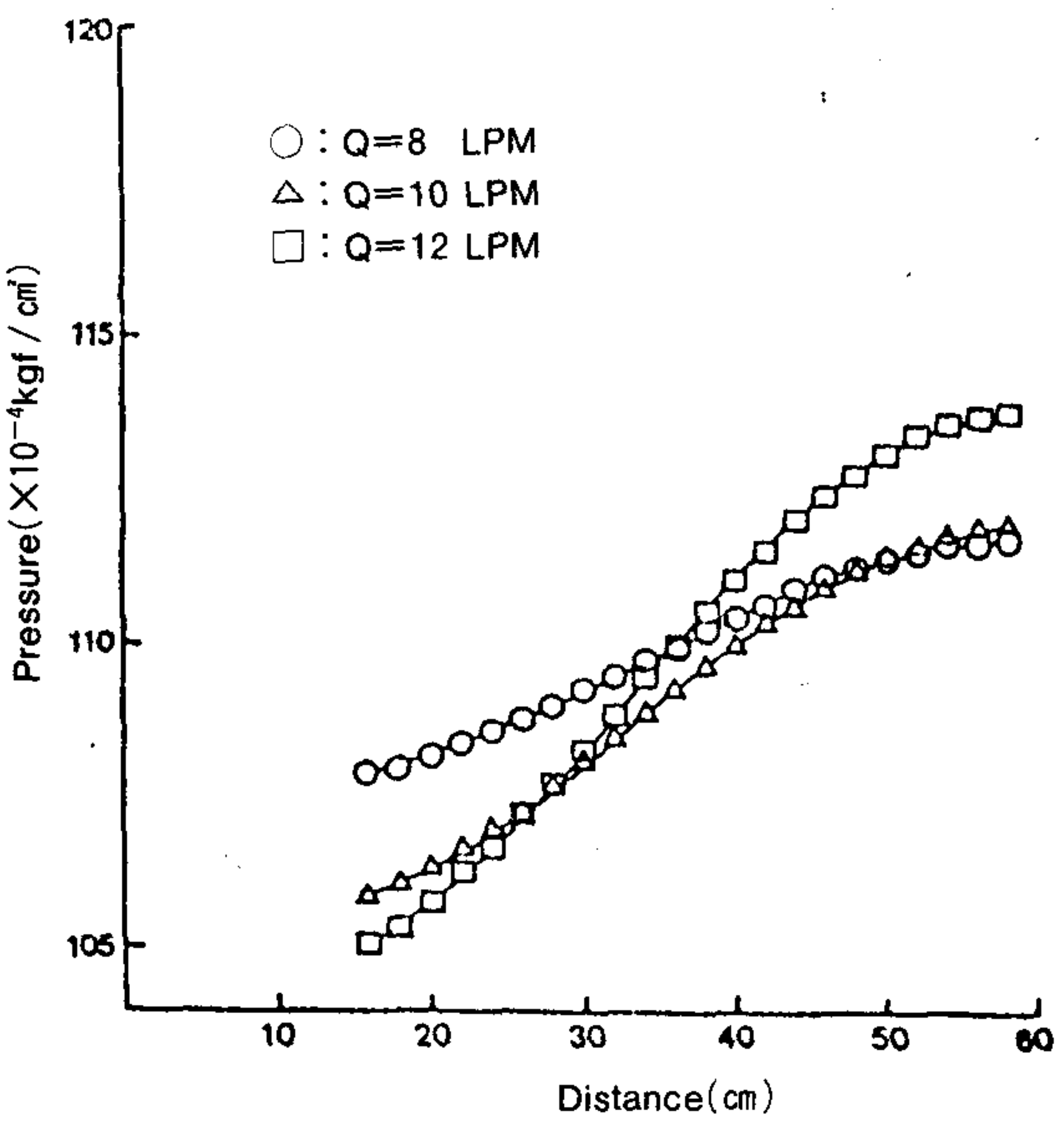


Fig.10 Pressure distribution within distributor

Setting dp/dx=0 in equation 7 results in the following differential equation which describes the main pipe diameter as a function of distance from the dead end of the perforation :

$$\frac{dD}{dx}=\frac{D}{2x}-\frac{f}{4} \qquad (9)$$

The differential equation was solved for the hydraulic diameter D as a function of x, The result is given as follows :

$$\frac{D}{D_L}=\left(\frac{x}{L}\right)^{1/2}\left(1+\frac{fL}{2D_L}\right)-\frac{fx}{2D_L} \qquad (10)$$

If the distributor is manufactured in accordance with the above equation, it might be predicted that further stable stratification and higher storage efficiency are obtainable.

CONCLUSION

During the heat storage, when the flow was lower, the temperature difference was larger and the ratio of diameter to height of the tank was higher, the momentum exchange decreased. As for this experiment, when the flow rate was 8 liter/min, the temperature difference was 30℃ and the ratio of diameter to height of the tank was 3, the momentum exchange was minimized resulting in a good thermocline and a stable stratification. In the case of using inlet ports, if the modified Richardson number was less than 0.004, full mixing occured and so unstable stratification occured, which mean that this could not be recommended as storage through thermal stratification. Using a distributor was better than using inlet ports to form a sharp thermocline and to enhance the stratification. It was possible to get storage efficiency of 95% by using the distributor, which was higher than a storage efficiency of 85% obtained by using inlet ports in same operation condition, Furthermore, if the distributor was manufactured so that the mainpipe decreases in diameter toward the dead end to maintain constant static pressure, it might be predicted that further stable stratification and higher storage efficiency are obtainable(le:more than 95%). The differential equation was solved for the hydraulic diameter as a function of distance from the dead end to obtain equal flow each perforation.

NOMENCLATURE

A_b=Total perforation area of distribution, mm^2
A_1=Cross section area of distribution, mm^2
C_p=Specific heat at constant pressure, KJ/K_M K
D=Diameter of the tank, mm
D=Diameter of the distributor, mm
E=Storage energy, J
f=Friction factor
g=Acceleration of gravity, 981 cm/sec^2
H=Height of the tank, mm
K=Velocity coefficient
h=Vertical length between the inlet position and outlet position, mm
L=Length of the distributor, mm

l=Length between the holes of distributor, mm
M=Flow rate, ℓ/min
p=Pressure, Kgf/cm^2
R_i =Richardson number
Q=Sensible heat, J
T_i =Temperature of the inflow water, ℃
T_s =Temperature of stored water, ℃
t=Charging time, min
U=Velocity, cm/sec

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ABSTRACTS SOLAR ENERGY VOL. 10, NO. 3, 1990

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Forced Convection Modelling of a Solar Central Receiver using Nonisothermal Cylinders in Crossflow

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