濟州大學校 產業技術硏究所 論文集, 第9卷, 1號, pp.64~71, 1998. 6
Cheju National Univ. R.I.I.T. Jour., Vol.9, No.1, pp.64~71, 1998. 6

# A Study of the Thermal Performance of Batch-Type Passive Solar Hot Water Systems

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# Batch-Type 설비형 온수급탕 시스템의 열성능에 관한 연구

천 원 기*

## ABSTRACT

Three batch-type passive water heating systems, which serve the dual function of absorbing solar energy and storing the heated water, have been designed and fabricated for the purpose of side-by-side tests at KIER. The batch systems evaluated are classified according to the design of the box and the arrangement of the storage tanks. Experimental and numerical results given here show the transient performance of these devices. It is also shown that enough hot water could be available in the early morning if the glazing is covered overnight by appropriate insulation. From this study a design has been selected for commercial development in Korea.

## I. Introduction

One of the most cost-effective schemes for harvesting the sun's energy is solar water heating [1, 2]. Tremendous amounts of research and development effort were expended on this topic during recent years [3, 4]. Two general approaches have been considered: active and passive. Active systems, which consist of rather complex sets of mechanical components, are losing popularity due to poor economic viability, slow progress in materials development, and a number of other reasons [5]. As a result, passive systems are often times preferred.

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One category of passive water heating systems is that of the batch-type heater. Batch-type passive solar systems overcome many of the difficulties found in active systems [6, 7, 8]. Batch-type systems have a generally simpler design and lower cost. One of the major drawbacks of the system is its nighttime energy losses to the ambient, but this can be substantially reduced by any of a number of possible approaches. Sodha et al. [9], Garg [7,8], and Chauhan and Kadambi [10] have made great strides in evaluating thermal performances of the batch type systems.

The KIER batch-type systems were constructed such that each unit has a pair of reflector/insulator covers to cut down nighttime energy losses. This can provide hot water availability in the morning. Three types of related designs were evaluated in the work reported here.

## II. Theoretical Development

### General Comments

The instantaneous heat balance equations used in the present study were originally derived by Garg [7] and Garg and Rani [8] in their analyses of solar water heaters. To apply the equations to our batch-type systems, appropriate modifications were made in the terms.

In analyzing the system, each component with significant mass was considered to have a temperature node and a corresponding heat balance equation was developed. The resulting system of equations was solved using measured data for solar radiation and ambient temperature, represented in terms of two Fourier series.

Two cases are considered in formulating the governing heat balance equations for the system-cases with or without nighttime insulation cover. Although two tanks were used in the design (described in detail later), only a single tank was considered in the analysis.

### Without a Nighttime Insulation Cover

Fig. 1 indicates the heat transfer mechanisms considered in our analysis. At each node the heat balance is written as follows.

First, for the glazing:

$$\alpha_g I A_g = m_g C_g \frac{dt_g}{d\theta} + h_{C,ga} A_g (t_g - t_a) + h_{r,gs} A_g (t_g - t_s) - h_{C,lg} A_g (t_1 - t_g) - h_{r,tg} A_g (t_t - t_g) \quad (1)$$

Now consider a balance on the tank surface.

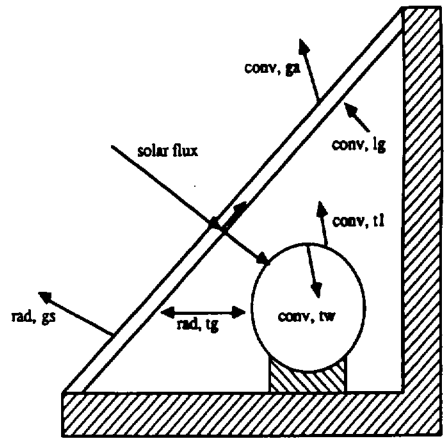



**Fig. 1** Heat transfer mechanisms in a batch-type passive solar hot water system.

$$\tau_g \alpha_t I A_g = m_t C_t \frac{dt_1}{d\theta} + h_{C,tw} A_w (t_t - t_w) + U A_t (t_t - t_a) \quad (2)$$

A balance on the water in the tank yields the following.

$$h_{C,tw} A_t (t_t - t_w) = m_w C_w \frac{dt_w}{d\theta} \quad (3)$$

where $t_a = t_s$, $t_1 = \frac{t_g + t_t}{2}$, $A_t = A_w$, and U is the overall heat transfer coefficient, tank to ambient.

The left hand side of Eqn (1) represents the net absorbed solar radiation. When an external reflector is used, this term (and a related one in the second equation) is augmented appropriately. The terms on the right stand for the heat capacity of the cover glazing, the convective heat loss to the ambient from the cover glazing, net radiation exchange between the cover glazing and the ambient, convective heat gain from the interior, and net radiation exchange between the tank and cover glazing, respectively. The terms in Eqns (2) and (3) are formulated similarly. Here, the initial conditions are given as

$$t_g(\theta=0)=t_1(\theta=0)=t_w(\theta=0)$$
$$=t_t(\theta=0)=t_a(\theta=0)$$

## With a Nighttime Insulation Cover

When a nighttime insulation cover is included in the analysis, the governing equations are modified as follows. First consider the glazing.

$$-m_g C_g \frac{dt_g}{d\theta} + h_{C,\lg} A_g(t_1 - t_g) + h_{r,tg} A_g(t_t - t_g) = U' A_g(t_g - t_a) \quad (4)$$

Here U' is the overall heat transfer coefficient for the loss though both the front and fixed insulation. On the tank surface:

$$-m_t C_t \frac{dt_t}{d\theta} = h_{C,tw} A_t(t_t - t_w) + h_{r,tg} A_t(t_t - t_g) + h_{C,t1} A_1(t_t - t_1) \quad (5)$$

A balance on the water in the tank yields the following equation.

$$h_{C,lw} A_g(t_t - t_w) = m_t C_t \frac{dt_1}{d\theta}$$

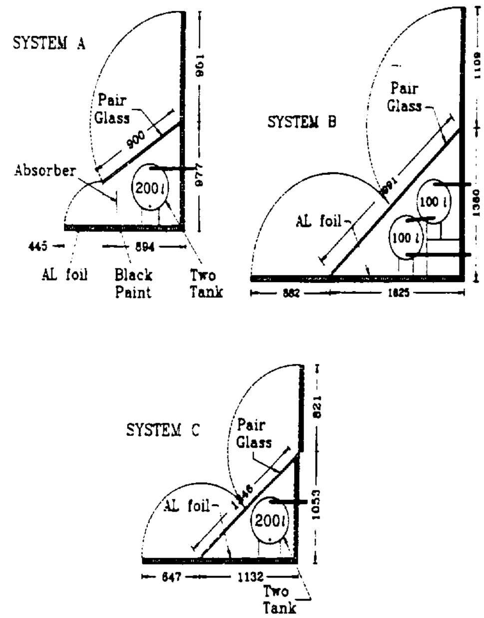
The initial conditions for Eqns (4-6) are found from the integration of Eqns (1-3) until the time that the insulating cover is shut.

## III. Experimental Investigation

### The Systems and Their Installation

Fig. 2 shows the three different configurations of batch type solar water heating systems tested in the present analysis. These are classified as systems A. B. and C.

A typical system contains two 100 liter capacity water tanks (16300 x L900). connected in series. in a well insulated box (100 mm high density EPS). The box has a double cover glazing (3mm glass+ 6mm air gap+3mm glass) inclined at an angle of 480 to the horizontal and facing south. Table 1 shows the design characteristics and the dimensions of the present systems.




1 : Main supply water valve 2 : Inlet valve
3 : Flowmeter 4 : Pressure gage
5 : Drain valve 6 : Digital flowmeter
7 : Bypass valve 8 : Outlet valve

**Fig. 2** Cross sectional view of batch-type passive solar hot water systems-A. B. C Type.

Each system operates on a very simple principle: As heated water is drawn off of the top portion of the second tank. supply water enters the bottom of the first tank via an inlet pipe (ø15). Each tank is fitted with a drain valve and a pressure relief valve.

An insulation/reflection cover is made with the same materials used for the box. One side of this cover that views the glazing is wrapped with aluminum foil so that it could be used as a reflector during daylight hours to enhance solar gain. The insulation/reflection cover is operated manually. By

**Table 1** Specifications of the Three Batch-Type Water Heaters

| System Type | A Type | B Type | C Type |
|---|---|---|---|
| Glazing Area | 2 $m^2$ | $2m^2$ | 2.36 $m^2$ |
| Tank Array | Row | Staircase | Row |
| Box Interior | Flat Black | Aluminum | Aluminum |
| Paint | Foil | | Foil |

The following items were common in all three systems:
Glazing description: Double glazed, with 3-mm glass separated by an air space of 6 mm.
Aperture orientation: 48° with horizontal, facing directly south.
Tank material: 2mm thick stainless steel, painted flat black.
Tank volume: two 100L tanks in each system
Box material: 1 mm black-coated steel sheet.
Box insulation: 100 mm thick EPS.

design, the cover could easily be set in any orientation within 10° increments.

An absorber plate (a 1 mm-thick black copper plate) was placed inside the box of the A-type system to promote natural convection with the hopes of increasing the temperature of the air trapped within it.

A diagram of a typical system arrangement is shown in Fig. 3.

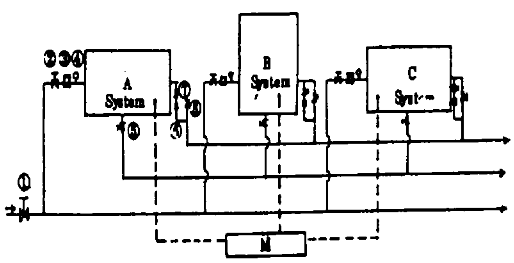



**Fig. 3** Schematic diagram of systems evaluated in the experiments.

## Distributor

As mentioned by many others [11-14], the degree of thermal stratification within the tank is very crucial and influences greatly the system performance. Some have recommended the use of a device that will promote thermal stratification [5]. In the design of the systems discussed here, a distributor was used for this purpose. The distributor used in the present system was made by drilling fifty equally-spaced holes of 2 mm in diameter on a 88 cm long copper tube. See Fig. 4. This permits thermal stratification to develop by slowing down the mixing of incoming water with the water already in the tank.

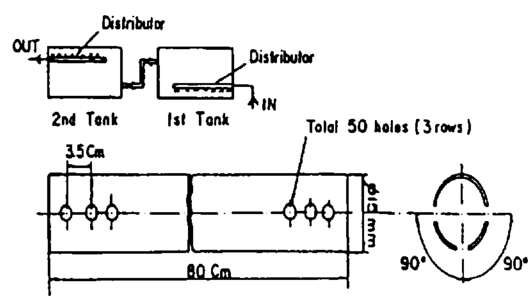
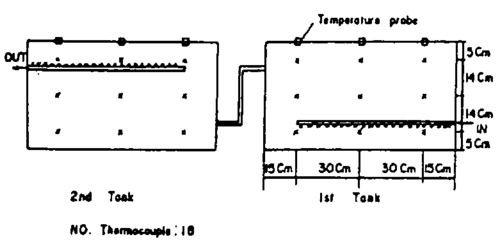



**Fig. 4** Diagram of the distributor used to enhance stratification and cut down on mixing when supply water flows into a tank.

## Measurements

As shown in Fig. 3, measurements were made for these three systems located side by side. Each series of tests began at 9 AM just after the tanks had been filled with fresh supply water. In order to obtain typical daily and seasonal data, test measurements were conducted on clear days for one full year (July 1985 through June 1986).

In Fig. 3. valves 1 and 2 were opened each morning for filling with the supply water. Outlet valve 8 was opened in the afternoon to evaluate daytime thermal performance. 7 indicates a bypass valve and 6 represents a cumulative flowmeter (Hersey Niagara 438, U.S.A.) which was used to measure the total flow and to calculate the total heat flux as water was withdrawn from the system. Flowmeter 3 (Nippon Flow Cel Co. FLT 18A) next to the inlet valve 2 was used to check the temperature distribution inside the tank when the incoming flow rate was held constant. With the outlet valve 8 closed, pressure gauge 4 measures water pressure to assure safe operation of the system. Drain valve 5 was used to prevent damage from freezing and to flush the system before starting a test to ensure as uniform starting temperature as possible.




a : Insolation
c : Ambient Temp.
b : Tank Temperature (Exp.)
d : Tank Temperature (Pred.)

**Fig. 5** Location of thermocouples.

Fig. 5 shows the positions of the thermocouples used the experiment. The mean temperature of water in the tank was calculated by taking the weighted-volume average of 18 measured temperature points.

## Ⅳ. Results and Discussion

Fig. 6 shows the mean water temperature inside the tank for the measured and predicted values. Agreement is fairly good both qualitatively and quantitatively during the main part of the day. As expected, the mean water temperature varies according to a relative balance between solar input and heat losses.

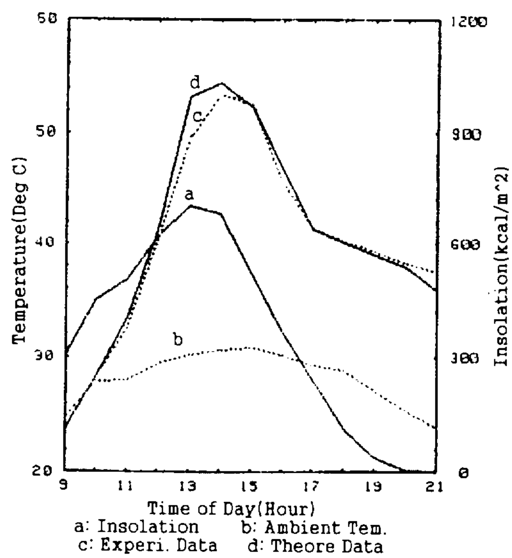



**Fig. 6** Comparison between experimental and theoretical average water temperature in the tank--B Type with no cover, Summer.

The monthly average collection efficiency is defined as

$$\eta = \frac{\int_0^{\theta} q_w d\theta}{A_g \int_0^{\theta} I d\theta} \tag{7}$$

The results for the A-, B-, and C-type systems aregiven in Fig. 7. The B type system showed better performance throughout the year compared to the A and C types. The annual average collection efficiency of the A-, B-, and C-type systems were 51.5%,

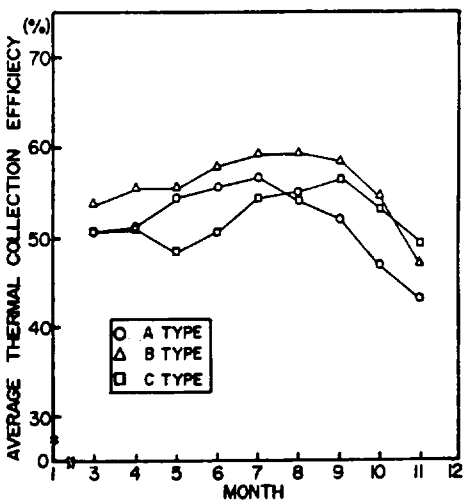



Fig. 7 Monthly average thermal collection efficiency--A. B. and C Types.

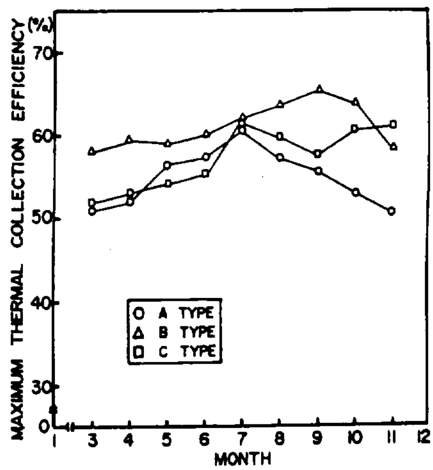



Fig. 8 Monthly average maximum thermal collection efficiency--A. B. and C Types.

55.7%. and 52.3%. respectively. The integrated collection efficiency up to the point where the maximum tank temperature is reached is defined as

$$\eta' = \frac{\int_0^{\theta} q_w d\theta}{A_g \int_0^{\theta} I d\theta} \qquad (8)$$

was also used as a parameter for indicating system performance. Fig. 8 presents the monthly-averaged values of this quantity for the A-. B-. and C-type systems. Note the similarity of these results to the plots given in Fig. 7. The annual average maximum collection efficiency for A-. B-. and C-type systems were 54.7%. 61.8%. and 57.3%. respectively. It is believed that the better thermal performance of the B-type system was achieved by the arrangement of storage tanks as well as its geometrical configuration which is thought to enhance stratification effects.

Fig. 9 shows the variation of mean water temperature inside the tank (B type) for three consecutive days without nighttime insulation cover and no water drawoff. This particular experiment

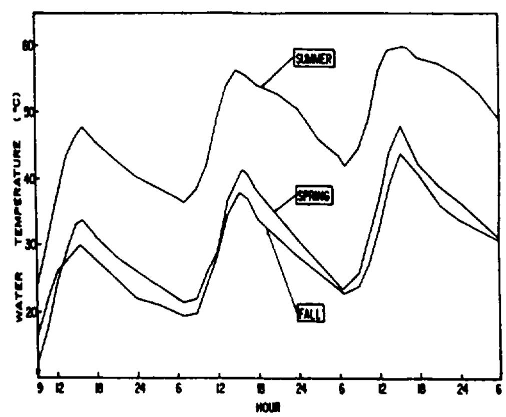



Fig. 9 Seasonal average water temperature rises in the tank for three consecutive Days--B Type.

has been conducted for each season except in winter. All three systems showed a similar pattern of fluctuations. The ambient conditions and solar flux showed similar variations each day during the time period shown. When tank temperatures were compared for the same hour of each consecutive day. they showed a gradual increase with time as can be seen from the plot.

Fig. 10 compares the temperature-height distribution

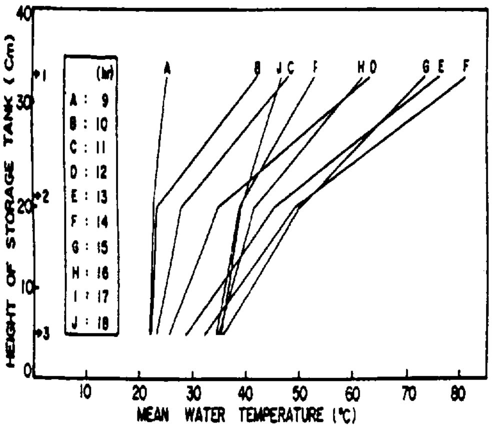



Fig. 10 Distribution of average water temperature for the height of the tank--B Type(July).

results of the system at various times of a typical day in July. The upper portion of tank water shows a sharp increase in temperature from 10 AM to 2 PM before it starts to level off till 5 PM. This trend is well-predicted since major heat collection takes place at top section of the tank As incident solar radiation achieved a maximum at around 2 PM. the mean tank temperature also reached its peak. The temperature difference between the top and bottom layer of water was 48.7 ℃ at this hour. Heat transfer within the tank is mainly governed by conduction phenomena which caused a slow redistribution of temperature.

Fig. 11 shows the temperature distribution of the B-type system when warm water was drawn off from the tank outlet and at the same time water entered the system. The presence of flat temperature gradient in the upper portion of each tank reflects the effect of distributors installed there.

One indication of the effects of the cover insulation is shown in Fig. 12. The two situations given there were for similar variations in ambient temperature. Following the achievement of the same maximum tank temperature. the temperature of the insulated tank remained significantly higher compared to the uninsulated tank.

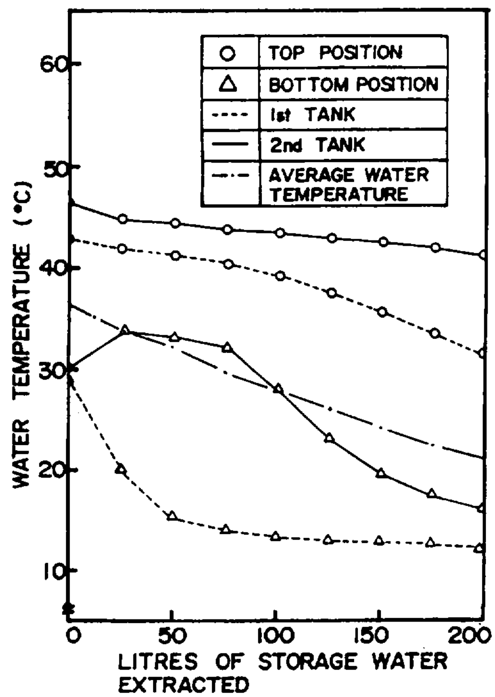



Fig. 11 Temperature variation of water with quantity drawn off at 18:00--B Type(May 7, 1986).

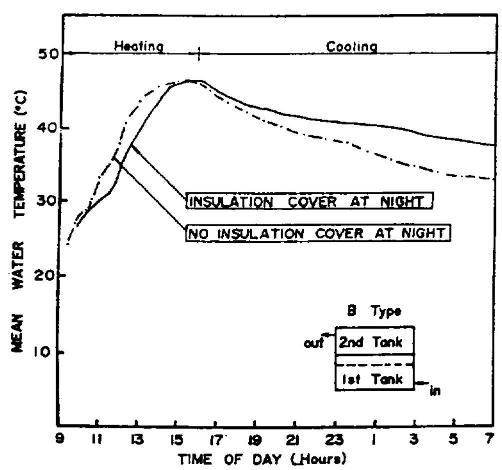



Fig. 12 Effects of cover insulation compared to a similar situation with no insulation--B Type.

The results were then compared with those of a commercial batch-type heater (Sun Runner Passive Heater. TEF. Model SR Jr. USA) under various operating conditions. Our designs performed in a very satisfactory manner compared to this other unit.

Attempts are currently underway to commercialize our design in Korea.

## V. Conclusions

A number of conclusions can be drawn from the present experiments and analyses.

1) Among three types of batch systems investigated here, the B-type (which has the stepwise tank arrangement) showed the highest thermal performance. Its annual collection efficiency of 55.7% seems very promising.

2) The step-wise tank configuration and the distributors of our design were very useful in maintaining a high degree of thermal stratification when hot water is drawn off from the top and supply water enters the bottom section of the tank during periods of operation.

3) Use of the insulation/reflection cover designed by our team was proven to be very effective in enhancing incoming solar radiation and in decreasing overnight heat loss.

4) Good agreement was shown between experimental and numerical results.

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