METHOD FOR SIZING OF SOLAR STORAGE TANK CONSIDERING DOMESTIC HOT WATER LOAD PROFILES

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1. Introduction

The storage tank of the solar thermal system is installed as a type of thermal buffer, because the time to accumulate the solar energy and the time to use the gathered energy do not match. The amount of water to store the excess collector output and return it when needed varies depending on the load profile. Therefore, the load profile should be considered when designing the storage tank. Even though the amounts of loads are equal, the required capacity of the storage tank varies with time when the load occurs. In order to use solar energy as much as possible, i.e. to increase the solar fraction of the system, the size of the storage tank should be estimated according to the load profile.

Various studies on the solar thermal system have been performed considering the load profile (Jordan and Vajen, 2001; Knusen, 2002; Lund, 2005). However, in the early design stages, the load profile is not reflected well in the sizing of the storage tank. The method which is commonly used to estimate the storage tank size in the initial design phase is in accordance with ASHRAE 90003. The minimum storage capacities per collector area for three different load profiles are presented in ASHRAE 90003, and it is proposed that the size of the storage tank is estimated by multiplying the value by the collector area. The recommended minimum storage capacities per collector area are shown in Table 1.

The above method proposes the appropriate size according to the load pattern, but the load profile types are limited. Because the load profile varies depending on various factors such as climate, building use, human occupation, it may be difficult to define the type of load profile within these three types. Sizing the storage tank using values which do not match can lead to a decline of the system performance.

Therefore, in this paper, the simplified method which estimates the storage tank size using the load profile of the building, instead of selecting the type of load profile, is presented. If the load profile of the building and simple information are available, this method can be applied.

The procedure of the study is as follows. First, a method for the sizing of the solar storage tank considering the load profile by using the principle of the storage is presented. A case study using the proposed method is then conducted for two types of load profile, and the results are compared with the results of the ASHRAE method. Then, the thermal performance (solar fraction, temperature) of the storage tank estimated by the two methods is analyzed by a developed simulation program. Consequently, the suggested method is evaluated based on the analysis.

Tab. 1: Storage capacity per collector area (recommended by ASHRAE)

Load pattern	Storage capacity per collector area [liter/m²]
7 days / week, a constant day-time load	20.4~28.6
5 days / week, a constant day-time load No weekend load	40.8
A constant night-time load	71.4~81.6

2. Method for the sizing of the storage tank considering the hot water load profile

2.1. Concept of the method

In order to consider the hot water load profile, a method based on a fundamental concept of storage was developed. In a solar thermal system, the available energy exceeds the load in the daytime, and at other times it is less than the load. Therefore, a storage subsystem is added to store the excess collector output and return it when needed. The concept of this method is to store the excess collector output during the daytime by comparing the daily production and consumption profile.

In Figure 1, the vertical shaded areas show the excess energy to be added to the storage and the horizontal shaded areas show the energy withdrawn from the storage to meet the loads. In the proposed method, therefore, the capacity of the storage tank which can store the amount indicated by the vertical shaded areas should be calculated by comparing the production and consumption profile. This method can be applied if the load profile of the building and the solar radiation data of the location are available.

2.2. Procedure of the method

The procedure of this method is as follows.

1. Calculate a maximum daily hot water load of a building.

2. Estimate the required collector area A_c depending on the ratio of the amount of the load heated by solar energy to the amount of the load required for demand (solar fraction) using equation (1).

$$A_c = (Q_L \times f)/(I_T \times \eta_c) \quad \text{(eq. 1)}$$

where A_c is the required collector area, Q_L is the maximum daily hot water load, f is solar fraction, I_T is the annual average hourly radiation value, and η_c is the collector efficiency.

3. Obtain the hourly collector useful gain Q_u, by multiplying the estimated collector area A_c, annual average hourly radiation value I_T and collector efficiency η_c.

4. Create the hot water load profile (i.e. calculate hourly hot water load Q_L), distributing the maximum daily hot water load according to the predicted hot water usage pattern of the building.

5. Calculate the sum the difference between the hourly collector useful gain Q_u and the hourly hot water load Q_L during the daytime as equation (2).

$$Q_{st} = \sum\{Q_u - Q_L\} = \sum\{A_c \times I_T \times \eta_c - \dot{m}_L \times c_p \times (T_{hw} - T_{sup})\} \quad \text{(eq. 2)}$$

where Q_{st} is the amount of heat to be stored, $\dot{m}_L$ is the mass flow rate of the load side, c_p is the specific heat of the water, T_{hw} is the desired hot water temperature, T_{sup} is the supply water temperature.

6. Calculate the size of the storage tank with a capacity of the amount of heat to be stored Q_{st} using the equation (3). The desired hot water temperature is usually 60℃.

$$m_{st} = Q_{st} / \{c_p \times (T_{hw} - T_{sup})\} \quad \text{(eq. 3)}$$

A case study using the suggested method above is introduced in the next section. For and adequate method, the evaluation of the estimated capacity of the storage tank by the method will be discussed.

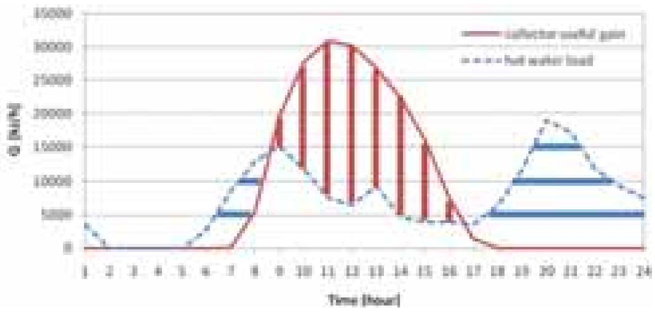


Fig. 1: Concept for the sizing of the storage tank

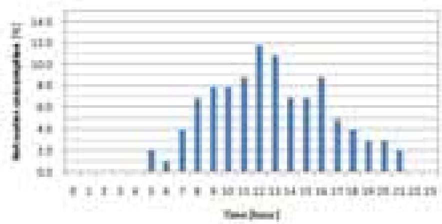
3. Case study for the sizing of the storage tank by the proposed method

The application of the method is shown through case studies. In order to verify if the sizing of the storage tank by the proposed method considers the effects of the load profile, case studies were carried out for two hot water load profile cases. The total daily hot water loads set equally. The profiles were selected, considering the temporal relationship with production the profile and the concentration of the load.

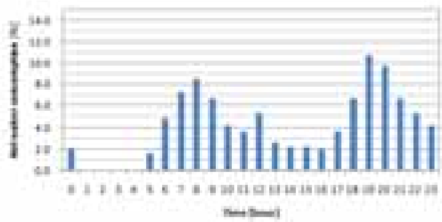
The profiles used for the case study are as follows.

- Case 1: For buildings such as commercial buildings, the load occurs mostly during the day. Because the load coincides with the availability of solar radiation, less storage is required. (Figure 2 (a))
- Case 2: For buildings such as residential buildings, the load is more concentrated in the morning and evening with poor solar radiation. Solar energy to be used for evening and the next morning should be stored. (Figure 2 (b))

To consider only the effects of the distribution, the amount of hot water demand for each case was set identically as mentioned above. Therefore, the two graphs in Figure 2 represent the same area. Other conditions for this case study are given in Table 2.



(a) Case 1: Example for commercial buildings



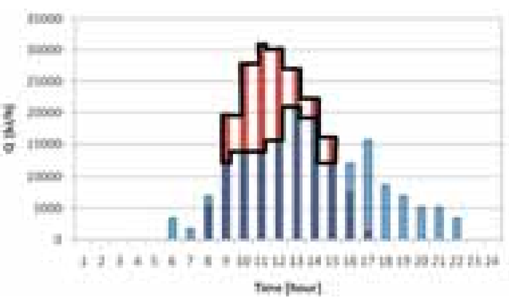
(b) Case 2: Example for residential buildings

Fig. 2: Hot water load profiles

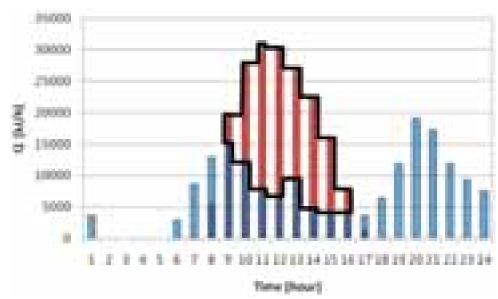
Tab. 2: System parameters for case study

Location	Seoul, Korea
Hot water usage	948ℓ/day at 60℃
Design solar fraction	80%
Collector	• Flat plate collectors (single cover and selective coated) • South facing with tilt of 45° • Efficiency 50%
Solar radiation	• Annual average value • Hourly solar radiation at 45° • Total daily solar radiation 3481 W/m²·d

The collector area was determined as 30m² according to the above conditions. Then, the hourly collector useful gain obtained using the above conditions and each case of the hot water load profile are plotted together as shown in Figure 3. The amount indicated by the parts marked with bold borders in Figure 3 should be stored. As a result of the calculation for the amount, it is determined that 65,209 kJ in case 1 and 118,004 kJ in case 2 should be stored.



(a) Case 1



(b) Case 2

Fig. 3: Amount of heat to be stored (in accordance with the proposed method)

Tab. 3: Difference with the result of the ASHRAE method

	Proposed method	ASHRAE method
Case 1 (commercial buildings)	300liter	600liter
Case 2 (residential buildings)	550liter	2,000liter

The values for m_{st} calculated using equation (3) are 277.9liter and 502.9liter for case 1 and case 2 respectively. Therefore, 300liter and 550liter are proposed as the appropriate size of storage tank in case 1 and case 2 respectively by considering the size actually manufactured and the clearance. As expected, if the load is more concentrated during the day-time such as in case 2, the required capacity of the storage tank is smaller.

The results of the proposed method were compared with the ASHRAE method. After selecting the type of presented load profiles from Table 1, the calculation was conducted. Case 1 was applied to 20.4~28.6 liter/m², and case 2 was applied to 71.4~81.6 liter/m². As a result of the calculation, the storage tank size is suggested as 600liter in case 1, and 2,000liter in case 2.

The calculated results obtained by both methods are displayed in Table 3. The table shows that there is a significant difference between the two methods. The result of the ASHRAE method is two times larger in case 1. Also, the result of the ASHRAE method is four times larger in case 2. Therefore, the result obtained by the proposed method should be evaluated. The thermal performance of the storage tank estimated by the proposed method is analyzed by a detailed simulation program in the next section.

4. Evaluation of the sizing of the storage tank by the proposed method

A simulation program has been developed in order to evaluate the thermal performance of the solar thermal system. The program consists of a collector module, a storage tank module, and a control module. In the storage tank module, the 'Multi-node model' that divides the storage tank into multiple nodes of equal volume is used to determine the temperature of the stratified storage tank by height. The temperature is calculated via the energy balance equation by numerical method to determine the temperature of each node. An analysis can be performed of the internal temperature distribution of the storage tank, the supply temperature to the load side, and the solar fraction; this is the ratio of the amount of load heated by solar energy to the amount of load required for demand.

Sets of simulations for each case were run for one year and the monthly load ratios were set up differently. When changing the size of the storage tank, the aspect ratios were made equal as much as possible, because the narrowness of the storage tank also affects the thermal performance of the storage tank. Various input data for simulation are given in Table 4.

Tab. 4: Input data for simulations

Period of simulation	1st January ~ 31st December (one year)											
Meteorological data	Solar radiation, ambient temperature data of Seoul, Korea											
Monthly hot water load ratio (%)	100	99	87	76	63	51	35	31	40	54	63	98
Monthly city water temperature (℃)	4	5.3	9.1	14	19.5	22	24.2	24.6	25.4	22.7	17.6	8.8
Storage tank	Cylindrical stratified storage tank with internal heat exchanger • Case 1 - 300liter (490 x 1600) / 600liter (620 x 1990) • Case 2 - 550liter (600 x 1950) / 2,000liter (920 x 3010)											
Heat exchanger	• Internal heat exchanger (plain tube) • Length : 30m, Efficiency : 70% • At the bottom of the storage tank											

4.1. Solar fraction of the solar thermal system

Table 5 and Table 6 show the monthly and yearly solar fraction of the system according to the tank size for case 1 and case 2 respectively. As can be seen, the annual average solar fraction of the 300liter tank which is determined by the suggested method is 1.4% higher than 600liter, and the annual average solar fraction of the 550liter tank is 3.7% higher than 2,000liter. The results can also be found in Figure 5. The black bars in Figure 4 represent the difference in the solar fraction of the system when the 300liter/550liter tank is higher.

In case 1, the monthly solar fractions of the 600liter tank are slightly higher (0.1 to 0.3%) only in winter, while the monthly solar fractions of the 300liter tank are higher (max. 4%) in all the other seasons. In case 2, the solar fractions of the 2,000liter tank are slightly higher (0.2, 1.9%) only for two months (February, December), while the solar fractions of the 550liter tank are higher (max. 16.3%) in all the other months. Also, the increase of the solar fractions in winter is not sufficient compared to the increased capacity. Therefore it is considered that choosing the 300L/550L tank could be appropriate in terms of cost and space.

The reason why the difference varies with the season can be verified through equation (4), which is a modified form of equation (3).

$$Q_{st} = m_{st} \times c_p \times (T_s - T_{sup}) \quad \text{(eq. 4)}$$

If the transferred energy from the collector Q_{st} is identical regardless of the size of the tank, the temperature difference of the hot water inside the storage tank ΔT varies depending on the size of the tank. A large storage tank has a large quantity of low temperature hot water, and a small storage tank has a small quantity of high temperature hot water. Therefore, the total supplied energy from the storage tank is similar in winter because a large quantity of hot water is used, but a small storage tank of high temperature is more advantageous in other seasons.

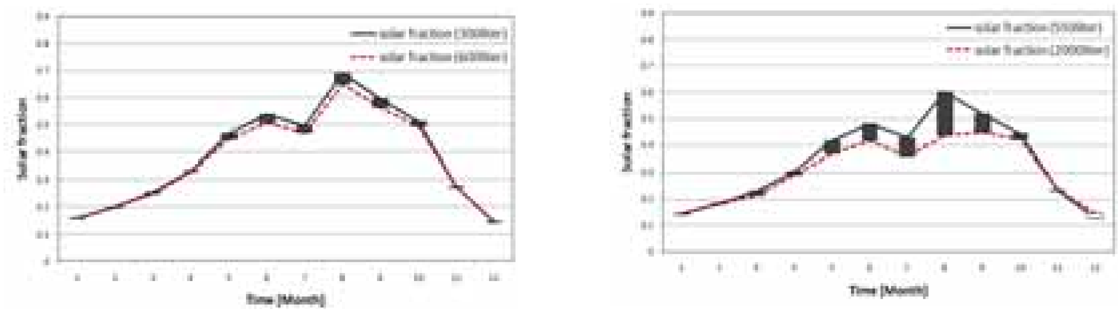
However, the temperature should be checked if the small storage tank is overheated. As a result of the confirmation, the maximum temperatures of the 300liter/550liter tank are 67.0℃/60.5℃. (Maximum temperatures of the 600liter/2,000liter tank are 62.7℃/47.4℃.) Thus, the estimated size of the storage tank obtained by the proposed method does not seem to have a problem with overheating. Rather it is considered that the temperature of the 2,000liter tank is too low and the tank might use more auxiliary power.

Tab. 5: Monthly and yearly solar fraction (Case 1) [%]

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Avg.
300liter	15.9	19.9	25.4	33.2	46.6	53.8	49.7	69.1	59.5	51.4	27.5	14.2	38.9
600liter	16.1	20.0	24.9	33.1	44.6	50.8	46.9	65.1	56.5	49.5	27.6	14.5	37.5

Tab. 6: Monthly and yearly solar fraction (Case 2) [%]

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Avg.
550liter	14.4	18.3	23.0	30.3	41.6	47.9	42.8	60.0	51.6	44.2	23.5	12.7	34.2
2,000liter	14.4	18.5	21.3	28.9	36.9	41.6	35.6	43.6	44.9	42.2	23.3	14.6	30.5



(a) Case 1 **(b) Case 2**

Fig. 4: Comparison of the solar fraction according to storage tank size

4.2. Supply temperature from the storage tank

In case 1, the temperature change of the hot water supplied to the load side from the storage tank is mainly divided into two forms depending on the season (load ratio). The temperature change in the other seasons appears in the form similar to Figure 5, while the temperature change in winter which has high monthly hot water load ratio appears in the form similar to Figure 6.

Figure 5 shows the temperature change from May to November. During this period, the 300liter tank continuously maintains a 5-10 degrees higher temperature, but when there is insufficient solar radiation, it has a lower temperature than the 600liter tank. However, if the sufficient solar radiation is reached, the temperature increases quickly and a higher temperature than the 600liter tank is maintained.

Figure 6 shows the temperature change of hot water in winter. It shows that the temperature of the 300liter tank starts quickly falling to a lower temperature from the morning, and again the temperature rapidly rises to a higher temperature.

In the enlarged part of the graph in Figure 6, the area between the dotted lines refers to the amount that can be supplied at a higher temperature if the tank size is 600liter, and the remaining area refers to the amount that can be supplied at a higher temperature if the tank size is 300liter. In January which has the highest monthly load ratio, the two areas are similar. Also, with a smaller monthly load ratio, the area representing the amount that can be advantageous if the tank size is 300liter increases. However, at this time, Q_{solar} considering both the temperature difference and the amount of hot water should be analyzed.

Examining this further, it can be seen that the temperature decreases in the morning when solar radiation occurs. This is because it takes time for the solar radiation reaching the collector to affect the temperature of the hot water supplied to the load side; this is because there is a time lag between the solar radiation and the temperature increase of hot water supplied to the load side. Even though the solar radiation occurs, if the rate to discharge is faster than the rate to charge, the temperature decreases.

At the design stage, the size of the storage tank was calculated by subtracting the hourly hot water load Q_L from the hourly collector useful gain Q_u assuming that the solar radiation can be used immediately. Therefore, the size of the storage tank should be modified to consider the time lag.

Case 2 showed similar results to those of case 1. The temperature change in the remaining seasons appears in a form similar to that shown in Figure 5, while the temperature change in winter, when there is a high monthly hot water load ratio appears in a form similar to that shown in Figure 6.

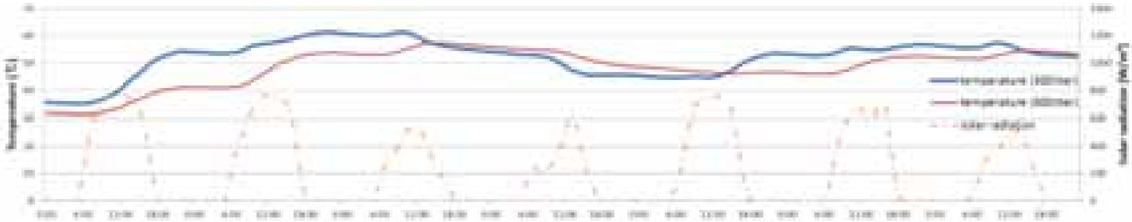


Fig. 5: Example of the temperature of the hot water supplied to the load side from the storage tank (except winter)

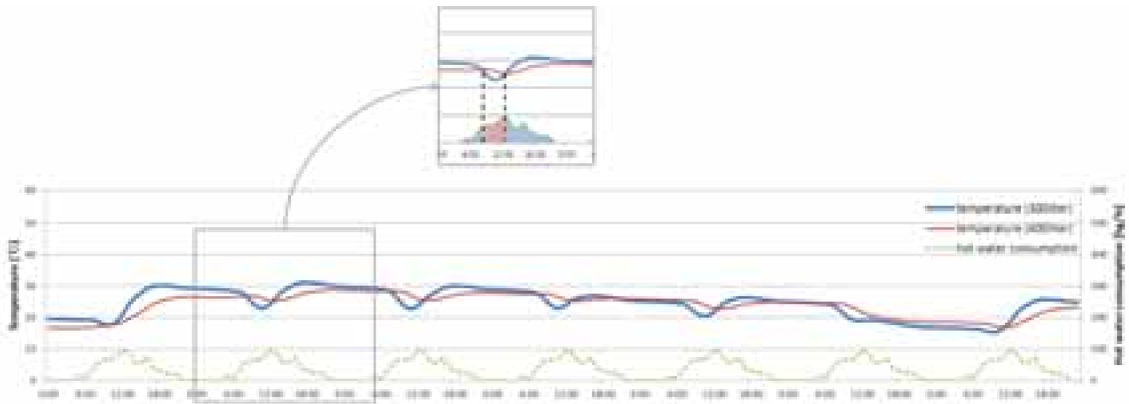


Fig. 6: Example of the temperature of the hot water supplied to the load side from the storage tank (in winter)

5. Discussion and conclusions

A method was proposed for the sizing of the solar storage tank considering the load profile. The procedure of the method is described in section 2. The application of the suggested method was shown through a case study. The case study using the proposed method was conducted for two types of load profile, and the result is compared with the value of the ASHRAE method. The result of the case study shows a significant difference to the result of the ASHRAE method. Therefore, for the evaluation of the result by the proposed method, the thermal performance (solar fraction, temperature) of the storage tank estimated by the proposed method is analyzed by a detailed simulation program.

As a result of the simulation, the annual average solar fraction of the 300liter tank which is determined by the suggested method is 1.4% higher than 600liter, and the annual average solar fraction of the 550liter tank is 3.7% higher than 2,000liter. The solar fractions of the storage tank estimated by the proposed method are higher (max. 4 to 16.3%) in all seasons except winter. The solar fractions of the storage tank estimated by the ASHRAE method are slightly higher (0.1 to 1.9%) only in winter, and the increase of the solar fractions in winter is not sufficient compared to the increased capacity. In conclusion, it is considered that choosing the 300liter/550liter tank could be appropriate in the terms of cost and space.

In terms of the supply temperature to the load side from the storage tank, the storage tank estimated by the proposed method mostly maintains a 5-10 degrees higher temperature (except on a sunless day) in all seasons except winter, although there are some fluctuations in winter. High solar fraction and high supply temperature lead to reduction of auxiliary power consumption which saves the energy. Thus, the thermal performance of the storage tank estimated by the proposed method seemed to be acceptable even though the size significantly differ to the calculated size obtained by the ASHRAE method.

Therefore, it seems to be appropriate to estimate the storage tank size using the proposed method in order to consider the effect of the load profile. However, in order to use the solar energy even when the solar radiation is low yet the average temperature is low, a larger storage tank capacity should be used.

In this method, the size of the storage tank was calculated by subtracting the hourly hot water load Q_L from the hourly collector useful gain Q_u assuming that the solar radiation can be used immediately. However, a time lag occurs between the solar radiation and the temperature increase of hot water supplied to the load side. Therefore, future work will improve the method considering the time lag.

6. Acknowledgement

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7. References

ASHRAE 90003, 1988. Active Solar Heating Systems Design Manual, American Society of Heating. Refrigerating, and Air-Conditioning Engineers.

Jordan, U., Vajen, K., 2001. Influence of the DHW load profile on the fractional energy savings: a case study of a solar combi-system with TRNSYS simulations. Solar Energy 69, 197-208.

Knudsen, S., 2002. Consumers' influence on the thermal performance of small SDHW systems-Theoretical investigation. Solar Energy 73, 33-42.

Kulkarni, G.N., Kedare, S.B., Bandyopadhyay, S., 2007. Determination of design space and optimization of solar water heating systems. Solar Energy 81, 958-968.

Lund, P.D., 2004. Sizing and applicability considerations of solar combisystems. Solar Energy 78, 59-71.

Matrawy, K.K., Farkas, I., 1996. New technique for short term storage sizing. Renewable Energy 11, 129-141.

Raffenel, Y., Fabrizio, E., Virgone, J., Blanco, E., Filippi, M., 2009. Integrated solar heating systems: From initial sizing procedure to dynamic simulation. Solar Energy 83, 657-663.