A SIMULATION OF THE THERMAL STORAGE PERFORMANCE OF THE METAL FIN EMBEDDED CONCRETE

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ABSTRACT

The primary aim of the present study was to evaluate thermal storage performance of the storage medium embedded with metal fins and to prepare and accumulate design data. Thus, basic study was performed on concrete structure embedded with metal fins by means of model experiment and numerical analysis.

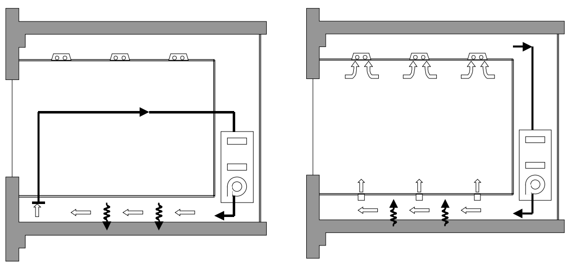
As the measurement, it was confirmed that thermal storage time was reduced and storage efficiency was improved due to the embedding of metal fins. Forthermore, Numerical analysis was carried out by using number of fins, embedding depth, and materials of fins as parameters, and general guidelines for the working design were determined.

INTRODUCTION

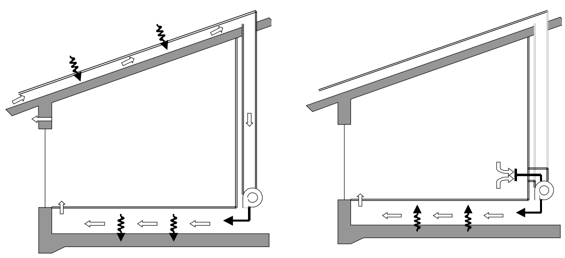
From the viewpoint of the protection of global climate in recent years, it is now essential and indispensable to promote effective utilization of natural energy and saving of energy when construction of buildings is planned. For the purpose of effectively utilizing energy, a wide variety of short-term thermal storage systems have been proposed for the utilization of heat for daytime use by storing the excessive electric power at nighttime. The former method is used to store excessive electric power during nighttime and to reduce power load during daytime. The latter method is utilized for the heating system using solar heat. One of such methods is to heat up the air by using excessive electric power or solar heat as heat source and to store the heat by blowing hot air to the building. (Hereinafter, this is abbreviated as “building thermal mass storage”).

Fig. 1 shows example of building thermal mass storage of presant study’s target. According to this method, heat is stored in the thermal storage medium by convection heat transfer between fluid and solid medium. On the other hand, the use of a finned plate is known as a method to increase heat transfer amount between solid medium and fluid, and this can be applied for the building thermal mass storage. However, sufficient basic data are not available at present on the effects to increase thermal storage efficiency or on the parameters such as number and materials of fins, and embedding depth. For this reason, not many application examples are known so far in the use of fins for building thermal storage.

The primary aim of the present study was to evaluate thermal storage performance of the thermal storage medium embedded with metal fins and to prepare and accumulate design data. Thus, basic study was performed on concrete structure embedded with metal fins by means of model experiment and numerical analysis. In the present report, we will discuss the experimental effects to evaluate thermal storage performance of fin-embedded thermal storage medium, and we also present the results of numerical analysis on the influence of parameters such as materials and number of fins, embedding depth, and so on.



Heat Storage (Midnight)   Heat Extract (Daytime)
(a) Storage System Using Midnight Electric Power



Heat Storage (Daytime)   Heat Extract (Nighttime)
(b) Storage System Using Solar Radiation

Figure 1   Example of Building Thermal Mass Storage

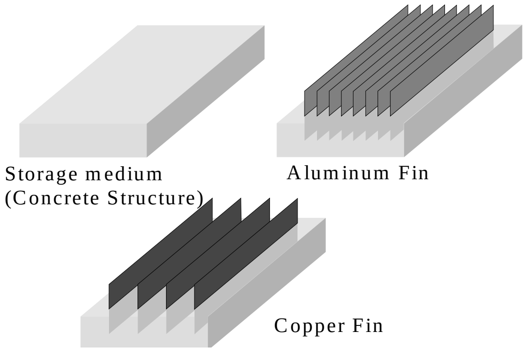


Figure 2 Metal Fin Enbedded Concrete

(a) Experiment Space (b) Fin Embedded Concrete

Figure 3 General Features of Experiment

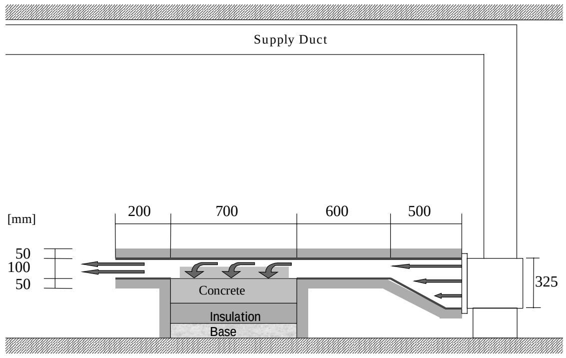


Figure 4 Section of Experiment device

BUILDING THERMAL MASS STORAGE

A wide variety of diurnal short-term thermal storage systems have been proposed to store sensible heat and latent heat in solid medium or in fluid for effective utilization of natural energy or for utilization of excessive electric power during nighttime for daytime use. As the method of thermal storage, ice thermal storage method, water thermal storage method(ASHRAE, 1995), and soil thermal storage method(Sakai, et al., 2001) are known. However, these methods have problems in installation cost, or in limitation of the space for installation. On the other hand, in the building thermal mass storage method, special attention is given on thermal capacity of the building itself, and heat is stored in walls and floor slabs. In this method, it is possible to reduce the cost of installation or the limitation in installation space and it can also be used for the existing building, and it is now widely propagated.

In the building thermal mass storage now generally in application, hot air or cold air is blown to the objects such as floor slabs, and heat is stored in thermal storage medium. Specifically, it is a method to carry out heat transfer through convection heat transfer between fluid and solid medium. When the air is used as a thermal medium, convection heat transfer rate is lower compared with water. For this reason, there are problems that thermal storage time is longer or utilization of thermal storage capacity is insufficient.

On the other hand, the finned plate is used for increasing the heat transfer amount between solid medium and fluid, and this is widely used on the surface of coil such as fan coil. In the building thermal mass storage also, it would be possible to increase heat transfer amount and to reduce thermal storage time or to control thermal storage performance if the thermal storage medium is provided with fins. However, because sufficient data is not available on the effects of the embedding of fins for the promotion of thermal storage efficiency or because of the lack of basic data on parameters such as materials and number of fins, embedding depth, and so on., there are not many application examples of the use of fins for building thermal mass storage at present. Under such circumstances, we performed basic evaluation on concrete structures embedded with metal fins by using model experiment and numerical analysis in order to more clearly define thermal storage performance of the fin-embedded thermal storage medium and to prepare and accumulate design data.

OUTLINE OF MODEL EXPERIMENT

The primary aim of the present study was to evaluate thermal storage performance in building thermal mass storage using the fin-embedded thermal storage medium and to prepare and accumulate design data. As the first stage of the study, basic evaluation was performed using model experiment. Fig. 2 shows a thermal storage medium (fin-embedded concrete structure), and Fig. 3, 4 shows general features of the experiment system. In the experiment, a concrete structure of 120 x 350 x 700 mm was used, and fins (aluminum plate and copper plate) of 180 x 1 x 660 mm were embedded to the depth of 90 mm into the thermal storage medium. Heat insulating material of 50 mm in thickness was arranged around the thermal storage medium. In the present study, it was assumed to use a thermal storage method to heat up the air by utilizing excessive electric power and solar heat as heat source and to store heat by blowing hot air to the building structure. Measurement was made in a case where the air was blown to upper portion of the thermal storage medium. An air-conditioner was used as the heat source required for heat storage and heat extract.

Table 1   Experiment and Simulation Cases

Case	Wind Velocity [m/s]	Fin Material	Conductivity λ [W/mK]	Capacity Cρ [kJ/m^{3}K]	Fin Location	Depth [cm]	Length [cm]	Notes
1	1.0	Non	1.624	2013.47	Non	Non	Non	Exp.
2	2.3	Non	1.624	2013.47	Non	Non	Non	Exp.
3	3.6	Non	1.624	2013.47	Non	Non	Non	Exp.
4	1.0	Aluminum	236.756	2373.46	A B C D	9	9	Exp.
5	2.3	Aluminum	236.756	2373.46	A B C D	9	9	Exp.
6	3.6	Aluminum	236.756	2373.46	A B C D	9	9	Exp.
7	1.0	Copper	386.628	3428.33	A C	9	9	Exp.
8	2.3	Copper	386.628	3428.33	A C	9	9	Exp.
9	3.6	Copper	386.628	3428.33	A C	9	9	Exp.
10	3.6	Copper	386.628	3428.33	A B C D	9	9	Non
11	3.6	Concrete	386.628	3428.33	A B C D	9	9	Non
12	3.6	Steel	47.931	3436.71	A B C D	9	9	Non
13	3.6	Stainless	25.311	3206.48	A B C D	9	9	Non
14	3.6	Tile	1.275	2612.06	A B C D	9	9	Non
15	3.6	Glass	0.774	2021.84	A B C D	9	9	Non
16	3.6	Linoleum	0.186	1172.08	A B C D	9	9	Non
17	3.6	Board	0.116	519.06	A B C D	9	9	Non
18	3.6	Aluminum	236.756	2373.46	A	9	9	Non
19	3.6	Aluminum	236.756	2373.46	AC	9	9	Non
20	3.6	Aluminum	236.756	2373.46	A B C D	3	9	Non
21	3.6	Aluminum	236.756	2373.46	A B C D	6	9	Non
22	3.6	Aluminum	236.756	2373.46	A B C D	9	3	Non
23	3.6	Aluminum	236.756	2373.46	A B C D	9	6	Non

The experimental conditions are summarized in Table 1. Measurement interval was 1 minute. The temperature of the blown air during thermal storage was 30°C, and the temperature of the thermal storage medium at the initiation of thermal storage was 15°C. This is different from the condition of actual building thermal mass storage, but it is considered as sufficient for the purpose of confirming the thermal storage performance.

OUTLINE OF NUMERICAL ANALYSIS

In order to identify the thermal storage condition in detail and to declare the influence of fin characteristics, we made a simulation code according to the finite volume method (Patanker, 1980) . The fundamental equation is shown at Table 2.

In the numerical analysis, the test sample was used as 2-dimensional model. It was divided to meshes of 364 x 59 (thermal storage medium 350 x 24) for analysis. Minimum width of mesh was 1 mm. The time dependence term approximately used the full implicit scheme (Δt = 1 minute), other term was used central scheme. Heat radiation on the surface of the thermal storage medium was not considered. Calculation model is shown in Fig. 5.

Evaluation was performed on 23 cases in all by varying the parameters such as air flow rate, fin material, and so on.

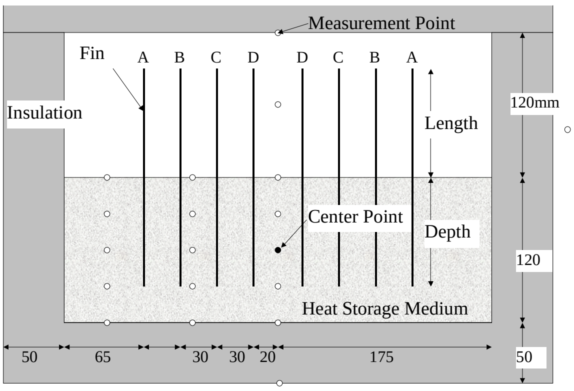


Figure 5   Simulation Model (2 dimensional)

Table 2 Basic equation

$$\frac{\partial C\rho\Theta}{\partial t} = \frac{\partial}{\partial x_j}\left(q_j\right) \quad (1)$$

solid part:

$$q_j = \lambda \frac{\partial \Theta}{\partial x_j} \quad (2)$$

Surface:

$$q_j = \alpha_c(\Theta_{surface} - \Theta_{air}^{experiment}) \quad (3)$$

The cases under evaluation are summarized in Table 1. In Cases 1 - 9, comparison was made with experiment.

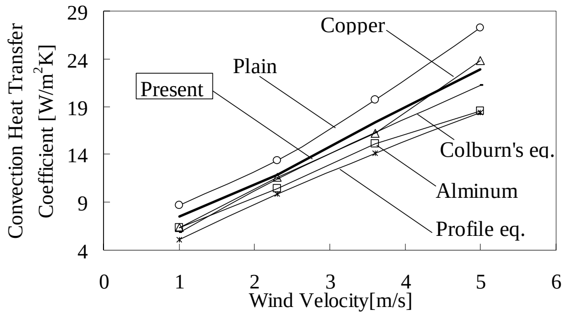


Figure 6 Results of Convection Heat Transfer Coefficient α_c Estimation

Measured values were used for temperature of the blown air (30°C), temperature of the atmosphere and the initial temperature. In Cases 6 and 10 - 17, calculation was made on 8 types of fins when fin materials were different. Number of embedded fins used was compared in Cases 6, 18 and 19 where number of fins was 2, 4 and 8 respectively. Evaluation was made on depth of embedded fins in Cases 6, 20 and 21, and the influence of length of projected portion of fin was evaluated in Cases 6, 22, and 23 with the length of projection being 3, 6, and 9 cm respectively.

Prior to the analysis, convection heat transfer coefficient "α_c" between the blown air and the building structure was estimated. We analyzed several cases in which the value of α_c was made to change between 4 to 30 W/m^{2}K using our simulation code. And, the case in which it agreed with the experimental result was made to be a value of α_c. The results of estimation are shown in Fig. 6. The tendency in the estimated values was consistent with that of the profile method or Colburn's equation(ASHRAE 1997). Thus, average value obtained from the values in plain concrete structure and in the structure embedded with aluminum fins was adopted in all of the cases under study.

COMPARISON BETWEEN EXPERIMENTAL RESULTS AND ANALYSIS RESULTS

For the verification of accuracy of the numerical analysis, the analysis results were compared with the experimental results. The test samples in Cases 1 – 3 (without fin) are referred as plain test samples. Those in Cases 4 – 6 (embedded with aluminum fins) are referred as aluminum test samples(Al), and those in Cases 7 - 9 (with copper fins) are referred as copper test samples(Cu).

Thermal Storage Performance

The changes over time of the temperature at the central point of the test samples in the experiment and in the numerical analysis during thermal storage for each blown air flow rate are shown in Fig. 7. In the copper test samples, the results of calculation agreed well with experimental results. In the plain test samples, the values were fairly consistent with each other except that the calculated values were lower by about 1°C. The tendency in temperature increase was consistent well in the cases of the aluminum test samples, while the calculated values were by about 2°C higher than the experimental values. These differences may be attributable to the value of "α_c" as defined in the preceding section.

In all of the cases, temperature increase was higher in the order of plain test samples, copper samples, and aluminum samples. The temperature increase in aluminum and copper samples were more remarkable compared with the other cases, and this reveals that thermal storage performance was higher when fins were embedded. Also, temperature increase was higher in the test samples embedded with fins compared with the plain test samples. Because the time to reach the steady state was shorter, it was confirmed that the thermal storage performance was improved due to the embedding of fins.

Heat Extract Performance

Fig. 8 shows the changes over time of the temperature of the central point of the test samples during heat radiation as evaluated by the experiment and numerical analysis. In the experiment, measurement was made continuously for the cases of thermal storage and heat extract. In this respect, for the test samples not reaching the steady state, heat radiation experiment was started at lower temperature. In view of the comparison with experimental results, the same values as in the experiment were used in the heat radiation analysis as the temperature of the test samples in the initial stage. Similar to the cases of thermal storage, the tendencies in the results of experiment and numerical analysis were consistent well with each other.

Compared with the plain test samples, temperature decrease was more remarkable in the fin-embedded test samples, and the time required to reach the steady state was shorter. The dependency of heat radiation performance on air flow rate could be confirmed in the fin-embedded test samples. This means that heat extract amount may be controlled well by the adjustment of air flow rate. By the comparison with the experimental results in thermal storage and heat radiation, it was confirmed that the analytical method adopted in the present study showed higher follow-up performance to the changes of fin materials and air flow rate. The value of "α_c" adopted in the present study was not turned to dimensionless, but it may be adaptable for generalization to some extent. In future, we are planning to study on the possibility to control heat radiation amount by the adjustment of air flow rate.

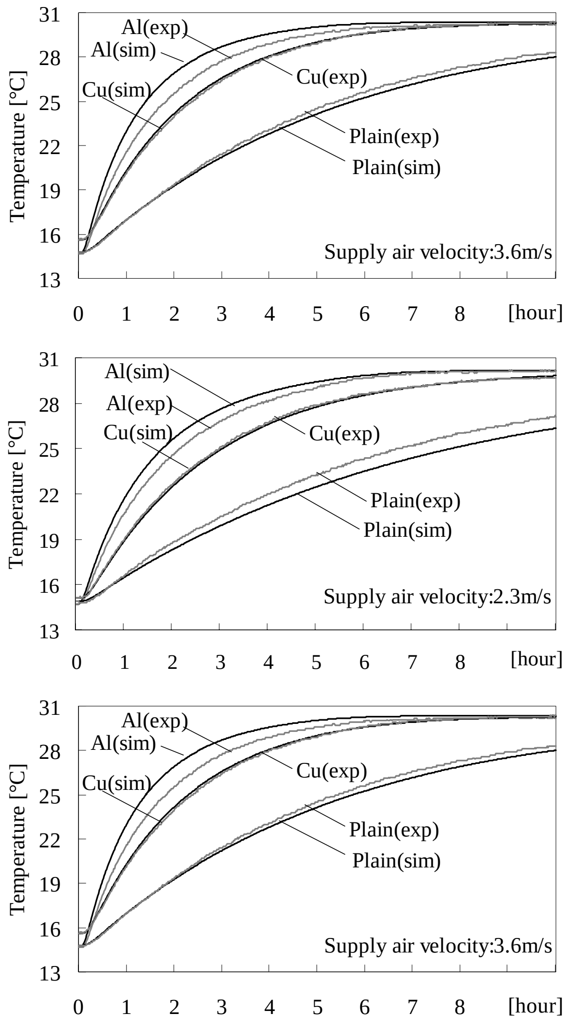


Figure 7 Temperature Fluctuation at Central Point Durring Thermal Storage

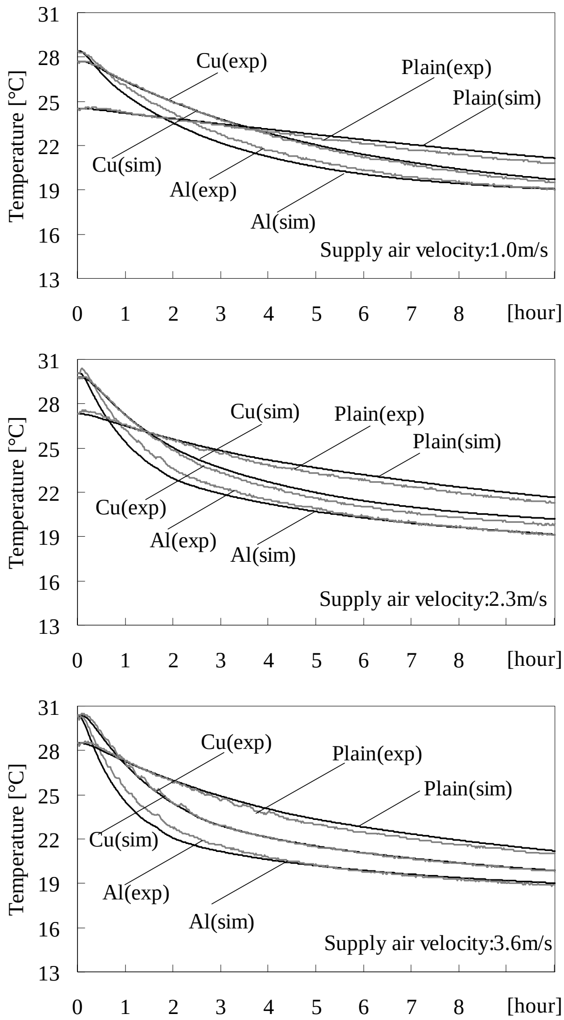


Figure 8 Temperature fluctuation at central point During Thermal Extract

Temperature Change in Storage Medium

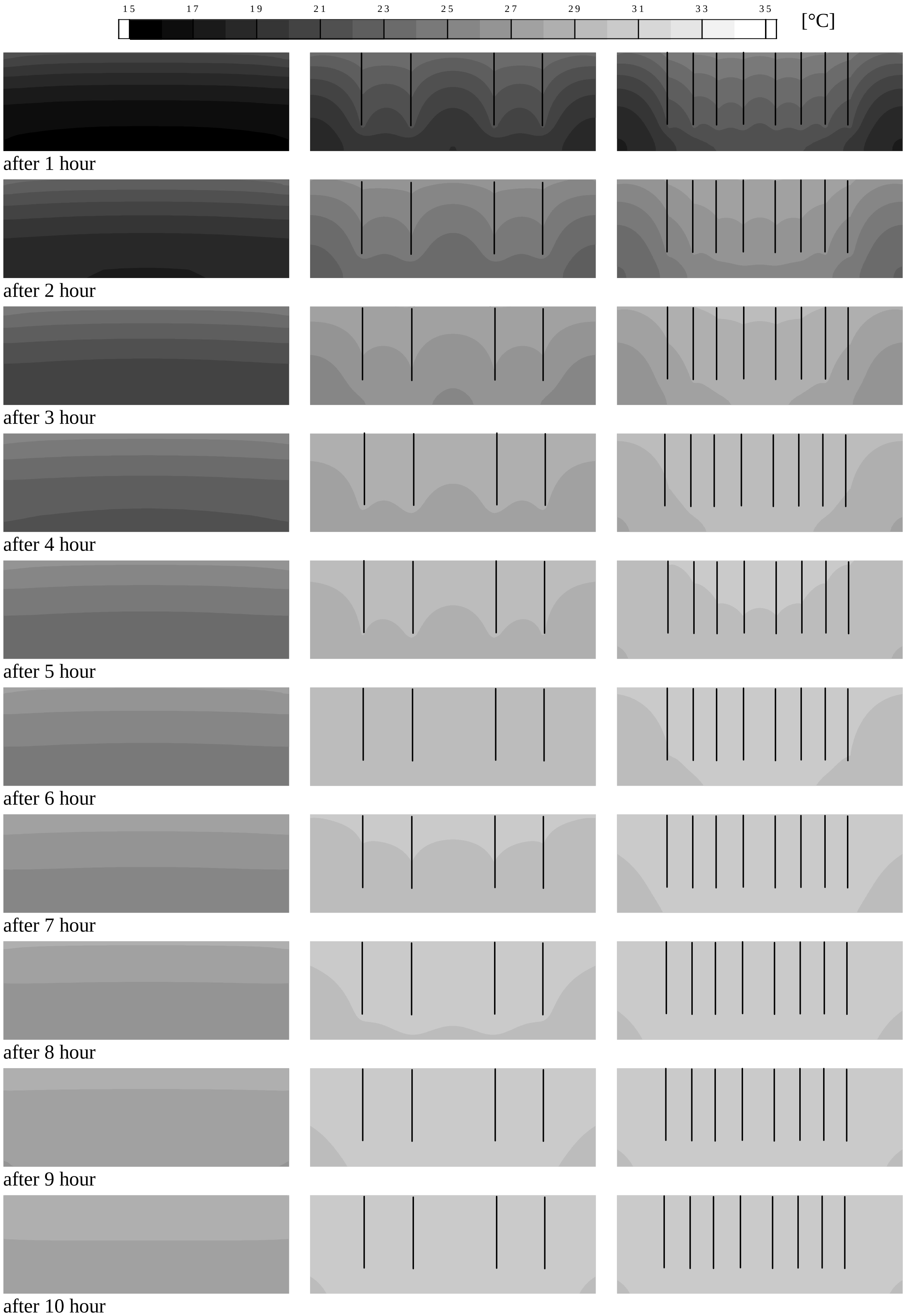
The changes over time of temperature distribution at the central portion of the samples during thermal storage are shown in Fig. 9 for the Cases 3, 6, and 9 based on numerical analysis.

The plain test samples without fin showed laminar temperature distribution, and it was evident that heat was transferred uniformly from the surface to the lower portion. The copper or the aluminum test samples embedded with fins exhibited a tendency extremely different from that of the plain test samples. Temperature distribution showed concave configuration near the fins, while convex configuration was seen between the fins, and temperature increase over the entire thermal storage medium was higher. This may suggest that, when fins are embedded, heat transfer into the interior of the thermal storage medium was enhanced through fins and the temperature was increased with the fins as the center of such increase. Although not shown in the figure, similar tendency was observed during heat extract.

NUMERICAL EXPERIMENT

In the preceding section, we have seen that results of simulation are in good agreement with the measurement results. In order to obtain the guideline, we made attempt the numerical experiments on the fin situation. Numerical analysis was performed on number of fins, fin materials, embedding depth, and length of the projected portion, which were difficult to identify in the experiment.

Fig. 10 shows the cases where fin material (i.e. thermal conductivity) was changed (Cases 6, and 10 - 17). Fig. 11 shows the cases where number of fins was changed (Cases 6, 18 and 19). Fig. 12 shows the cases where embedding depth was changed (Cases 6, 20 and 21), and Fig. 13 shows the cases where length of projected portion was changed (Cases 6, 22, and 23).



(a) Plain (b) Copper Fin (c) Aluminum Fin

Figure 9 Temperature Distribution in Thermal Storage medium (Simulation Results)

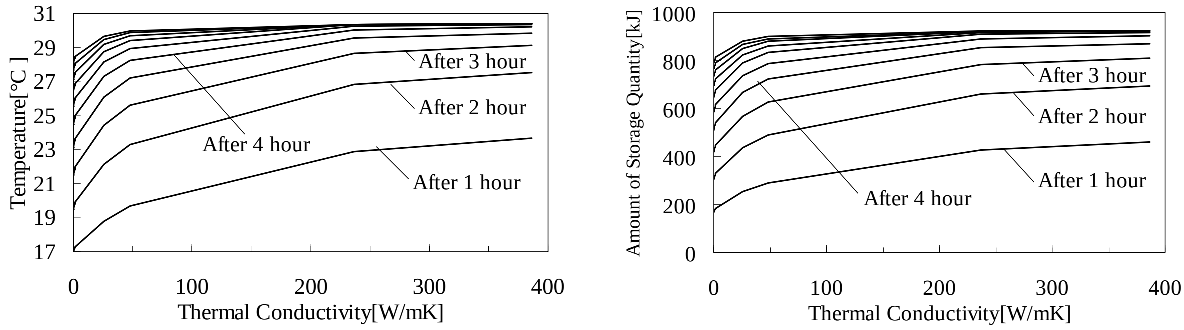


Figure 10 Influence of Fin Material

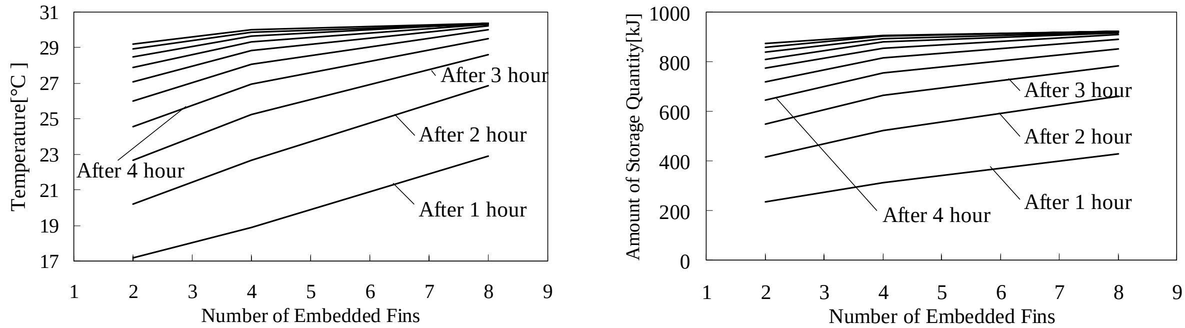


Figure 11 Influence of Number of Fins

The changes over time (every hour) of the temperature at the central point and the amount of heat storage quantity are summarized in the figures.

Fin Material

The number of fins was 8, embedding depth was 9 cm, and length of projected portion was 9 cm. During the period 1 - 2 hours after the initiation of thermal storage, it could be confirmed that the temperature at the central portion tended to increase with the increase of heat transfer coefficient. For aluminum fin (λ= 236) and copper (λ = 386), the difference 2 hours after the initiation of thermal storage was low. This reveals that the fin material having somewhat higher heat transfer coefficient should be used.

Number of embedded fins

Aluminum was used as fins, embedding depth was 9 cm, and length of projected portion was 9 cm. At one hour after the initiation of thermal storage, the more the number of fins was, the higher the temperature at the central point was increased. This is because temperature increase in the interior is higher when distance between fins is narrower (Fig. 9). Temperature difference was higher up to about 4 hours after the initiation of thermal storage, and this suggests that number of fins and distance between embedded fins exert strong influence on the thermal storage performance.

Depth of embedded fins

Fin material was aluminum, number of fins was 8, and length of projected portion was 9 cm. Temperature increase was low when depth of embedded fins was 3 cm. The reason for this may be that the temperature was compared at a point 6 cm in depth, and when depth of embedded fin was 3 cm, heat was not sufficiently transferred to the measuring point. The results were almost the same in case embedding depth was 6 cm and 9 cm, but it appears that temperature distribution may be different at the depth of 6 cm or lower. The effects are better when the fins are embedded into the interior of the thermal storage medium from comparison of thermal storage amount.

Length of projected portion of fin

Fin material was aluminum, 8 fins were used, and embedding depth was 9 cm. With the increase of the length of the projected portion of fin, temperature tended to increase. When the length of the projected portion of fin was longer, surface area of fin increased. It appears that this was caused by the increase of heat transfer amount to fin from the blown air.

From the solution of the above, it was confirmed that the number of embedded fin was important than the other.

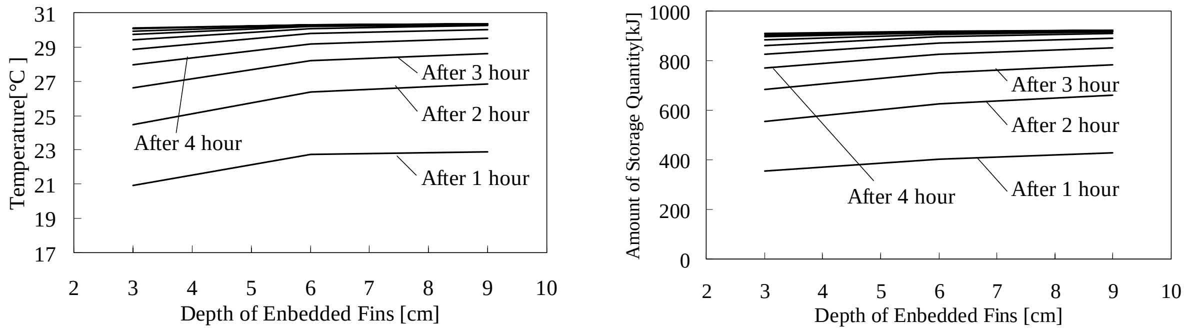


Figure 12 Influence of Depth of Embedded Fins

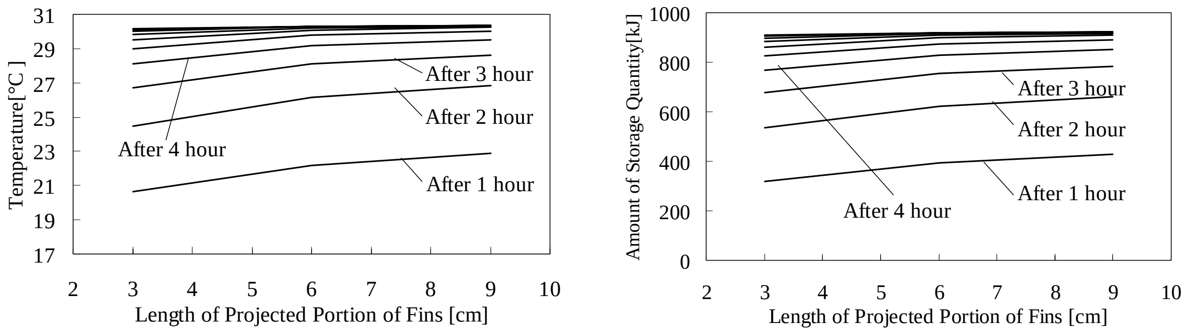


Figure 13 Influence of Length of Projected Portion of Fins

CONCLUSIONS

For the concrete thermal storage medium embedded with metal fins, evaluation was made on the influence of number of fins and fin materials, and so on. on thermal storage and heat extract by using experiment and numerical analysis. The conclusion is summarized as follows:

The results of simulation showed good agreement with the trends in the measurement results, and it was demonstrated that sufficient accuracy can be assured when it is evaluated for the effect of the fin installation situation for the present system.

From temperature distribution in the heat storage body, heat accumulating conditions were assessed in detail. As a result, the effectiveness of the fin for heat accumulation could be confirmed.

Numerical experiments was performed on fin material, number of fins, and so on, which were difficult to confirm in the experiment. it was confirmed that the number of embedded fin was important than the other.

In future, we are planning to evaluate air flow rate, temperature of the supply air, and volume of thermal storage medium suitable for practical applications by using experiment and numerical analysis.

ACKNOWLEDGEMENTS

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NOMENCLATURE

λ: Thermal conductivity	[W/mK]
$C\rho$:Thermal capacity	[kJ/m^{3}K]
αc: coefficient of heat transfer rate by convection	[W/m^2]
Θ: Temperature	[°C]