A SIMULATION OF AN UNDERGROUND HEAT STORAGE SYSTEM USING MIDNIGHT ELECTRIC POWER AT PARK DOME KUMAMOTO

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ABSTRACT
The purpose of this study is to investigate how much the peak daytime demand for electricity is reduced by an underground heat storage system that uses surplus electricity during the nighttime. In this paper, we report on a numerical simulation method and the results from an energy performance simulation of this system at Park Dome Kumamoto, a Kumamoto Prefecture indoor athletic facility. The simulation results were in good agreement with the measurements, and that shows that this simulation method is applicable for the prediction and optimization of an underground heat storage system for other conditions.

INTRODUCTION
Park Dome, a Kumamoto prefecture indoor athletic facility, was built in 1997(Figure 1). With a field of about 11,000 square meters, the entire Park Dome is located under a dome with a double pneumatic-film structure. The design utilizes and conserves natural energy by a swirl flow natural ventilation system, underground thermal tunnel and an underground heat storage air-conditioning system using reduced-rate nighttime electric power.

An underground heat storage system has been adopted to reduce power requirements for air-conditioning in lounge area(Figure 2), particularly, during periods of peak daily load. The area of the lounge is 204 square meters. The lounge is located on the western side of the athletic field and the designed open space.

An air-source heat pump is used as the heat source for this system. The thermal energy made by heat pump in nighttime, is stored underground in polyethylene pipes(Figure 3). In daytime, the thermal energy is extracted from underground, and provided for lounge by an air-conditioning unit.

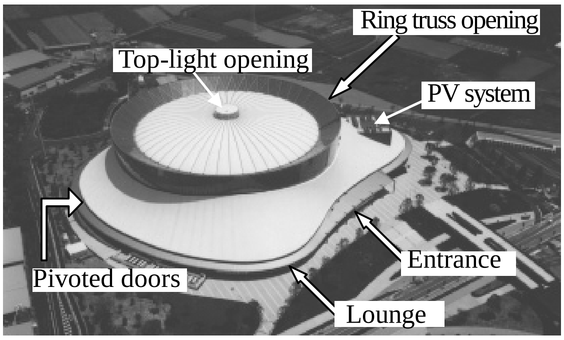

Figure 1. Outside view of Park Dome

Figure 2. Inside view of Lounge

Figure 3. Polyethylene pipes

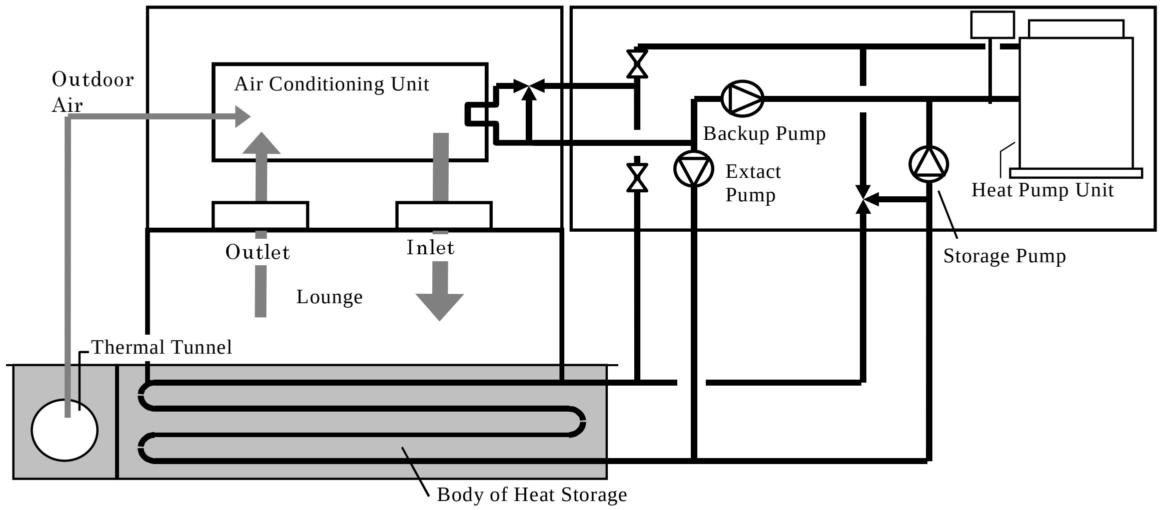

Figure 4. An underground heat storage system in Park Dome

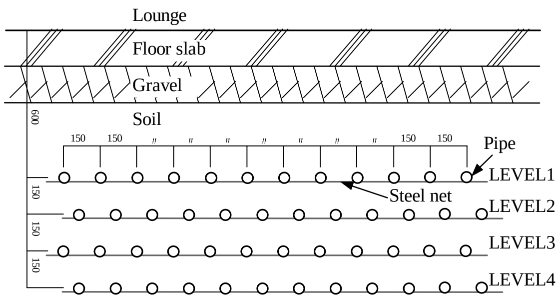

Figure 5. Section of the body of heat storage

An Underground Heat Storage System

Figure 4, shows the underground heat storage system at Park Dome. The system consists of five units, a heat storage, heat source, air-conditioning, control and measurement unit. The thermal energy is stored in the earth through polyethylene pipes using midnight electric power, which is the extracted to be used as a heat source for air-conditioning.

The earth beneath the athletic fields serves as a heat storage area, where the pipes(with 0.025 diameter and a total length of 4,800 meter) are embedded. The pipe depth was determined from 60 to 105cm under ground level after considering the availability of execution due to the presence of base beams. The cooling/heating water flows into the pipes diverged through a header. The storage pipe arrangement consists of 12 horizontal levels and 4 vertical levels with interval of 150mm, the length of each pipe being 100 meter. A section of the pipe system layout is shown in Figure 5. The pipe intervals have been determined after a case study using a simulation code(Ishihara et al., 1997).

In order to store energy in the earth, the circulating water first flows into the top level and this flows out through the deepest level pipes, and reversely if energy should be extracted from the storage system, because the return water temperature becomes lower and not vice versa. We also decided to lay sprinkler pipes at the top level in order to supply sufficient water to the soil, so as to prevent possible heat-characteristic modifications caused by a change in the water content of the soil during heat storage, and especially to avoid reduction of the thermal conductivity of the soil while the heating system is in operation. Furthermore, the fin ability of the pipes improved by using a steel net.

Heat is generated by this system through a heat pump chilling unit, a circulating pump, and a buck-up pump, in case supplement heat is necessary or heat is insufficiently stored. Air conditioning on the other hand consists of an Air-handling unit, a duct and a circulating pump. Heat storage, heat extraction and back up, are automatically set into operation by a timer and a bulb control function depending on the water temperature.

MEASUREMENT

In order to improve and optimize the effectiveness of the earth heat storage system, measurements were conducted at 150 different points of the system and the data obtained were then stored in a MO-disk of a personal computer in a 5 minute interval. The measurements concerned soil temperature, soil moisture content, water flow, water temperature, airflow volume in the duct and air temperature. From that stage on, heat storage/extraction and the system’s overall efficiency were estimated according to the measurement results.

The measurements were made during the summer season in 1998. During the measurement, air-conditioning unit is operated by a timer from 10:00 to 18:00, the heat pump unit is operated by a timer from 22:00 to 8:00.

SIMULATION

For the purpose of general improvement of an underground heat storage system, we developed the simulation code based on finite differential method. In the thermal conductivity analysis in burying the heat transfer pipe in the soil, there are many cases in which solid part and flow in the pipe are solved in the separate equation. In this method, the contact between pipe and soil must be beforehand defined.

In the meantime, the heat balance equation of the flow in the pipe is able to express the convection-diffusion equation. Then, we adopted the convection-diffusion equation for solving underground heat storage as shown in Table 1.

Control volume method (Patanker, 1980) is used in the discretion, and it defines temperature mesh center. The difference scheme on the time term adopted on perfect implicit method, convective term on up-wind scheme, diffusion term on the central scheme. Figure 6 shows the model of underground heat storage part. The heat storage part. The heat storage part is parallelepiped of 2.665m width, 2.25m depth, 100m length. The heat storage part is being divided into 93×44×100 in unequal interval orthogonal mesh. The physical property for the simulation is shown at Table 2. The flowchart is shown in Figure 7.

The heat pump chilling unit is modified, from the measurement results, by adding temperature gradient of 5.6 deg.C in compressor of 2 operations and 2.6 deg.C in the 1 operation night. The change of the water temperature in heat storage in the chiller unit is sending it out to the soil. The air conditioning load in the daytime is being calculated according to the equation in Table 1 which made ambient temperature and time (24 hours are controlled) to be a variable in order to reproduce the air conditioner conversive heat quantity by the observation.

RESULTS

The measurement result of the temperature in the heat storage part is shown in Figure 8, and the calculation result is shown in Figure 9.

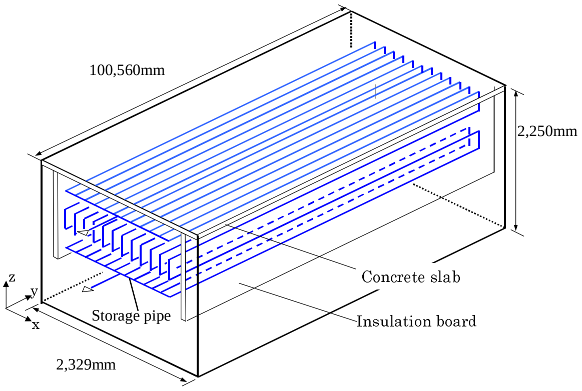

Figure 6. Simulation model

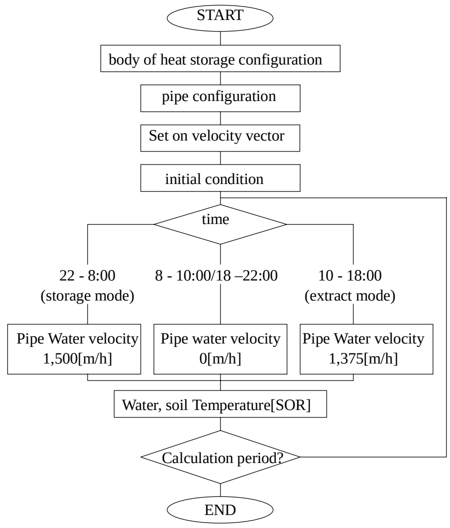

Figure 7. Flow chart

Table 1. Basic equation

$$\frac{\partial \theta}{\partial t} + \frac{\partial u_j \theta}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k \frac{\partial \theta}{\partial x_j} \right) \qquad (1)$$

where k is;

solid part : $\lambda/c\rho$,

water part : $Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$

Heat pump:

1 compressor drive, temp. gradient of 2.6 deg.C

2 compressor drive, temp. gradient of 5.6 deg.C

Air conditionning load:[W] (by measurment)

=-2343*t+1938*θo+9665

Table 2. Thermal constant of materials

	Heat conductivity λ[W/m ° C]	Thermal capacity $C\rho$[kJ/m^3 ° C]
Soil	0.64	2302.3
Gravel	0.62	2344.2
Concrete	1.35	1929.8
Wire netting	45.00	3759.0
Heat storage pipe	0.37	——
Water	——	4173.4
Insulation	0.06	

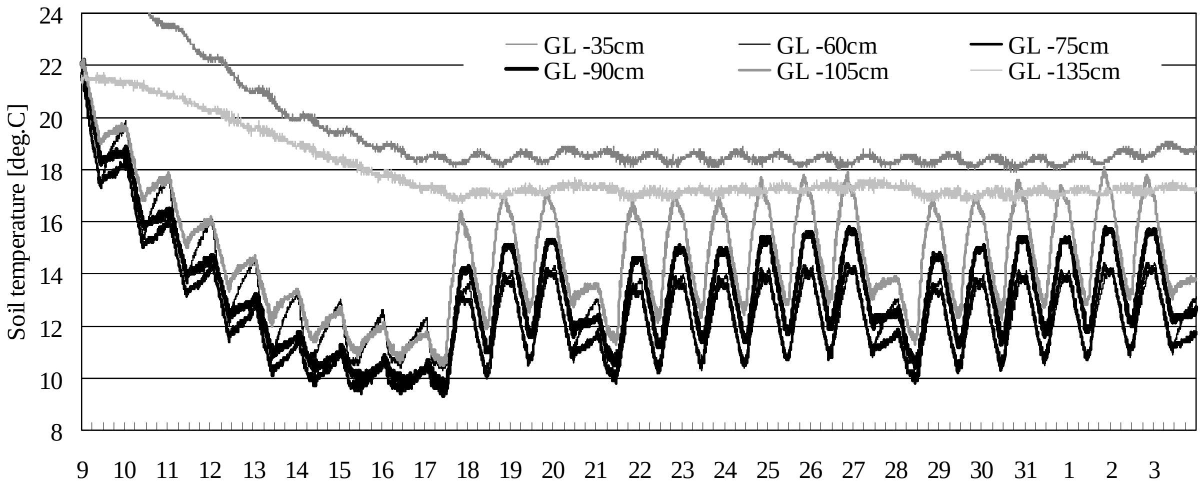

Figure 8. Fluctuation of soil temperature (Measurement, 1998/7/9 – 8/4)

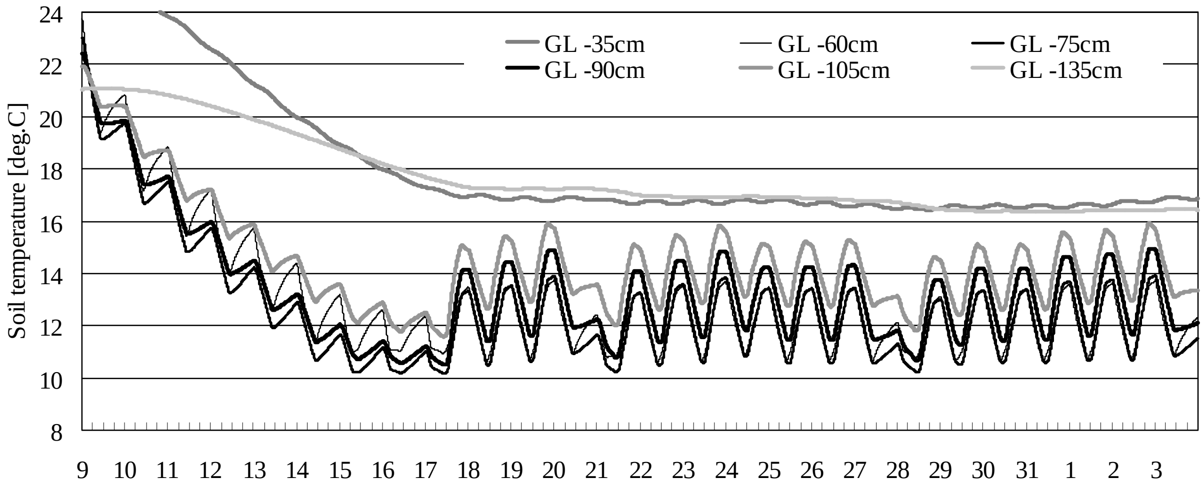

Figure 9. Fluctuation of soil temperature (Simulation, 1998/7/9 – 8/4)

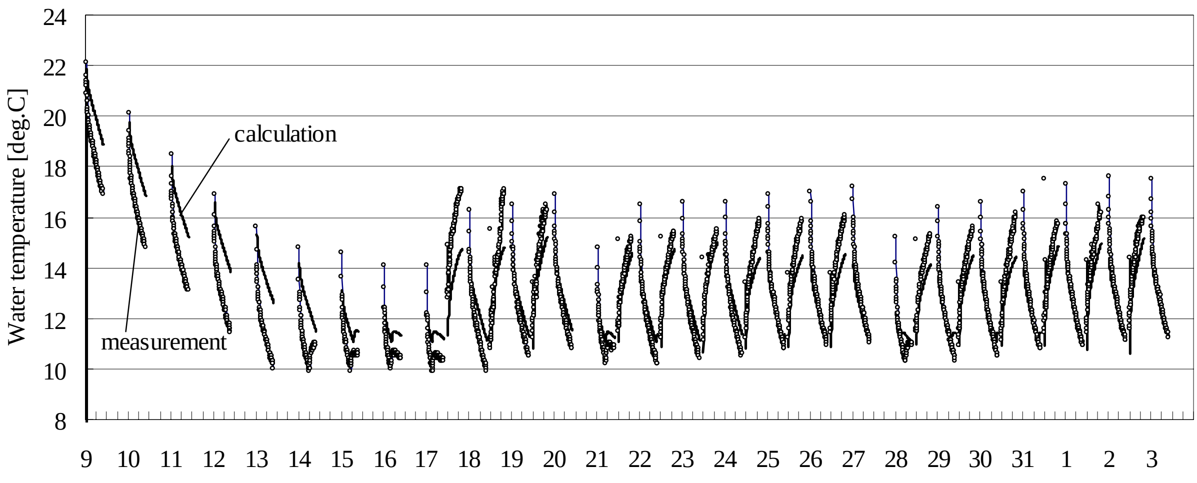

Figure 10. Fluctuation of outlet water temperature in heat storage/extract pipe

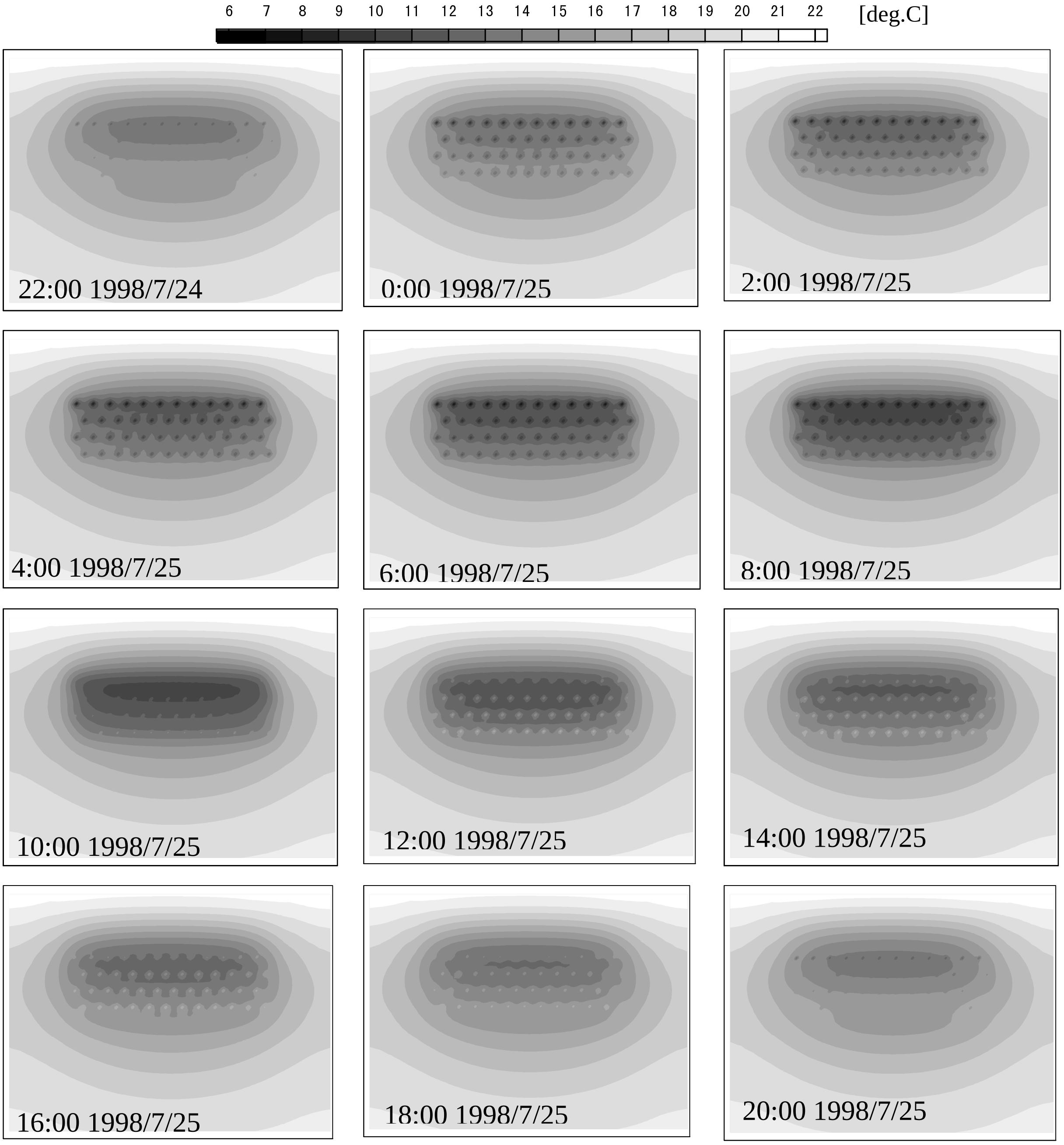

Figure 11. Soil temperature distribution (heat storage and extract process)

From 1998/7/9 to 7/17 we carried out the storage operation only, and after 7/18 we carried out both the storage and extract operation. On the closure day of 7/21 and 28 there is storage operation only.

From Figure 8 and 9, it appears that there is good correlation between the measured and calculated values of inside soil temperatures. The results of the simulation of the soil temperature at GL-105cm are actually lower than the measurement; however, there is close correlation of the trend of the temperature reduction in the precooling stage, the fluctuation on the closure day, and lower limit of soil temperature.

The fluctuation of outlet temperature of the heat storage pipe is shown in Figure 10. At the air conditioning period, the return water temperature (the inlet temp. of air conditioner) from the soil, it is about 2 deg.C larger than measurement. The other period, the difference of temperature has positioned within 1 deg.C.

Figure 11 shows, simulation result of the soil temperature at the heat storage part central every 2 hours in July 24th 22:00 ～ 25th 20:00. In the night, soil temperature around the pipes becomes gradually lower. Soil temperature distribution in which the heat storage ends at 8:00, minimum becomes 10 deg.C.

The soil temperature is kept low until 10:00 when the extraction of heat begins. In the extraction of heat from 10:00 to 18:00, the pipe circulating water flows from the fourth level, and it escapes from the first level. Therefore, the temperature gradually rises between first level and second level. It is considered from the fluctuation of first temperature distribution, that only the pipe on the first level seems to work effectively for extraction and storage.

OPTIMIZATION

In this paper, it was proven that simulation result corresponded to the observation result well. Then, using developed program, 16 cases were calculated in order to clarify the relationship between volume of heat storage body and air conditioning load.

The capacity of the heat storage body is correspondent estimated by calculating y direction (Figure 6) length of the heat storage body by changing. And, it also changes the circulating water flow volume. The pipe position lying in the ground and spacing of the pipes were identical to Figure 5. The analysis condition were made to be the pre-cooling period until the heat pump was stopped, and it does 1 week storage and extract afterwards.

The period of pre-cooling is shown in Figure 12. The X-axis shows the length of pipe and area of heat storage part and the Y-axis shows air-conditioning load and flow rare. It can be observed from the figure that the optimum range of this system is the case in which the precooling period is the 4 - 7 day.

CONCLUSIONS

In this paper, we reported on the outline of the heat storage system and simulated thermal performance of heat storage part. The results obtained to this stage are as follows:

The measured value and calculated value correspond well to the variation of the temperature of the soil inside.

The simulation results prove that this system can be very effectively applied in real architectural projects and contribute in alleviating cooling loads in Kumamoto.

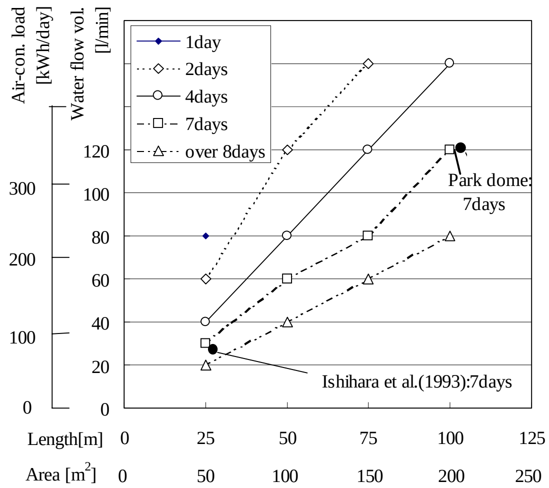

Figure 12. Optimum range of this system

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NOMENCLATURE

u: water velocity of pipe[m/h]

θ: solid/water temperature[deg.C]

λ: Heat conductivity[W/mdeg.C]

Cρ:Thermal capacity[kJ/m^{3}deg.C]

αc: coefficient of heat transfer rate by convection[W/m^2]

Nu: Nusselt number

Re: Reynolds number

Pr:Prandtl number