An Environmental Building Design Using Natural Energy and the Thermal Storage Capacity of a Building Mass

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ABSTRACT HEADING

This paper presents an environmental design that utilizes thermal storage and natural energy to meet the diverse performance requirements of an office building in Japan. The building could be made self-sustainable for a duration of three days by installing a well and a wastewater tank. Additionally, the air-conditioning system employed thermo active building systems (TABS) to eliminate uneven temperature distribution. The results indicated that a heat source system utilizing heat from well water could potentially reduce the annual energy consumption due to air-conditioning by 20%, thus suggesting a highly efficient use of medium-temperature water.

INTRODUCTION

In recent years, building functions have diversified to include improved energy savings, thermal comfort, wellness, and resilience. In particular, it is important to effectively use natural energy such as solar energy, geothermal energy, and wind energy in Japan since it not only experiences disasters such as earthquakes and tsunamis but also has scarce natural resources. Renewable energy, although clean, cannot solely maintain public infrastructure and building functions. Further, generation of large quantities of stable natural energy is challenging since it is significantly affected by weather conditions. Therefore, this study attempted to address this issue by presenting an environmental design that focused on utilization of the thermal storage capacity of the building mass as well as natural energy to efficiently meet the diverse performance requirements of an office building scheduled to be constructed in an urban area of Japan.

BASIC DESIGN POLICY

The design requirements of the target office included development of disaster countermeasures, adoption of a seismic isolation structure, strengthening of the building resilience [1] functions in the event of an emergency, reduction in utility and water costs, and improvement of comfort at daily life. Seismic isolation structure is a technology for mitigating the effects of earthquakes on structures through the introduction of flexibility and energy absorption capability. The basic policy design is presented in Figure 1.

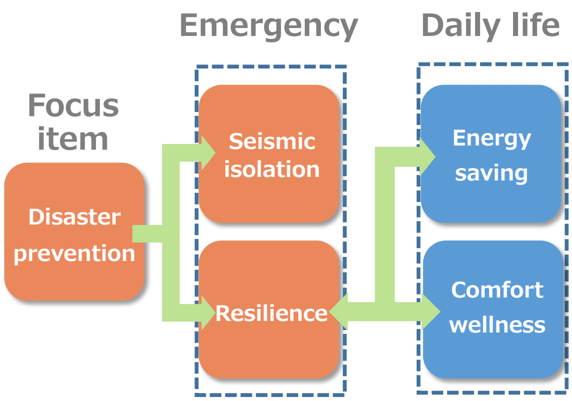


Figure 1 Basic policy concept.

Figure 2 Perspective image.

Table 1. Architectural Outline

Building area	~5,380 ft² (500 m²)
Total floor area	~21,500 ft² (2,000 m²)
Main use	Office
Construction site	Tokyo, Japan
Main structure	Steel structure

Figure 2 presents the completed expected view of the building. Table 1 presents the architectural overview of the building. In this study, verification was conducted to maximize the building volume under the constraint that the sun shadow should not fall to the side of a park existing in close proximity of the building for a certain time period.

Additionally, the project focused on rebuilding existing offices. Therefore, a questionnaire survey was conducted among the executives to determine the existing problems and improvement suggestions for the offices. Several problems and improvement suggestions were related to shortage of space and air-conditioning. In particular, temperature unevenness and cold feet resulting from a cold draft emerged as relevant issues. It is said that Japanese women with low basal metabolism are more likely to feel the coldness of their feet due to cold drafts [2, 3]. It was a Japanese woman who complained about the coldness of the foot in this questionnaire. The existing building relied on convection air-conditioning based on a single heat source. The results of the survey allowed design improvement to further improve user satisfaction.

Design Concept

The following design concept was developed to realize the basic design policy and address problems in the existing offices.

A "multi-infrastructure supply plan" based on construction of well and drainage tank powered by emergency generator was designed to ensure that the building did not rely solely on public infrastructure for electricity, water, and sewerage. The building could be made self-sustainable for a duration of three days by the "multi-infrastructure supply plan". This plan is also contributed to save energy and water resource in daily life [4]. It was found that the water temperature of the deep well in the vicinity of the construction was uniform at approx. 18°C throughout the year. This temperature was approx. 18°C lower than the peak of the outside air in the summer in Japan, approx. 18°C higher than the peak of the outside air in winter. Therefore, it was possible to reduce the thermal load difference between the outside air temperature by utilizing well water as a heat source for pre-cooling and preheating. The energy savings achieved by reducing the heat source load was estimated at approx. 7%.

The combination of an air-conditioning system employed thermo active building systems (TABS) [5] and the multi-infrastructure supply plan could address issues in the existing offices, reduce utility costs, create energy-savings, and ensure a comfortable working environment. The schematic diagram of the air conditioning system is presented in Figure 3. The plan for the building interior included no ceiling and installation of 70 mm of concrete on the slab. Subsequently, a pipe was driven through to allow radiation heating and cooling from the ceiling. Further, floor blowing air-conditioning was designed for treating the perimeter load as well as the air outside the window surface. Additionally, floor cooling in the portion of the under slab that was exposed to the outside was prevented by hot water floor heating. Finally, a transport fan was installed to promote air circulation and tabletop fans were installed for office workers who experienced lack of air flow to allow individual control.

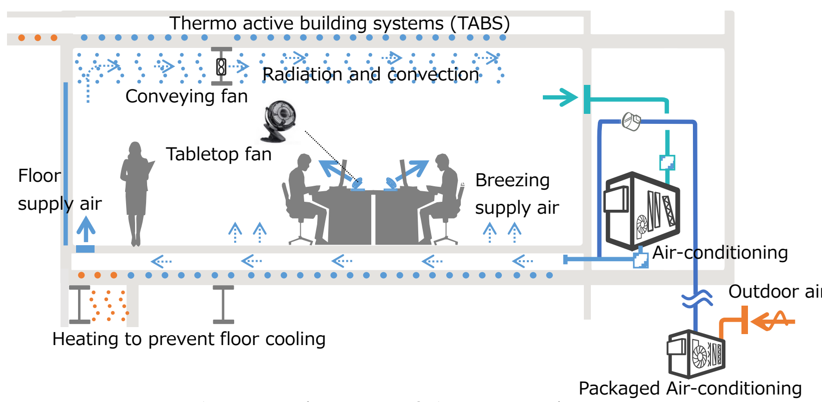


Figure 3 Schematic diagram of the air conditioning system.

ENVIRONMENTAL PLANNING

The air conditioning system is presented in Figure 4. The air conditioning system was planned cascade heat utilization. First, heat from well water occurred through a heat exchanger, was utilized for radiation heating and cooling. Subsequently, this was used for pre-cooling the outside air. Water utilized for heat exchange underwent filtration treatment and was subsequently stored in the chore water tank for use in toilets. Therefore, two distinct cycles was created: heat and water resource utilization.

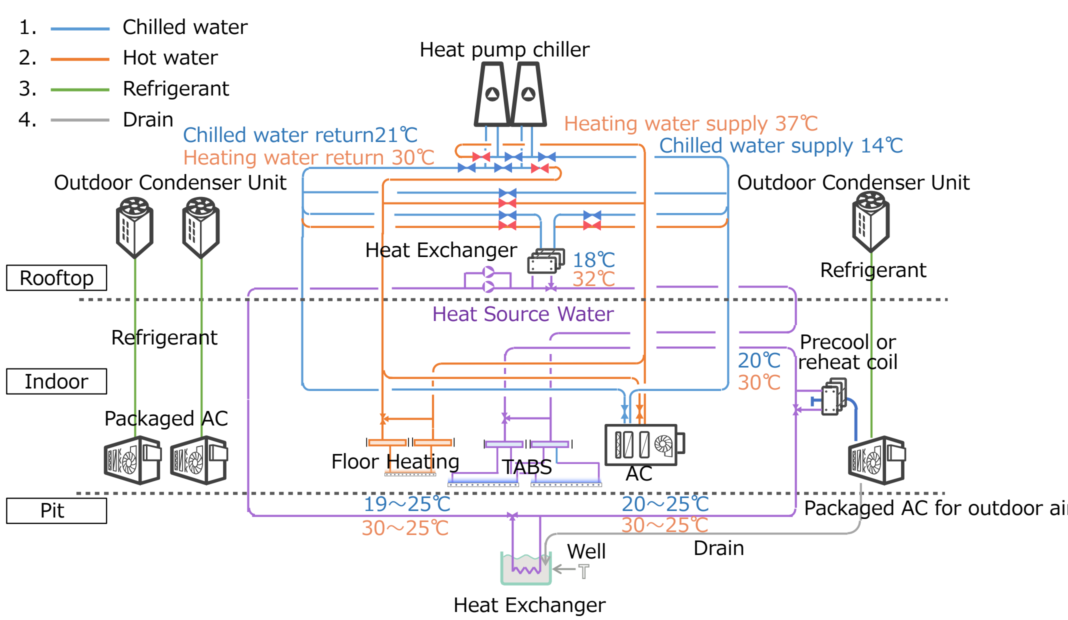


Figure 4 Schematic diagram of an air conditioning system..

Additionally, an air-cooled heat pump chiller was provided to supply chilled water at 14 °C and hot water at 37 °C to ensure high energy efficiency. Because the heat pump's compressor power could be saving by rising an evaporate temperature of an evaporator in summer and dropping a condensation temperature of a condenser in winter [6]. Furthermore, a plan to treat the sensible and latent heat of the outdoor air by a packaged air conditioner were provided. Moreover, the flow paths of drainage could be switched from regular direct discharge to an emergency drainage tank, thus allowing storage of drainage for three days. In the case of 14 °C supply, only sensible heat treatment was covered. The latent heat both of the outside and indoor air was treated by the packaged air conditioner.

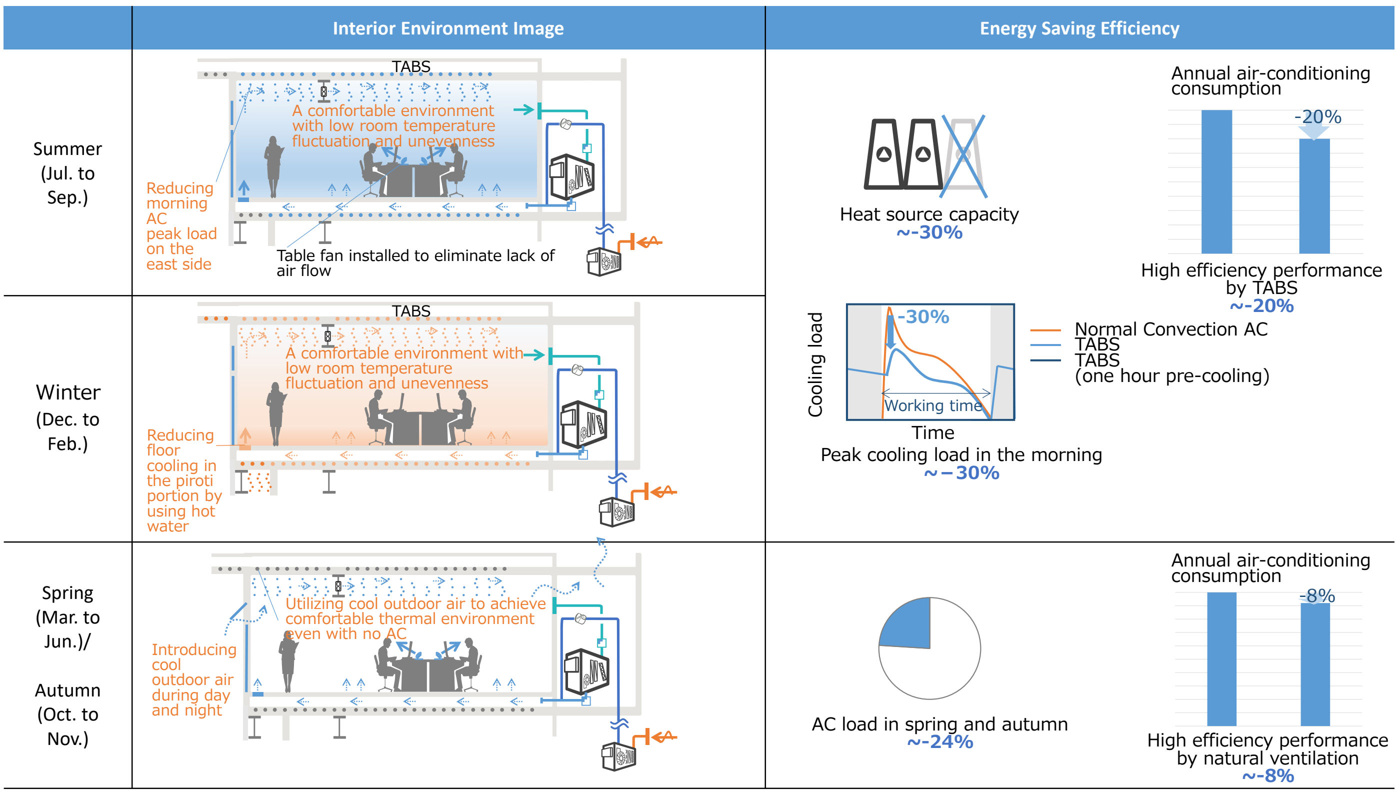


Figure 5 Operation of seasonal air-conditioning and estimation of energy savings.

Figure 5 presents operation of seasonal air-conditioning and estimation of energy savings. A reduction in the peak air-conditioning load was expected during summer due to TABS. Cooling load peak by TABS introduction from the simulation results, to be described later, became an estimate that was cut by approx. 30%. Therefore, the heat source capacity at the design stage was also able to be reduced by 30% more than a typical building based on the results. In particular, the suggested building plan was characterized by a large opening on the eastern surface. Therefore, the effect of peak load cuts was likely to be higher than a building with southern, northern, or western surface. The design also included floor heating and thermal insulation of the portion of the under slab that was exposed to the outside to overcome thermal weaknesses during winter.

In this study, we aimed to realize a thermal environment characterized by low room temperature fluctuation and unevenness by the thermal storage capacity of a building mass [7, 8, 9].

In addition, a 20% reduction in the annual energy consumed due to air-conditioning was indicated from the simulation results, to be described later.

Further, the thermal load treatment during mid-spring and autumn utilized natural ventilation, night purge, and thermal storage capacity. In particular, introducing the cool outdoor air at night likely increased the amount of natural energy used. The simulation results, to be described later, show that by performing 9 hours' outdoor air introduction at night in spring and autumn, from the effect of thermal storage capacity of building mass, the cooling load in spring and autumn was expected to be reduced by 24%. In addition, it was estimated that the reduction of the load would have the effect of reducing the annual air-conditioning energy consumption by approx. 8%.

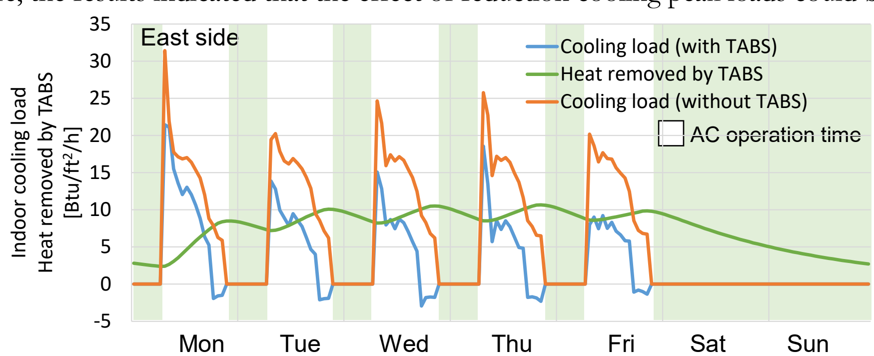
Simulation of building and air-conditioning system

In this study, I utilized an integrated Building Energy Simulation Tool, BEST, developed in Japan [10, 11]. The characteristics of the calculation method of this simulation tool are as follows.

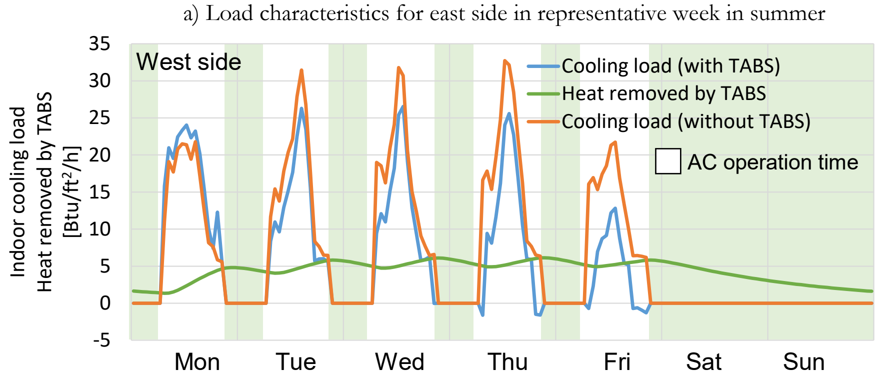
1. Architectural and facility combination calculation: Explicit method, which results in one numerical solution, the unknown number of the new step is determined from the known number of the present step by a simple algebra calculation, at 5-minute intervals.
2. HVAC: Free combination is possible by independent calculation of each piece of equipment.
3. Radiation panel: non-stationary calculation is forward difference method, heat dissipation from the pipe is replaced with a uniform heating surface in the floor by utilizing the fin efficiency.

Thermal load and air-conditioning system simulation was performed for basic analysis of the TABS. Further, calculations for different scenarios such as introduction or absence of the TABS were performed. Moreover, the peak load cut effects in this building were showed by comparing the load processing characteristics of the east and west openings. In the simulation, 70 mm of concrete added to the underfloor space and the cooling / heating pipe for TABS driven into it were modeled in accordance with the architecture and facility plan.

The load variation characteristics were calculated for the presence and absence of TABS during the representative week (Figure 6). The introduction of TABS was estimated to reduce the peak heat load of air-conditioning by up to 30% on the east perimeter. Further, in comparison with the west perimeter, the east perimeter indicated higher load reduction. The figure 9 also showed a net shift of peak load to a later time of the day with TABS compared to the base case. Therefore, the results indicated that the effect of reduction cooling peak loads could be high.



a) Load characteristics for east side in representative week in summer

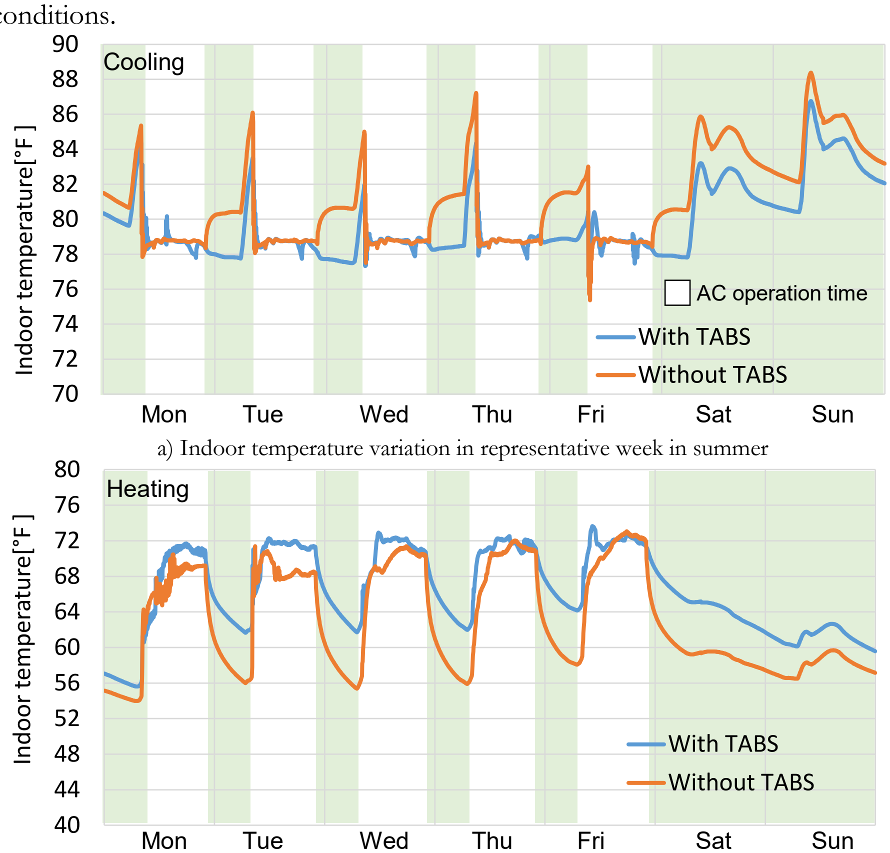


b) Load characteristics for west side in representative week in summer

Figure 6 Load characteristics for east and west sides in the presence and absence of TABS.

The introduction of the TABS could reduce the capacity for both air-conditioning system. Additionally, it could reduce temperature variations in non-air-conditioned times and improve the indoor thermal comfort. Figure 7 presents the estimated variation in room temperature due to cooling and heating during the representative week. The room temperature at night during cooling period was estimated to rise by approximately 2.0°F (1.2 °C) after stopping the air-conditioning in the absence of TABS, and the temperature during the heating period was estimated to reduce to nearly 14°F (7.8 °C). On the other hand, the temperature during cooling period in the presence of TABS was stable and estimated to reduce to ~1°F (0.5 °C), and the temperature during heating period was estimated to reduce to ~9°F (5 °C). By introducing TABS, room temperature variations became smaller during both cooling and heating periods. In particular, in contrast to convection air-conditioning, the suggested system reduced the room temperature during the cooling period after switching off the air-conditioning.

Furthermore, the suggested design could reduce the convection air-conditioning load which would consequently decrease the fan power. Moreover, improvements in the efficiency of the air-conditioning system were expected due to utilization of well water as the heat source. Subsequently, the energy consumption characteristics of the building were estimated (Figure 8). The results indicated increased efficiency of the heat source system and a significant reduction in the fan power. By adopting TABS, the chilled water temperature was higher than the general flow air conditioning, the hot water temperature could be set low. The heat pump chiller in this project had the property that COP is improved by 13% by raising the chilled water temperature from the normal 7 °C to 14 °C, and COP is improved by 20% by reducing the hot water temperature from the general 45 °C to 37 °C (Figure 9). In addition, the air transport power could be greatly reduced by TABS. In this plan, it was possible to reduce the rated power by approximately 50% as compared to general air conditioning. The energy-saving effect of the air-conditioning equipment by TABS introduction was expected to be approx. 20% per year based on a simulation which took into account the above conditions.



a) Indoor temperature variation in representative week in summer

b) Indoor temperature variation in representative week in winter

Figure 7 Indoor temperature variation with and without TABS.

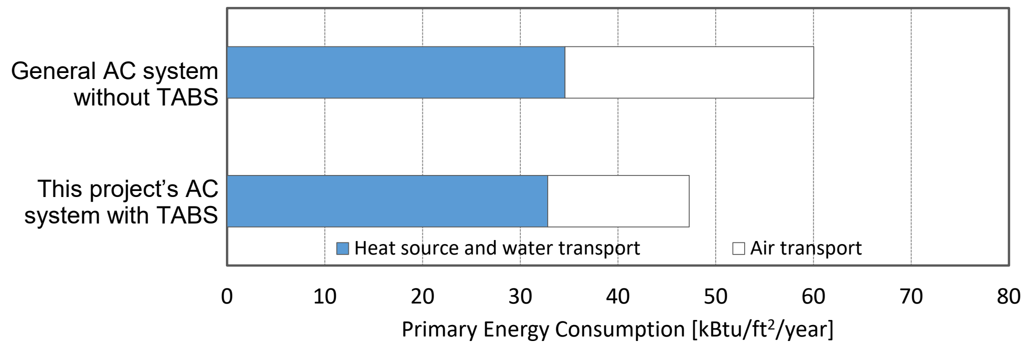


Figure 8 Energy savings due to TABS.

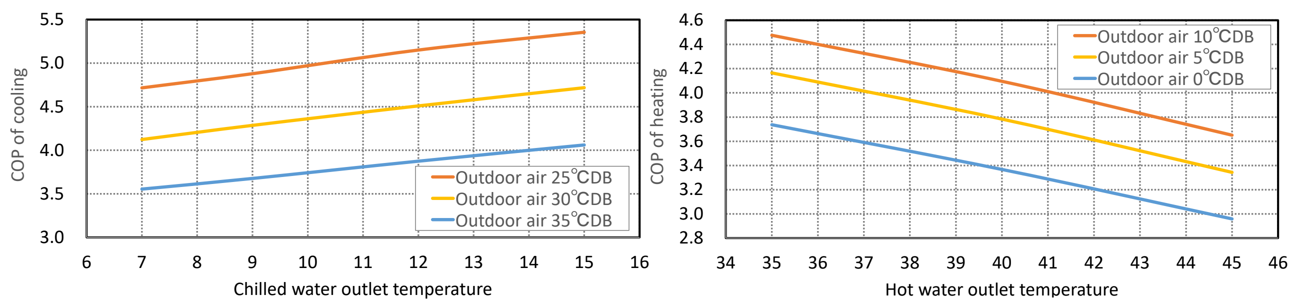


Figure 9 Heat pump chiller characteristics

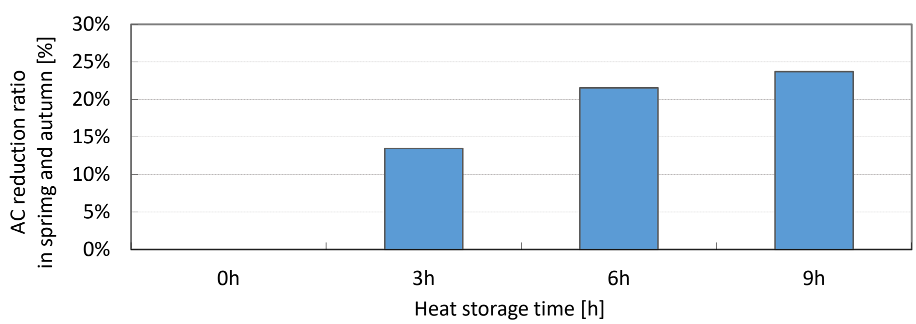


Figure 10 Load reduction due to introduction of outdoor air and TABS

The spring and autumn season are different from summer since the outdoor air is cool at night in Japan and could be used as a thermal storage capacity more effectively. Therefore, a quantitative assessment of the total load reduction due to the thermal storage during night-time was conducted for spring and autumn (Figure 10).

The results indicated that the longer the thermal storage time, the higher the reduction in the daytime air-conditioning load. A 24% reduction was estimated for the spring and autumn term air-conditioning load.

CONCLUSIONS

This study focused on the thermal capacity of the building mass to develop an environmental plan that utilized the heat and water resources of the well water. This plan is likely to contribute to saving energy and natural resources, ensuring comfortable thermal environment and wellness, and improving building resilience without relying on public infrastructure during emergency. The utilization of well water and thermal storage capacity reduced energy consumption due to air-conditioning by 20%. The simulation results indicated that a stable indoor thermal environment with only a few drafts could be realized during both summer and winter. Future plans include conducting performance verification at the operational stage after completion of the building.

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