Performance Verification of the Free-cooling System in Summer and Moderate Seasons

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ABSTRACT: Some models of this building and equipment are newly created by life cycle energy management (LCEM) tool. On these models, the main purpose is to verify performance and study feasibility of the free-cooling (FC) system in summer and moderate seasons. As a result, the adequacy of these models was checked, and effective operating rate (EOR) of Sapporo and Sendai, Japan was calculated in order to analyze the effects of shutdown on weekends, room temperature setting and operating time.

Keywords: free-cooling, BEMS, LCEM, effective operating rate

INTRODUCTION

Since the Japan earthquake on March 11th, 2011, it has further increased the importance of the passive and low energy architecture in Japan. Although it is necessary to design the highly insulated and airtight buildings and to effectively use the natural energy, a creation of HVAC system corresponding to these buildings has been delayed. In a recent previous study, the author verified the effects of energy conservation by the system efficiency, free-cooling (FC) contribution ratio and night shift rate [1]. It was based on operational performance of thermal storage cooling by the FC system utilizing cooling tower for an environment-conscious office building in the center of Sapporo, Japan.

In this study, some models of this building (high insulation + thermal storage) and equipment (high efficiency air source heat pump chiller + closed cooling tower) are newly created by life cycle energy management (LCEM) tool [2]. On these models, the main purpose is to verify performance and study feasibility of the FC system in summer and moderate seasons. Concretely, the effects of shutdown on weekends, room temperature setting and operating time on the FC system are analyzed through numerical simulation. This will be expected to create the high efficiency HVAC system using a passive design.

BUILDING OVERVIEW

Fig. 1 shows the building facade and indoor space, and Table 1 lists the building data. This building locates in Sapporo, Japan (43 degrees north latitude). The heating load reduction in winter and the effective use of cool climate in summer are planned. Several energy conservation technologies are installed to a part of office on the 4F ~ 8F. The concrete systems are as follow; 1) FC utilizing closed cooling tower, 2) thermal storage cooling and heating using pipe buried in a floor slab, 3) floor supply air conditioning via raised access floor, 4) outside air cooling bypass via outdoor air unit, 5) natural ventilation via open ceiling space, 6) solar lighting using multistage mirror.

Fig. 2 shows the typical floor plan, and Fig. 3 shows the cross-section. Layout plan can be freely, and air conditioning zoning is divided into north and south. Open ceiling space (void) including the elevator and staircase in the center space is planned, which is a route of natural light intake and natural ventilation exhaust. The building specification consists of exterior wall and windows of highly insulated type that are suitable for cold regions and floor slab of buried piping type that utilizes the heat capacity. From the inside, exterior wall is ordinary concrete 250 mm + polystyrene foam 100 mm + precast concrete 85 mm. Windows is Low-E insulating glass. From the upside, floor slab is carpet 8 mm + raised access floor 135 mm + lightweight concrete 65 mm + ordinary concrete 135 mm. Furthermore, cross-linked polyethylene (PEX) tubing 22 mm (nominal diameter 16 mm, pitch 200 mm) and welded wire mesh 10 mm are buried in lightweight concrete.

Figure 1: Building facade and indoor space.

Table 1: Building data.

Item	Data
Type	Office, store
Structure	RC, partly S
Scale	B1F ~ 8F
Site area	863 m^2
Building area	770 m^2
Total floor area	6970 m^2
Eave height	32.775 m

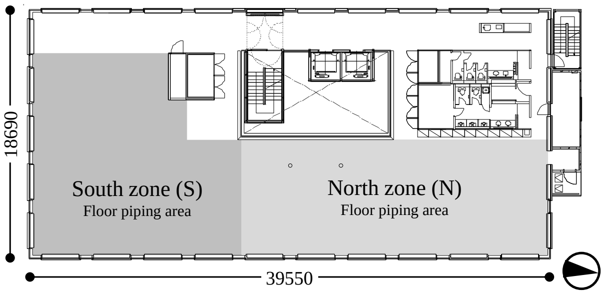

Figure 2: Typical floor plan.

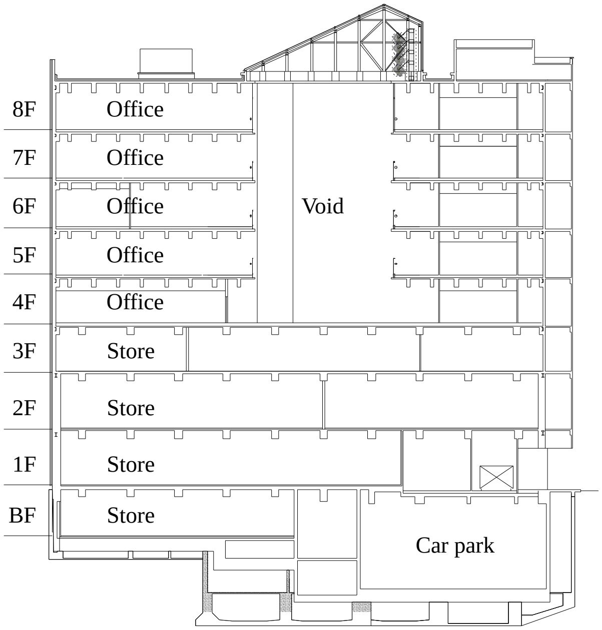

Figure 3: Cross-section.

HVAC OVERVIEW

Fig. 4 shows the heat source and air conditioning systems diagram, and Table 2 lists the heat source equipment detail. The heat source equipment consists of high efficiency air source heat pump chiller (R-1) and closed cooling tower provided for FC (CT-1). In cooling period, the chilled water of 7 ºC on R-1 is used by outdoor air unit (OAU). The high temperature cold water of 17 ~ 20 ºC on CT-1 is used by air handling unit (AHU) and pipe system buried in a floor slab (floor piping). In short, these systems are combination of thermal storage cooling and heating by conveying water and floor supply air conditioning by conveying air. However, if FC is not available, the high temperature cold water is produced with plate heat exchanger (HEX-1, HEX-2).

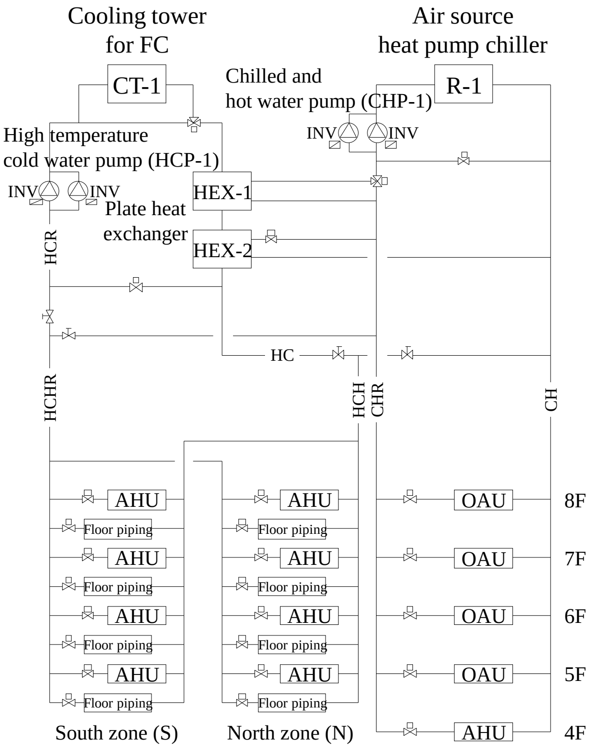

Figure 4: Heat source and air conditioning systems diagram.

Table 2: Heat source equipment detail.

Item	Value
Air source heat pump chiller (R-1)	
Cooling capacity	212 kW
Input	48 kW
Cooling tower for FC (CT-1)	
Cooling capacity	43.5 kW
Input	2.6 kW
Plate heat exchanger (HEX-1)	
Amount of heat exchange	99 kW
Plate heat exchanger (HEX-2)	
Amount of heat exchange	43.5 kW
Chilled and hot water pump (CHP-1) (× 2)	
Flow rate	350 L/min
Input	2.2 kW
High temperature cold water pump (HCP-1) (× 2)	
Flow rate	237 L/min
Input	3.7 kW

While the operation of each equipment is based on weekdays, it is temporarily made on weekends and holidays. Specifically, R-1 is operated during office hours in response to outside air load, and during early morning in response to sensible heat load (complement of thermal storage cooling). On the other hand, CT-1 is operated at 1:00 ~ 8:00 for thermal storage cooling (floor piping), and at 9:00 ~ 19:00 for floor supply air conditioning (AHU).

AMOUNT OF HEAT REMOVAL

Fig. 5 shows the daily amount of heat removal by cold water. It means the sum of amounts of heat removal by OAU (1 unit), AHU (2 units) and floor piping (north and south zones) set on the 7F. As a result of the relationship analysis between it and daily average outside air temperature, a positive correlation was shown with each other. Cold water was in high demand when outside air temperature reaches around 13 ºC, and the amount of heat removal increased to 325 MJ/day for every 5 ºC rise in temperature.

Fig. 6 shows the share rate of air conditioning system, and Fig. 7 shows the histogram of share rate. In cases that the amount of heat removal was small and less than 300 MJ/day, the individual operation of AHU and floor piping respectively was more frequently. The frequency ratio was especially high on AHU. Meanwhile, in cases that the amount of heat removal was large, the share rate of AHU and floor piping were adjusted. When the share rate of AHU was 40 % and that of floor piping was 40 or 70 %, the frequency ratio was higher.

NUMERICAL SIMULATION BY LCEM TOOL

LCEM tool which Minister of Land, Infrastructure, Transport and Tourism released was used and numerical simulation was done in order to verify performance and study feasibility of the FC system in summer and moderate seasons. The models of thermal storage and air conditioning equipment were created by reference to a previously described office building. The specification of heat source equipment (R-1, CT-1) and pump (HCP-1) was based on Table 2. However, because an object of thermal storage in building was not installed into LCEM tool, an object of thermal storage in water was used. On the basis of this object, the models were created by modifying a part of specific gravity, specific heat and expression within an object. It was assumed that surface and internal temperature in building was constant.

COMPARISON WITH BEMS DATA

Fig. 8 shows the comparison of water inlet and outlet temperature. The period between June 6th and September 8th, 2011 on numerical simulation by LCEM tool was calculated. The comparison with building and energy management system (BEMS) data was done on June 25th to July 1st including the day when outside air wet bulb temperature was the lowest and on August 13th to August 19th including the day when outside air wet bulb temperature was the highest. Moreover, after climate conditions, amount of water and thermal load in an office space were input, water inlet and outlet temperature was output. In each case, because the slope of the approximate curve was close to 1.00, and the value of LCEM model was generally consistent with that of BEMS data, the adequacy of these models was checked.

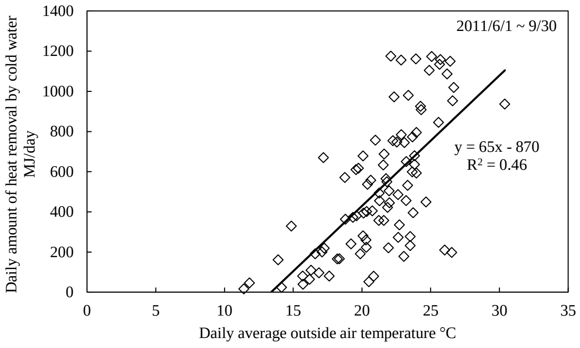

Figure 5: Daily amount of heat removal by cold water.

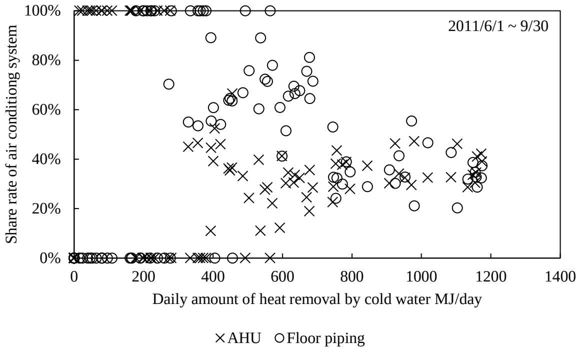

Figure 6: Share rate of air conditioning system.

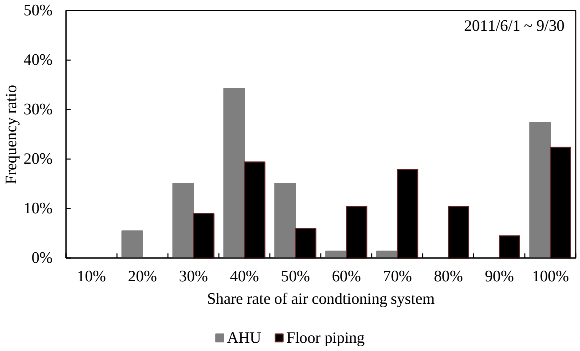

Figure 7: Histogram of share rate.

CALCULATION CONDITIONS

Table 3 lists the calculation conditions, and Table 4 lists the simulation cases about share rate. As the differences of climate conditions, target cities are Sapporo and Sendai, Japan where FC is expected in summer and moderate seasons. Operating time of air conditioning system was based on 9:00 ~ 19:00 (AHU) and 1:00 ~ 8:00 (floor piping). Since August, room temperature setting has been changed from 24 ºC (6/9 ~ 7/31) to 26 ºC (8/1 ~ 9/8). In addition, the simulation cases were set using examples from the share rate of AHU and floor piping. Thermal load in an office space was calculated using approximate expression in Fig. 5.

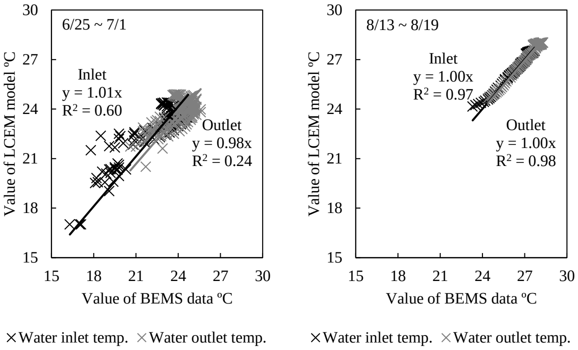

Figure 8: Comparison of water inlet and outlet temperature.

Table 3: Calculation conditions.

Item	Detail
Amount of water (primary side)	
AHU	Rated × 60 % L/min
Floor piping	Rated × 70 % L/min
Amount of water (secondary side)	
AHU	25 L/min
Floor cooling	40 L/min
AHU INV-speed	
$13 <= t_o < 21$	55 %
$21 <= t_o < 25$	75 %
$25 <= t_o$	100 %
Operating mode	
Daytime	FC (CT-1)
Nighttime	Mainly FC (CT-1) & Partly non FC (R-1)
OA, RA ($13 < t_o$)	
$t_o <= t_i$ setting	OA = 0.9 × Q m^3/h RA = 0.1 × Q m^3/h
$t_o > t_i$ setting	OA = 540 m^3/h RA = Q – OA m^3/h
Nomenclature	
t_o	Outside air temperature ºC
t_i	Room temperature ºC
Q	Design flow rate m^3/h

Table 4: Simulation cases about share rate.

Case	AHU : Floor piping
Case 1	10 : 0 (AHU only)
Case 2	7 : 3
Case 3	6 : 4
Case 4	5 : 5
Case 5	4 : 6
Case 6	3 : 7
Case 7	0 : 10 (Floor piping only)

EFFECTIVE OPERATING RATE

In this study, effective operating rate (EOR) was defined in order to analyze the effects of shutdown on weekends, room temperature setting and operating time on the FC system.

$$\mathrm{EOR}\ (\%) = \frac{\text{Operating time of FC (h)}}{\text{Days of simulation} \times \text{Operating time} \left(\frac{\mathrm{h}}{\mathrm{day}}\right)} \times 100$$

While it was possible to back-calculate not EOR but energy consumption with the system efficiency [1], EOR was calculated as preliminary steps in order to be focused on feasibility study of the FC system.

EFFECTS OF SHUTDOWN ON WEEKENDS, ROOM TEMPERATURE SETTING AND OPERATING TIME

Fig. 9 shows the effects of shutdown on weekends. In order to calculate EOR on weekdays only, it was assumed that thermal load in an office space on Saturday and Sunday was zero. In AHU, regardless of the operating conditions on weekends, there is almost no increase in room temperature at the start of operation on Monday, and EOR did not change. On the other hand, in floor piping, low EOR was shown since surface and internal temperature in building was high in accordance with shutdown on weekends. Therefore, it can be said that it is desirable to continuously operate floor piping compared to AHU even in the holiday in order to actively utilize FC.

Fig. 10 shows the effects of room temperature setting. EOR is shown in the case of increasing room temperature setting by 2 ºC and in the case of considering dew point temperature to determine surface condensation on a floor slab and predicted mean vote (PMV) to evaluate thermal comfort for office workers. Moreover, AHU is only shutdown on weekends. EOR was raised by increasing room temperature setting on Case 4 to Case 6 in AHU and all cases in floor piping. In particular, it was possible to cover fully FC only in floor piping. In addition, PMV was good in the case of considering dew point temperature on AHU. However, because EOR is significantly reduced, it is necessary to consider dehumidification as needed.

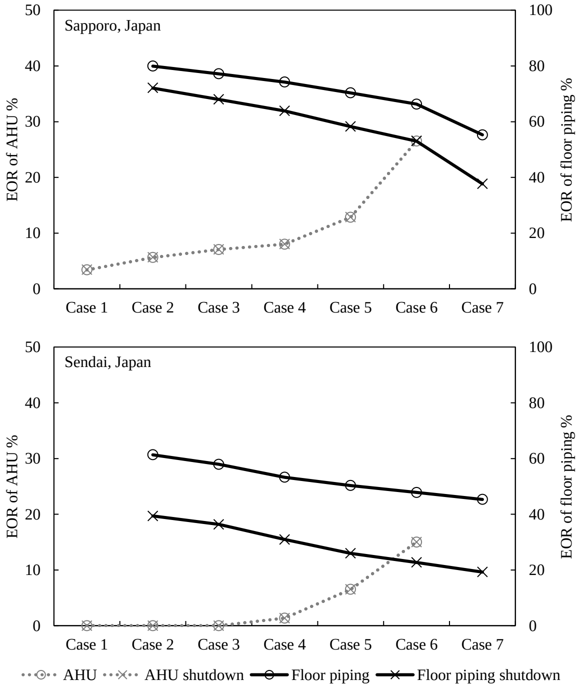

Figure 9: Effects of shutdown on weekends.

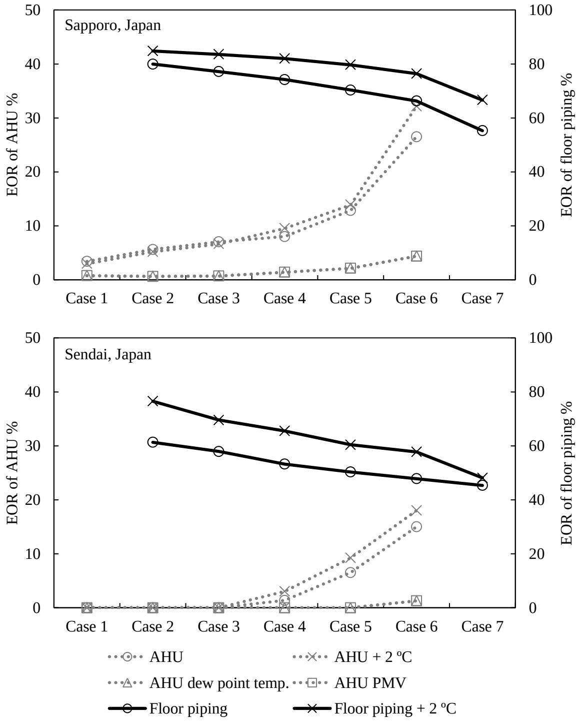

Figure 10: Effects of room temperature setting.

Table 5 lists the simulation cases about operating time, and Fig. 11 shows the effects of operating time. Operating time was changed at regular intervals in Case 1 to Case 4 (AHU) and Case 4 to Case 7 (floor piping) of low EOR. In Case 4 of both AHU and floor piping, EOR was raised since the amount of heat removal per hour was consequently decreased by longer operating time. Therefore, it is thought that an extension of operating time is useful as one of the methods to enhance EOR on the FC system.

Table 5: Simulation cases about operating time.

Case	System	Operating time
Case A	AHU	9:00 ~ 19:00 (10 h)
Case B	AHU	9:00 ~ 20:00 (11 h)
Case C	AHU	8:00 ~ 19:00 (11 h)
Case D	AHU	8:00 ~ 20:00 (12 h)
Case E	Floor piping	1:00 ~ 8:00 (7 h)
Case F	Floor piping	23:00 ~ 8:00 (9 h)
Case G	Floor piping	21:00 ~ 8:00 (11 h)

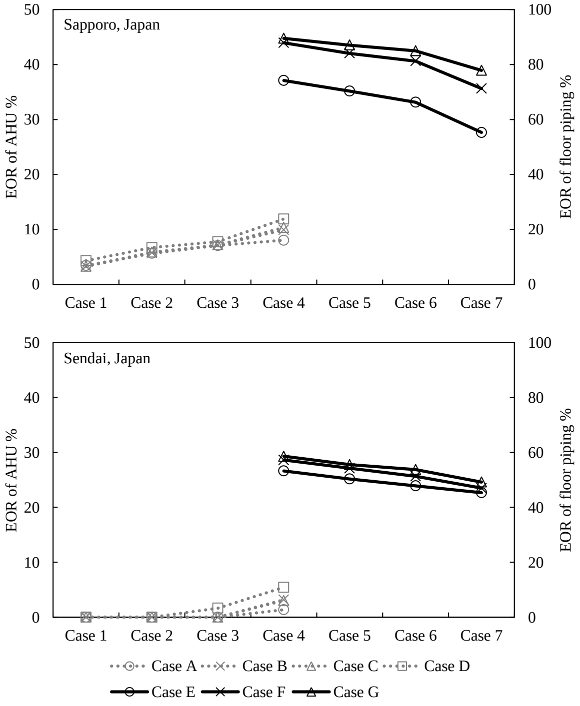

Figure 11: Effects of operating time.

CONCLUSION

1. The daily amount of heat removal by cold water and the share rate of air conditioning system needed for the calculation conditions of numerical simulation were analyzed to verify performance of the FC system in summer and moderate seasons.

2. Because an object of thermal storage in building was not installed into LCEM tool, the models in which an object of thermal storage in water was modified. In addition, as the result of comparison between BEMS and LCEM, the adequacy of these models was checked.
3. EOR of Sapporo and Sendai, Japan was calculated in order to analyze the effects of shutdown on weekends, room temperature setting and operating time, and the feasibility of the FC system in summer and moderate seasons was shown.

ACKNOWLEDGEMENTS

The authors thank Takafumi Kajiyama and Miyuki Morita (Taisei Corporation) who provided valuable BEMS data.

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