# Suggestion and verification of thermal storage heating and cooling systems by a simplified predictive control

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## SUMMARY

In this research, we suggested thermal storage heating and cooling systems by a simplified predictive control for highly insulated office buildings and verified the usefulness of this control technique on the basis of energy conservation and thermal comfort in offices. At first, the calculation procedures of a simplified predictive control were shown. From the viewpoints of energy conservation and thermal comfort, it was very effective to supply heat continuously, such as continuous operation or nighttime operation, in the heating season, and to supply heat intermittently, such as intermittent operation or nighttime operation, in the cooling season.

## INTRODUCTION

Recently, bills related to energy conservation were enforced and revised in Japan, and buildings have become highly insulated and air tightened. In contrast with European countries, external insulation has gradually spread around cold districts in Japan, like Hokkaido, where internal insulation has generally been used. However, under the present conditions, even with externally insulated buildings of reinforced concrete, problems related to control techniques such as suspending operations on Saturday and Sunday and overheating room air temperature in the daytime, could not be always solved. From the above, the main purpose of this research is to suggest a newly simplified control technique and to verify the usefulness of this control technique on the basis of energy conservation and thermal comfort in offices. Heating and cooling systems used in this research utilize thermal storage heating and cooling systems consisting of piping laid inside the floor slab and transporting water to pipes with minimal power.

## OUTLINE OF BUILDING MODEL AND SIMPLIFIED PREDICTIVE CONTROL

In this research, we postulated a building model and reproduced the thermal fluctuations of an actual building by numerical simulation. This model is of an externally insulated office building that had introduced thermal storage heating and cooling systems, built in Sapporo (Figure 1). The scale of this model was the standard scale of government buildings in Hokkaido (total floor area: 3000 [$m^2$]), the details of which are as follows: four-storied building, total floor area 3168 [$m^2$], length of east-west direction 45 [m] and length of south-north direction 17.6 [m]. Concrete volume of this model is shown as the thickness of exterior walls 120 [mm] and slab 150[mm] by adjusting the direction of the depth (z) to a two dimensional model (x-y) in the direction of cross section in each direction. As insulation specifications, EPS external insulation with exterior walls (100 [mm]) and roof slab (150 [mm]) were adopted. Insulation performance became Perimeter Annual Load (PAL) 201 [$MJ/m^2$ year] (heating PAL 74 [$MJ/m^2$ year], cooling PAL 127 [$MJ/m^2$ year]). This value is equivalent to a 30% reduction in the standard value of bills related to energy conservation, and means that this is a very highly insulated building model.

Thermal storage heating and cooling systems are constructed by diverting hot and cold water to cross-linked polyethylene piping (13A) laid inside a floor slab. The depth of piping laid inside the floor slab is 70 [mm], at an interval of 150 [mm]. We have explained a simplified control technique for these systems. We transcribed the simplified control technique suggested in this research into a simplified predictive control, and show the calculation procedures below (Table 1, from a) to d)). Three case studies were done in which the operation methods presumed intermittent operation, continuous operation and nighttime operation (Table 2).

a) Calculation of predictive thermal load: Predictive thermal load was calculated by using mean values for a day of HASP meteorological data. The 2005 calendar was adopted, and thermal load caused by heat gain and ventilation was defined as zero on Saturday and Sunday. When natural room air temperature changed between 22 and 26 [degrees centigrade], this period was defined as the moderate season (*M*). As a result, the maximum predictive heating load became about 1292 [kWh/day] (January 20 (Thursday)) in the heating season (H), and also the maximum cooling load became about 1475 [kWh/day] (July 27 (Wednesday)) in the cooling season (C) (Figure 2).

b) Calculation of equipment capacity of heat source: Equipment required as capacity of heat source for 10-hour intermittent operation or 24-hour continuous operation was calculated by using predictive thermal load. As a result, in the case of intermittent operation, maximum heating and cooling capacity became 153.3 [kW] and 151.9 [kW], and also in the case of continuous operation, 143.1 [kW] and 76.2 [kW] (Figure 3).

c) Calculation of water temperature setting: It was presumed that floor area, which evolved or absorbed heat for heating and cooling, was 3168 [m$^2$] and ceiling area was 2376 [m$^2$]. Water temperature setting was calculated to supply predictive thermal load based on the thermal resistance from the center of the pipe to the surfaces of the floor and ceiling.

d) Calculation of approximate water temperature setting: As thermal storage heating and cooling systems were presumed so as to control the constant flow rates of water, water temperature setting repeatedly change throughout the day corresponding to predictive thermal load. However, in order to make it usable as a simplified predictive control, we defined it approximately by the change throughout the year as approximate water temperature setting.

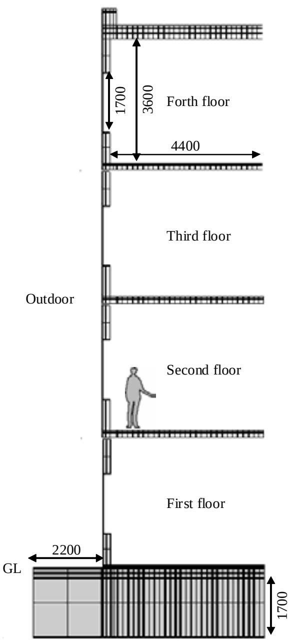



Figure 1. Building model

Table 1. Calculation processes of predictive thermal load

| Calculation processes |
|---|
| Predictive heating load [Wh/day] = $Q_1 - Q_2 - Q_3 + Q_4 + Q_5$ |
| Predictive cooling load [Wh/day] = $- Q_1 + Q_2 + Q_3 - Q_4 - Q_5$ |
| Thermal load of walls [Wh/day] = $Q_1$ = *Siguma* (*Siguma* $K_n \times S_n \times (T_i - T_o)$) |
| Thermal load caused by solar radiation [Wh/day] = $Q_2$ = *Siguma* (*Siguma* $S_n \times J_n \times SC$) |
| Thermal load caused by heat gain [Wh/day] = $Q_3$ = 87859.2 [W] × 8 [h/day] (9:00 ~ 17:00) |
| Thermal load caused by infiltration [Wh/day] = $Q_4$ = 0 |
| Thermal load caused by ventilation (V) [Wh/day] = $Q_5$ |
| = 0.34 × 12672.0 [m$^3$/h] × ($T_i - T_{od}$) × 8 [h/day] (9:00 ~ 17:00) |
| **Notes** |
| $K_n$ : Thermal transmittance of $n$ [W/m$^2$ K], $S_n$ : Area of $n$ [m$^2$] |
| $J_n$ : Value of solar radition of $n$ (HASP, 0:00 ~ 24:00) [W/m$^2$] |
| $SC$ : Shading coefficient (0.46) |
| $T_i$ : Room air temperature for design |
| (Heating season (H): 22 [degrees centigrade], Cooling season (C): 26 [degrees centigrade]) |
| $T_o$ : Mean outdoor air temperature for a day (HASP, 0:00 ~ 24:00) |
| $T_{od}$ : Mean outdoor air temperature during the daytime (HASP, 9:00 ~ 17:00) |
| Thermal load caused by exterior walls (W) [Wh/day] = $Q_1 + Q_2 + Q_3 + Q_4$ |
| $T_o$ on $Q_1$ in the cooling season ⇒ $T_{SAT}$ (Equivalent outdoor air temperature) |
| 87859.2 [W] = 41.6 [W/m$^2$] × 3168 [m$^2$] × 2 / 3 |
| 12672.0 [m$^3$/h] = 30.0 [m$^3$/person h] × 0.2 [person/m$^2$] × 3168 [m$^2$] × 2 / 3 |

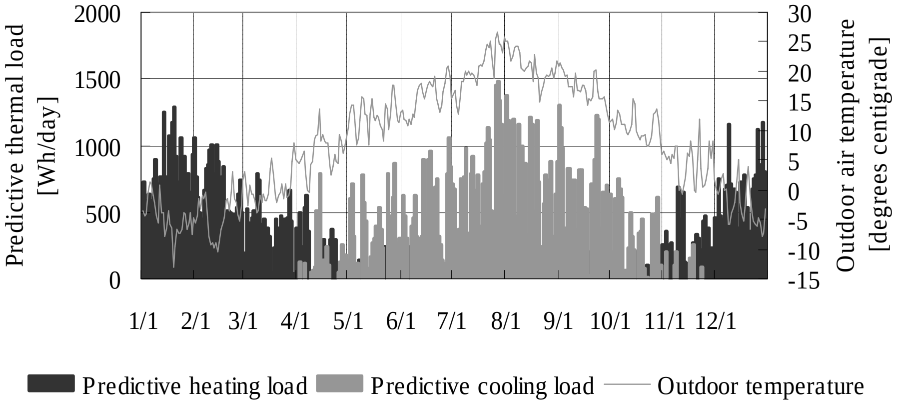



Figure 2. Predictive thermal load throughout the year

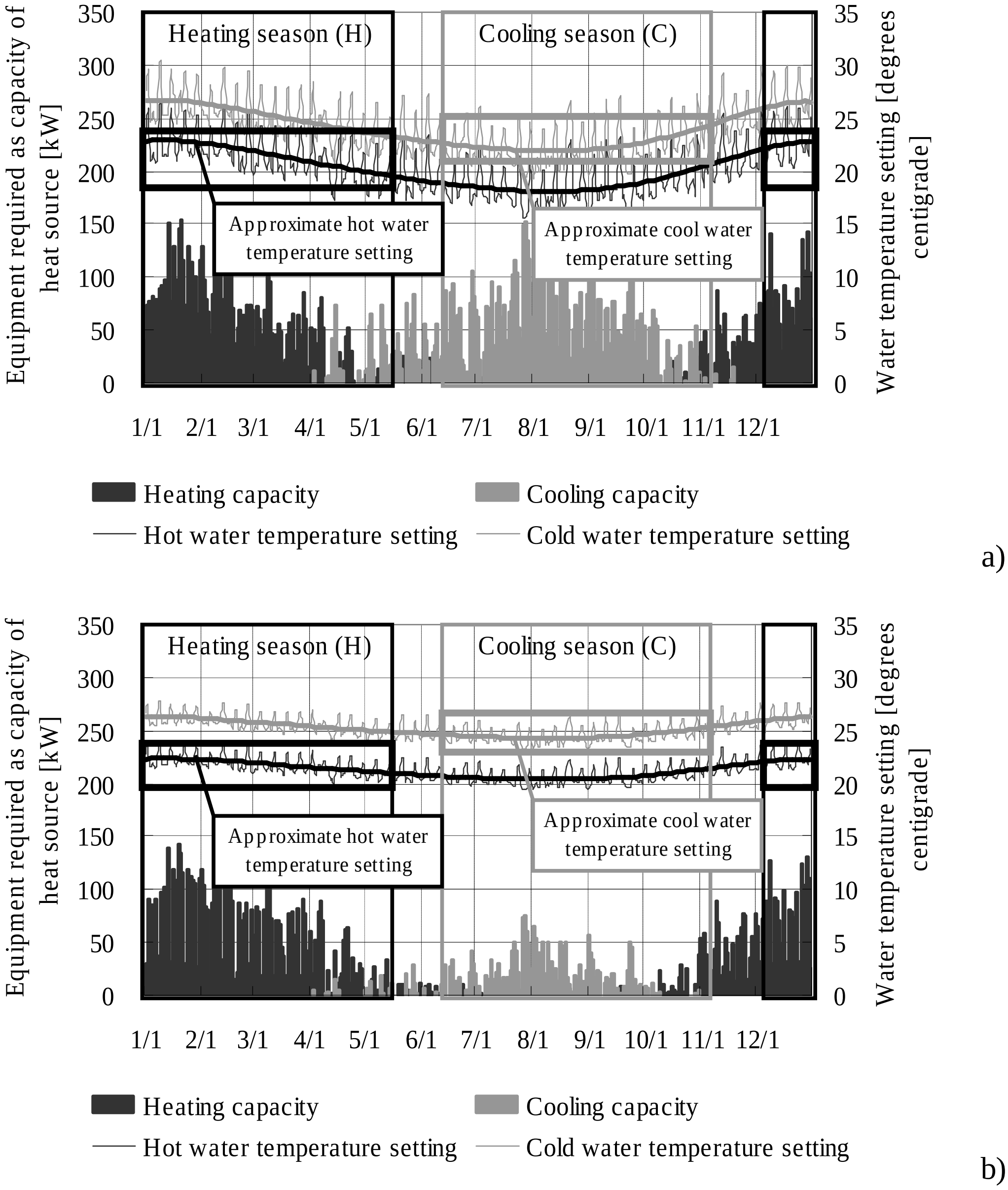



Figure 3. Equipment required as capacity of heat source and water temperature setting
a) 10-hour intermittent operation, b) 24-hour continuous operation

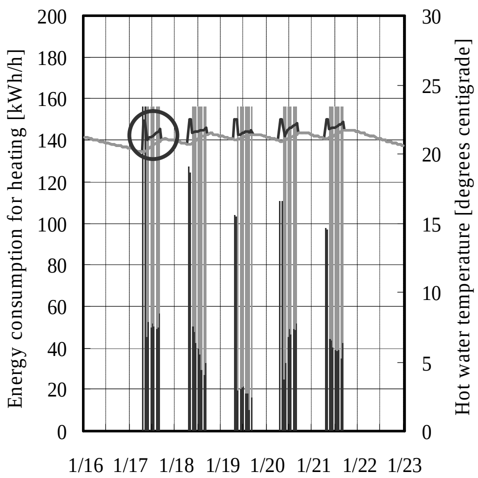
Table 2. Case Studies

| Case Studies | Operation methods | Operation hours for a day | Operation start time | Operation stop time | Equipment capacity of heat source[kW] | | Water inlet temperature [degrees centigrade] (y: Approximate water temperature setting, x = 184 (January 1)～548 (December 31)) |
|---|---|---|---|---|---|---|---|
| CASE1 | Intermittent operation | 10 hours | 7:00 | 17:00 | Heating season (H) | 156.5 | $y = 2.6E\text{-}15x^6 - 1.5E\text{-}11x^5 + 1.9E\text{-}08x^4 - 8.9E\text{-}06x^3 + 1.7E\text{-}03x^2 - 9.8E\text{-}02x + 19.3$ |
| | | | | | Cooling season (C) | 151.5 | $y = 3.8E\text{-}15x^6 - 1.7E\text{-}11x^5 + 2.0E\text{-}08x^4 - 9.2E\text{-}06x^3 + 1.8E\text{-}03x^2 - 1.0E\text{-}01x + 23.1$ |
| CASE2 | Continuous operation | 24 hours | 0:00 | 24:00 | Heating season (H) | 140.9 | $y = 1.1E\text{-}15x^6 - 6.2E\text{-}12x^5 + 7.7E\text{-}09x^4 - 3.7E\text{-}06x^3 + 7.2E\text{-}04x^2 - 4.1E\text{-}02x + 20.9$ |
| | | | | | Cooling season (C) | 77.7 | $y = 1.6E\text{-}15x^6 - 6.9E\text{-}12x^5 + 8.2E\text{-}09x^4 - 3.9E\text{-}06x^3 + 7.4E\text{-}04x^2 - 4.2E\text{-}02x + 24.8$ |
| CASE3 | Nighttime operation | 24 hours | 0:00 | 10:00 | Heating season (H) | 156.5 | $y = 2.6E\text{-}15x^6 - 1.5E\text{-}11x^5 + 1.9E\text{-}08x^4 - 8.9E\text{-}06x^3 + 1.7E\text{-}03x^2 - 9.8E\text{-}02x + 19.3$ |
| | | | | | Cooling season (C) | 151.5 | $y = 3.8E\text{-}15x^6 - 1.7E\text{-}11x^5 + 2.0E\text{-}08x^4 - 9.2E\text{-}06x^3 + 1.8E\text{-}03x^2 - 1.0E\text{-}01x + 23.1$ |

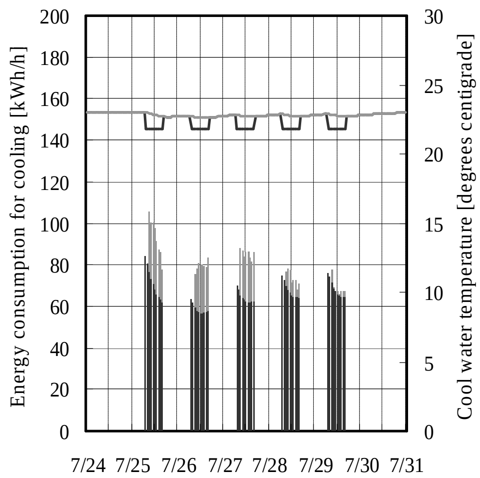
## VERIFICATION OF ENERGY CONSERVATION

Thermal load caused by exterior walls (W) was calculated from [specific gravity * specific heat * flow rates of water * (water inlet temperature - water outlet temperature)]. Thermal load caused by ventilation (V) was calculated from [specific gravity * specific heat * flow rates of fresh air * (room air temperature - outdoor air temperature)]. As thermal load caused by heat gain was considered heat source, approximate hot water temperature setting was very low. However, when the time to operate thermal storage fell on the time to intake fresh air, approximate hot water temperature setting had not arrived at the expected line even if hot water was heated with equipment of heat source(Figure 4 a), c)). Thermal load caused by exterior walls on January 17 (Monday) became larger than that on other days, so it was confirmed that suspending operations on Saturday and Sunday and continuous operation on weekdays were not reasonable. Therefore, it seemed that it is desirable to control by continuous operation on Saturday and Sunday for minimization of equipment capacity of heat source if it is possible to control by continuous operation on weekdays (Figure 4 c)).

On the other hand, nighttime operation obtained a good balance of heat supply between the time to operate thermal storage and the time to intake fresh air. So it was very effective for the problem of stopping operations on Saturday and Sunday (Figure 4 e), f)). Moreover, concerning the relationship between thermal load caused by exterior walls and differences between outdoor and indoor air temperatures, both showed a positive correlation. However, as outdoor air temperature was too cold in the heating season, thermal load caused by exterior walls on Monday increased about 2 times more than those on other days as a result of suspending operations on Saturday and Sunday (Figure 5). Although energy consumption for heating and cooling throughout the year for 24-hour continuous operation was about 5 % larger than that for 10-hour intermittent operation, it must be considered to have minimized equipment capacity of heat source in CASE2 (Figure 6).




a)

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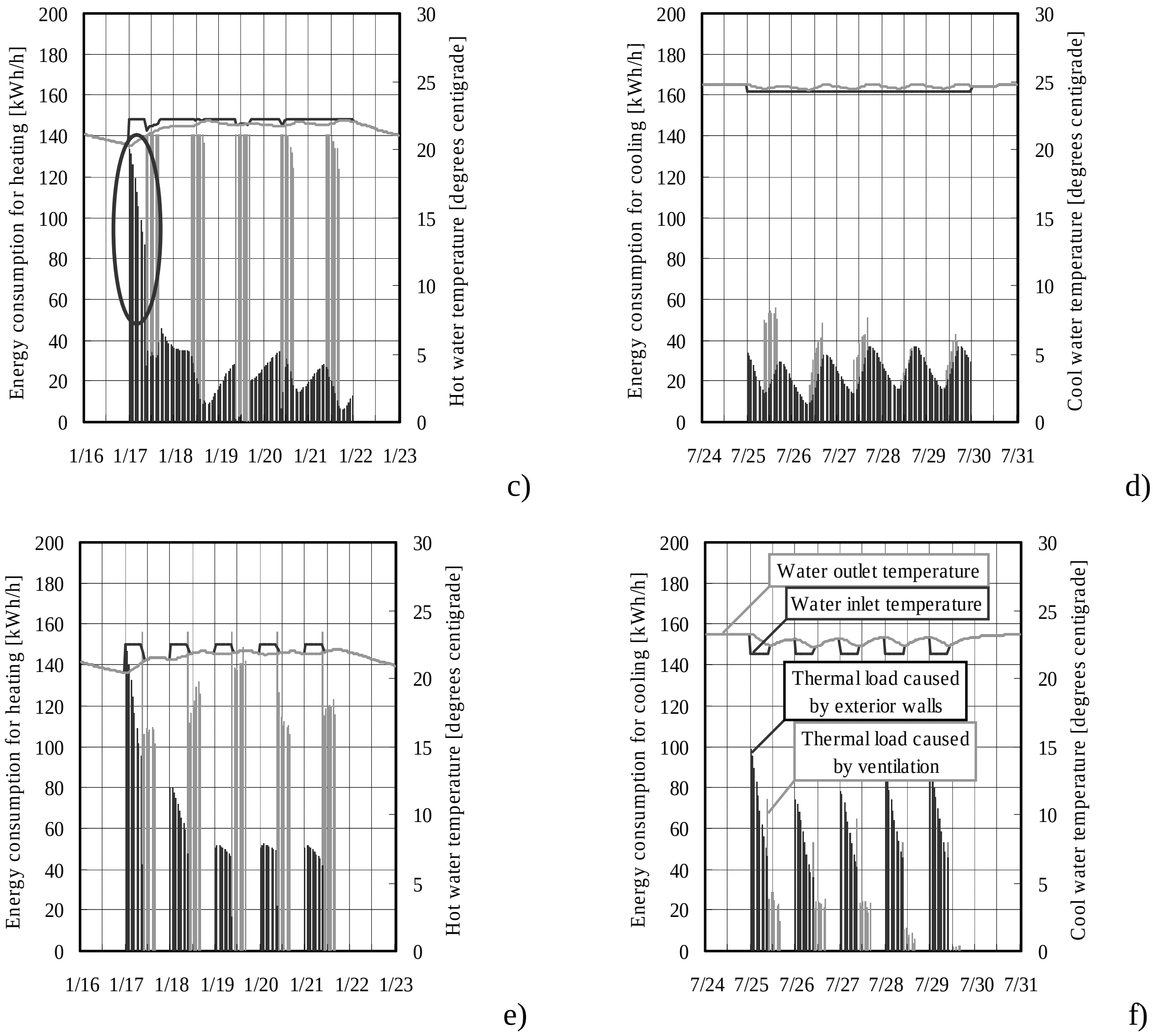



Figure 4. Energy consumption and water temperature

a) CASE1 (H), b) CASE1 (C), c) CASE2 (H), d) CASE2 (C), e) CASE3 (H), f) CASE3 (C)

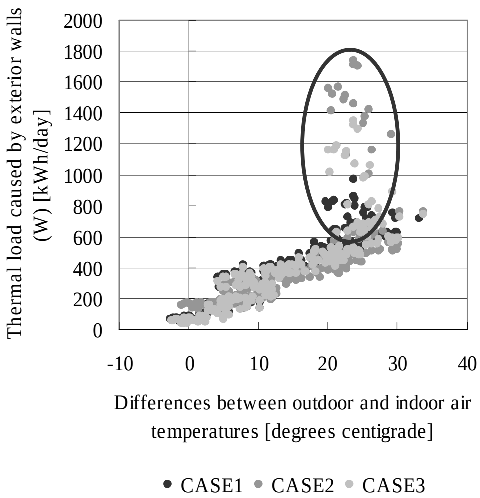



Figure 5. Relationship between thermal load caused by exterior walls (W) and differences between outdoor and indoor air temperatures

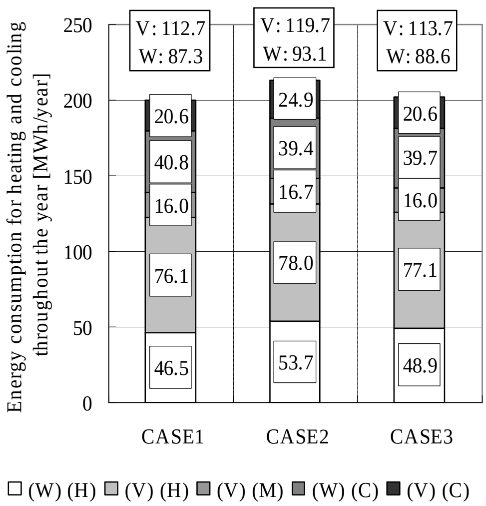



Figure 6. Energy consumption for heating and cooling throughout the year

## VERIFICATION OF THERMAL COMFORT

In the case of approximate water temperature setting, it was possible that the amount of heat required for a day was surplus or short. Yet, if room air temperature fluctuations could be accepted in the range in which office workers feel comfortable, this control technique may be positioned as a simplified predictive control premised on the permissible range of room temperature fluctuations in highly insulated office buildings. As a result, room air temperature (R) and floor surface temperature (F) during office hours were mostly stable, and the range of room air temperature swings settled at about 1.2 [degrees centigrade] (Figure 7, Figure 8).

Thermal comfort in CASE1 became PPD > 10% (PMV < -0.5) in only the heating season, which was affected by the problem of suspending operations on Saturday and Sunday (Figure 9 a)). In contrast, thermal comfort in CASE2 became PPD > 10% (PMV > +0.5) in only the cooling season, which was affected by the problem of overheating room air temperature in the daytime (Figure 9 a)). When room air temperature surpassed 26.5 [degrees centigrade], PPD increased rapidly, and the maximum PPD reached more than 20% (Figure 9 b)). Thermal comfort in CASE3 was very effective because PPD was not more than the recommended value even if we admit the permissible range of room temperature fluctuations (Figure 9 c)).

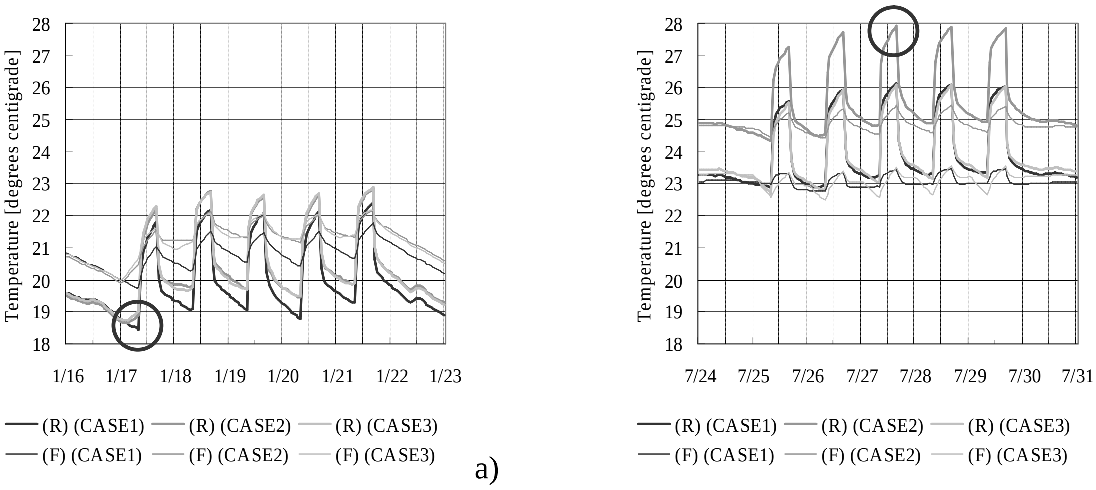



Figure 7. Room air temperature and floor surface temperature

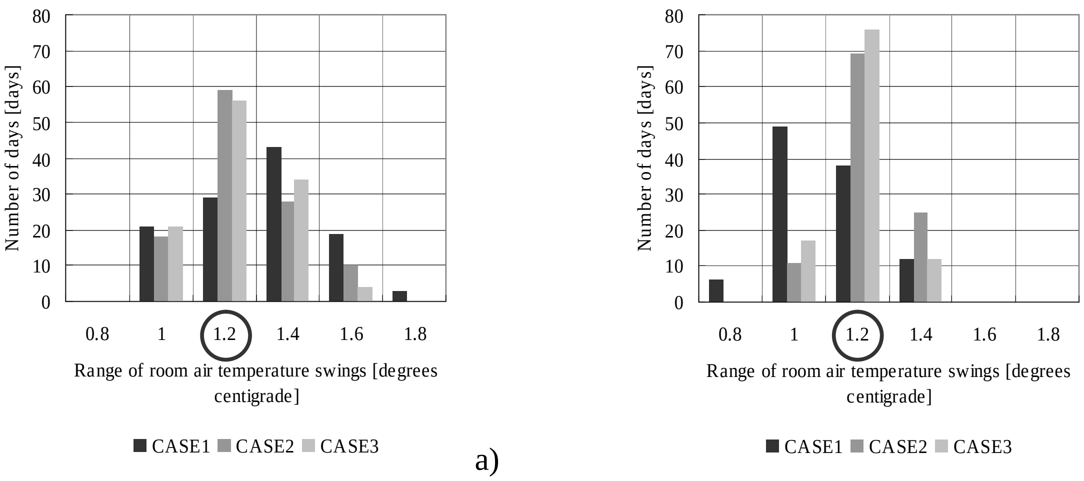
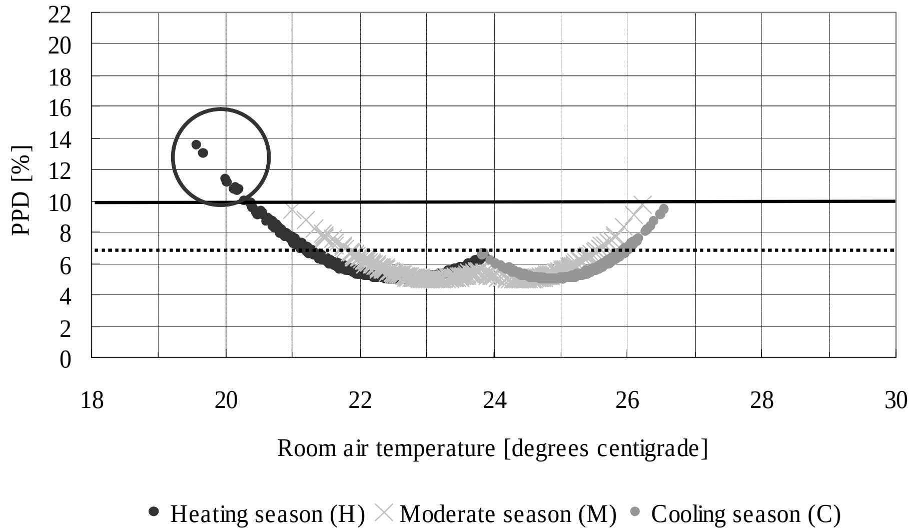
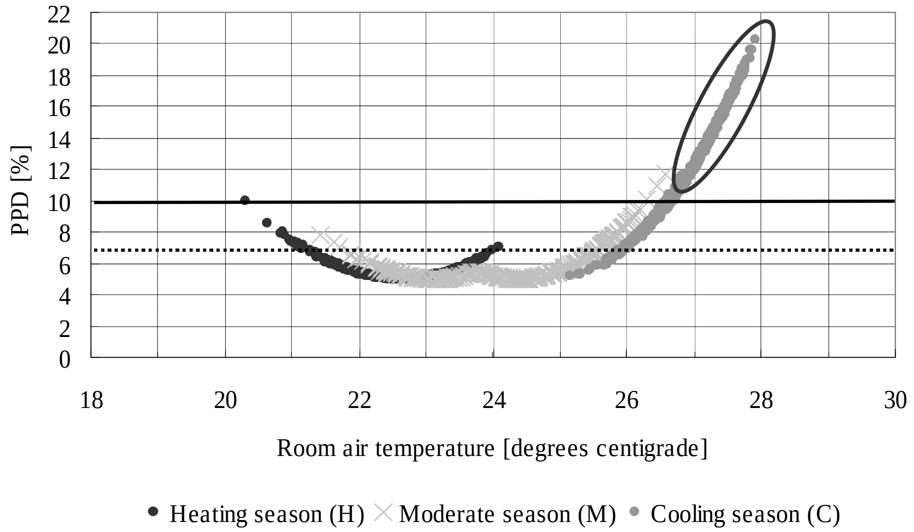



Figure 8. Frequency distribution of range of room air temperature swings

a) Heating season (H), b) Cooling season (C)




a)

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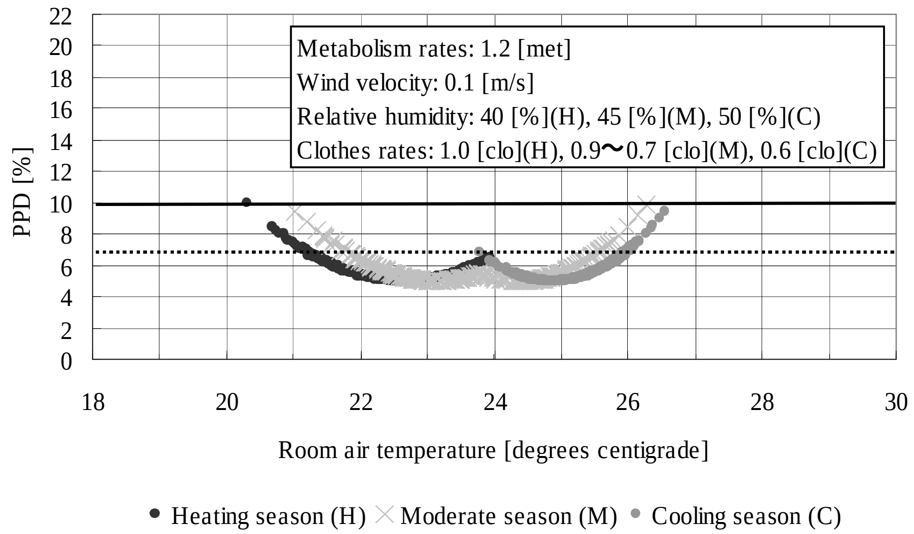


c)

Figure 9. Relationship between room air temperature and PPD
a) CASE1, b) CASE2, c) CASE3

## CONCLUSIONS

In this research, we suggested thermal storage heating and cooling systems by a simplified predictive control for highly insulated office buildings and verified the usefulness of this control technique on the basis of energy conservation and thermal comfort in offices. Principally, we considered the usefulness of continuous and nighttime operations in these systems. The results of numerical simulations were as follows:

1. The calculation procedures of a simplified predictive control were shown, and when the time to operate thermal storage fell on the time to intake fresh air during office hours, approximate hot water temperature setting had not arrived at the expected line.

2. Suspending operations on Saturday and Sunday and continuous operation on weekdays were not reasonable in the heating season because thermal load caused by exterior walls on Monday increased about 2 times more than those on other days.

3. Energy consumption for heating and cooling throughout the year for 24-hour continuous operation was about 5 %, for example about 4 [kWh/$m^2$ year], larger than those for 10-hour intermittent operation. However, it is possible to introduce continuous operation, though operation methods should be improved.

4. From the viewpoints of energy conservation and thermal comfort, it was very effective to supply heat continuously, such as continuous operation or nighttime operation, in the heating season, and to supply heat intermittently, such as intermittent operation or nighttime operation, in the cooling season.

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