Proposal of Optimal Control Method in order to reduce Mutual Interference of Air Conditioning Indoor Units

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ABSTRACT

In recent years, many multi-type package air conditioning systems for buildings have become widespread in office buildings in Japan, and there are many cases where one air conditioning space is shared by using several indoor air conditioning units. The advantages of multi-type package air conditioning system are that it is possible to operate and control individually for each indoor unit, and that the user can arbitrarily change the temperature setting of the indoor unit. On the other hand, these advantages cause air conditioning control problems such as air quality deterioration and mutual interference between adjacent indoor units. Therefore, this study aims at developing a new air conditioning control method that reduces air quality deterioration and influence of mutual interference by using model predictive control (hereinafter MPC) when sharing one air conditioning space with multiple air conditioning indoor units. In this paper, we carried out CFD (Computational Fluid Dynamics) analysis incorporating multiple-input multiple-output (hereinafter MIMO) MPC that controls each zone while considering the thermal environment between adjacent zones in an office where the set temperature differs between zones. Furthermore, we showed the effectiveness of this method (MIMO MPC) by comparing the single-input single-output (hereinafter SISO) MPC.

The following results were obtained: 1) when comparing the outlet air temperature, SISO MPC had a large fluctuation range of the outlet air temperature in the zone where the set temperature was 26 degree, but MIMO MPC was small. 2) The averaged room air temperature in the zone where the set temperature was 27 degree showed almost the same behavior in both control methods, but comparing the behavior of room air temperature at each point, the temperature fluctuation of SISO MPC was large, and the MIMO MPC was small. The reason for this is presumed that the fluctuation range of the room air temperature was suppressed in MIMO MPC in accordance with the difference in the behavior of the outlet air temperature in the adjacent zone. From the results of 1) and 2), the improvement of control performance and the reduction effect of mutual interference were confirmed by the introduction of MIMO MPC for the office with different set temperatures among each zone.

KEYWORDS

Mutual Interference, Model Predictive Control, Coupled Analysis, CFD Analysis, MATLAB/Simulink

1 INTRODUCTION

Multi-split packaged air-conditioning systems have recently become commonplace in office buildings in Japan, and in many cases one space is served by several indoor air-conditioning units. The advantage of a multi-split packaged air-conditioning system is that each indoor unit can be operated and controlled individually, with users being able to change the temperature settings of the indoor units as desired. However, this can cause air-conditioning control problems such as a deterioration in air quality and mutual interference between adjacent indoor units[1)]. In particular, when each air-conditioned zone has a different internal load and set temperature, the sensor temperatures are influenced by disturbances, the indoor units are driven harder than they need be, energy consumption increases[2)~4)], and indoor air quality worsens[5)~7)].

Given the aforementioned problems, the aim of this study was to develop a new air-conditioning control method that reduces the deterioration in air quality and the influence of mutual interference by using model predictive control (MPC) when one space is served by multiple indoor air-conditioning units. We carried out computational fluid dynamics (CFD) analyses incorporating multiple-input–multiple-output (MIMO) MPC that controls each zone while considering the thermal environment between adjacent zones in an office space in which the set temperature differs between zones. Furthermore, we showed the effectiveness of this method by comparing it with single-input–single-output (SISO) MPC.

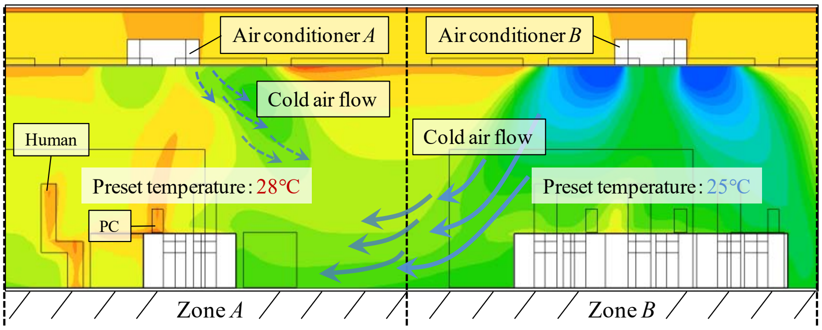


Fig.1 Image of mutual interference between adjacent indoor units

2 MUTUAL INTERFERENCE BETWEEN INDOOR AIR-CONDITIONING UNITS

According to previous research, when one space is served by several indoor air-conditioning units, those units behave differently depending on the uneven distribution of the internal load and differences in the set temperatures among the zones. As such, it is obvious that adjacent indoor units can experience mutual interference. Therefore, in this study we compare the influence of indoor units with different behaviors on their respective adjacent zones by means of a case study in which SISO MPC and MIMO MPC are incorporated separately in the air-conditioning control. We also show the effectiveness of the proposed method by comparing how the two control methods perform and how the room temperature changes.

3 OUTLINE OF CFD ANALYSIS

3.1 Analysis Model

Figures 2 shows the floor plan of analysis model. The analysis model simulates a general office space that has six zones in the form of two perimeter zones (hereinafter periES, periWS) and four interior zones (hereinafter inE01, inE02, inW01, and inW02). A ceiling-cassette air conditioner with four blowing directions is installed in the center of each zone. Furthermore,

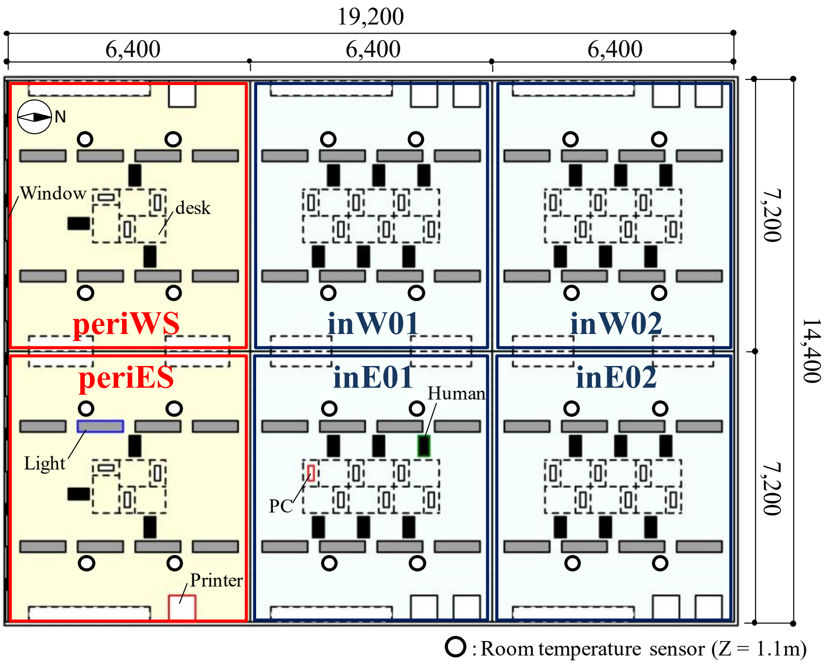


Fig.2 Floor plan of analysis model

four temperature sensors are installed at a height of 1.1 m in each zone, and their average value is taken as the room temperature in the zone.

3.2 Analysis Conditions

The CFD analysis conditions are listed in Table 1. The analysis period was 7,200 s during summertime, and analysis was performed under the conditions of the set temperature in each case. Regarding the control methods, conventional thermal ON/OFF control was used for the first 3,600 seconds, and SISO MPC or MIMO MPC was used for the second 3,600 seconds. As internal loads, a human body, office automation equipment, and lighting were installed as shown in Fig. 2; the load amounts are listed in Table 1[1), 8)]. In addition, the amount of heat received from solar radiation on the south- facing side of the building was calculated as the solar heat gain, and the thermal load due to absorption and transmission was given to the windows and blinds.

3.3 Analysis Cases

Table1. Analysis conditions for CFD analysis

Domain	19.2m *(X)* × 14.4m *(Y)* × 4.0m *(Z)*
Mesh	278 *(X)* × 235 *(Y)* × 55 *(Z)* = 3,593,150
Outlet boundary conditions	Temperature: Control by MATLAB/Simulink [°C], Flow rate: 1,680m^3/h, $k_{in} = (U_{in}/10)^2$, $\varepsilon_{in} = C_u^{3/4} \cdot k_{in}^{3/2}/l_{in}$
Inlet boundary conditions	Fixed velocity, zero-gradient condition
Turbulence model	Standard k-ε model
Wall boundary conditions	Velocity: Logarithmic law, Temperature: Convective heat transfer coefficient (= 4.6 W/m^{2}K)
Adjacent room boundary	27°C (Overall heat transfer coefficient: 9.0 W/m^{2}K)
Outdoor side boundary	30°C (Overall heat transfer coefficient: 23.0 W/m^{2}K)
Heat generation	Human: 36W/person(3.9W/m^2), Lighting: 13.4W/m^2, Solar radiation: 60.3W/m^2, OA equipment and PC: 60W/unit(6.4W/m^2), Printer: 151.2W/unit(5.4W/m^2),

U_{in}: Outlet air wind speed [m/s], k_{in}: Outlet air turbulence energy [m^2/s^2], ε_{in}: Dissipation rate of k_{in} [m^2/s^3], C_μ: Model constant (=0.09) [-], l_{in}: Length scale [m]

By means of coupled analysis using CFD and MATLAB/Simulink[9), 10)], we verified the effectiveness of MIMO control when the set temperatures of adjacent zones are different. In the analysis, case 1 involves SISO MPC, case 2 involves MIMO MPC, and we compared the control performance and behavior of outlet air temperature and room temperature in two cases.

3.4 Flow of Control in Coupled Analysis

In this study, we performed a coupled analysis using CFD for the office space with multi-split air conditioning and MATLAB/Simulink for the air-conditioning control. The flow of the coupled analysis is described below. First, the CFD receives data for outlet air volume, outlet air temperature, and outlet air humidity (hereinafter manipulating variables) from MATLAB/Simulink. Next, the CFD sets the read operation amount as a boundary condition, performs three-dimensional thermal fluid analysis, calculates the sensor temperature of each zone, outputs it to an intermediate file, and waits. MATLAB/Simulink then reads the sensor temperature of each zone and sets this as the initial value of the sensor temperature $y(t)$ at the current time t. From there, MATLAB/Simulink predicts the sensor temperature and optimizes the outlet air temperature so that the error between the set temperature and the room temperature is minimized. Finally, MATLAB/Simulink outputs the current outlet air temperature that was calculated by optimization to the CFD. As described above, the coupled analysis was performed by optimizing the manipulating variable and repeating these data transfers at the calculation time interval Δt of CFD.

3.5 Obtain Step Response used for SISO Control

First, an internal load is generated in each zone to create a steady state. After that, the outlet air temperature of periES is changed from 27°C to 16°C, and the prediction model of periES, is obtained. Finally, the prediction model inE01, inE02, periWS, inW01, and inW02 of the other five zones are also obtained in the same flow. In the SISO MPC, control is performed by incorporating these six step responses in the control law (Fig. 3). The predicted output model of each zone obtained at time $t+j$ is represented by Equation (1) because SISO MPC does not consider the influence from the adjacent zone.

$$y_{n_{SISO}}(t+j) = \sum_{k=1}^{\infty} a_n(k)\Delta u_n(t+j-k) + \sum_{k=1}^{\infty} b_n(k)\Delta d_n(t+j-k) \tag{1}$$

n: Zone position($n = 1 \sim m$), t: Current time
j: Prediction horizon, k: Sampling time of step response
$a_n(k)$: Step response factor to air-conditioner output in n zone
$b_n(k)$: Step response factor for disturbance output in n zone
$\Delta u_n(t+j-k)$: Step input of air-conditioner in n zone
$\Delta d_n(t+j-k)$: Step input of disturbance in n zone

3.6 Obtain Step Response used for MIMO Control

As described above, in the SISO MPC (e.g., a zone of periES), control is performed using only the step response. However, in reality the sensor temperature of periES is affected by air conditioners inE01, inE02, periWS, inW01, and inW02 in the same space. Therefore, the SISO MPC cannot consider the influence of air conditioners in adjacent zones, and it is difficult to perform control that reproduces the heat transfer phenomenon with mutual interference between the zones. Therefore, in the MIMO MPC of this research, each zone was controlled using a step response that considered the influence of the air conditioners in all zones. The step response used in the MIMO MPC was obtained by the following method. First, as with the SISO MPC, an internal load is generated in each zone to create a steady state. The outlet air temperature of the control target zone was then changed from 27°C to 16°C, and the step responses of the sensor temperatures of both the target zone and all the other zones are obtained. For example, when the outlet air temperature of periES is changed, the step responses of the other five zones are obtained simultaneously in addition to the step response of periES. In the same flow, the

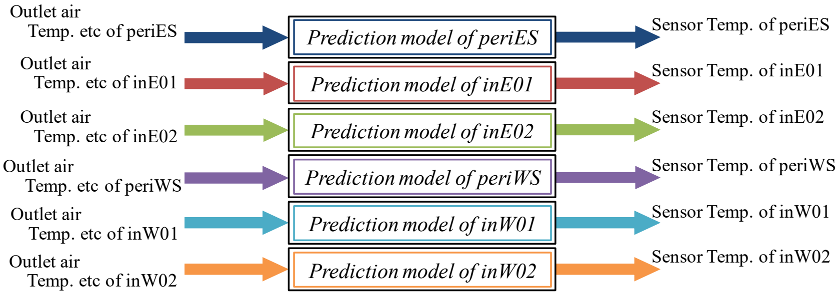


Fig.3 Image of SISO MPC prediction model

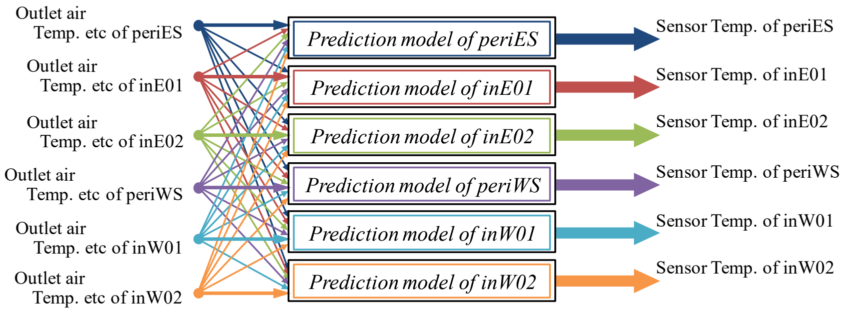


Fig.4 Image of MIMO MPC prediction model

step responses of inE01, inE02, periWS, inW01, and inW02 are obtained, and MIMO control is performed by incorporating a total of 36 step responses into the prediction model (Fig. 4). The predicted output model of each zone obtained at time t+j is represented by Equation (2) because MIMO MPC considers the influence from the adjacent zone.

$$y_{n\_MIMO}(t+j) = \sum_{i=1}^{m} \left\{ \sum_{k=1}^{\infty} a_{ni}(k)\Delta u_i(t+j-k) + \sum_{k=1}^{\infty} b_{ni}(k)\Delta d_i(t+j-k) \right\} \qquad (2)$$

n: Zone position ($n = 1 \sim m$), i: Zone number ($i = 1 \sim m$)
$a_{ni}(k)$: Step response factor to air-conditioner output of i zone in n zone
$b_{ni}(k)$: Step response factor for disturbance output of i zone in n zone
$\Delta u_i(t+j-k)$: Step input of air-conditioner in i zone
$\Delta d_i(t+j-k)$: Step input of disturbance in i zone

4 ANALYSIS RESULTS

4.1 Control Performance and Follow Ability at Room Temperature

Figures 5 and 6 show the room temperature and the outlet air temperature of representative zones in Cases 1 and 2, respectively, and Fig. 7 shows the control error (Root Mean Squared Error) of the room temperature in all zones in both cases. As shown in Figs. 5 and 6, when comparing the outlet air temperatures of the respective cases, the fluctuation range of the outlet air temperatures of the periWS and inW02 zones where the set temperature is 26°C, is large in Case 1 but small in Case 2. This is because while the control in Case 1 considers only the target zone, the control in Case 2 also considers the influence of the air conditioner and internal load of the adjacent zone. Moreover, the three east zones of periES, inE01, and inE02 show the same tendency as the three west zones, and consequently in Case 2 the control error of the zone whose set temperature is 27°C is reduced by approximately 0.4°C (Fig. 7).

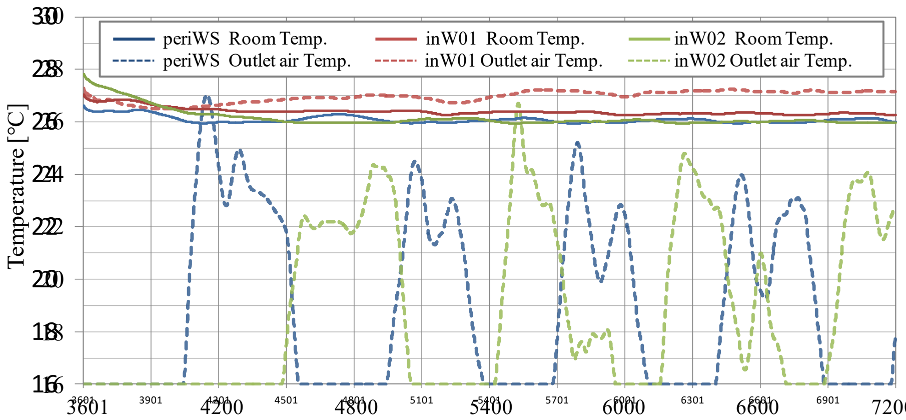


Fig.5 The room temperature and the outlet air temperature of representative zones in Case1(SISO MPC)

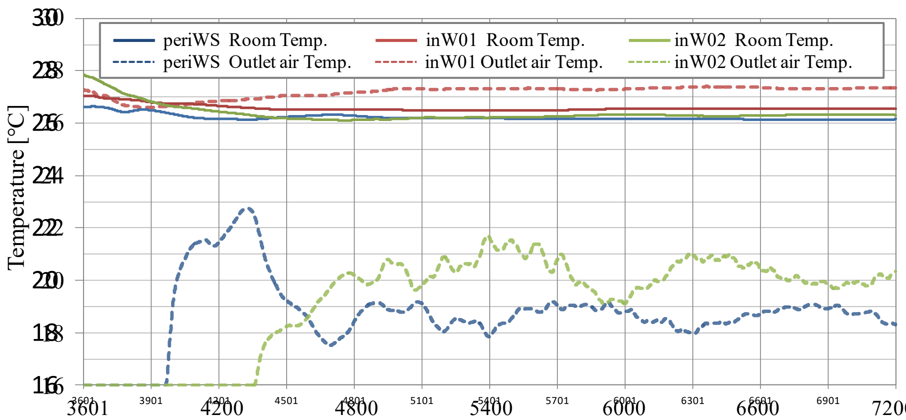


Fig.6 The room temperature and the outlet air temperature of representative zones in Case2(MIMO MPC)

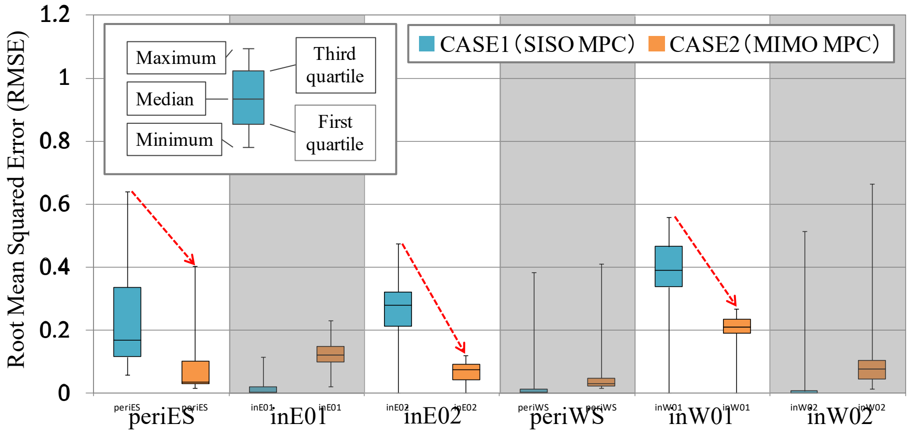


Fig.7 A temperature control error of the room temperature in all zones in Cases1 and 2

4.2 Mutual Interference due to Air Supply of Adjacent Indoor Units

Figures 8 and 9 shows the room temperature (each point) of the inW01 zone in Cases 1 and 2. Furthermore, Fig. 10 shows a temperature control error in the average temperature of the room in the inW01 zone, and Fig. 11 shows the temperature fields and flow fields of the vertical surface and horizontal surface at 5,400 s in Case 2. As shown in Figs. 5 and 6, the outlet air temperature and the room temperature of the inW01 zone have almost the same behavior in Cases 1 and 2. However, comparing the behavior of the occupancy-area sensor temperature (each point) in the inW01 zone shown in Figs. 8 and 9, the temperature fluctuation range in Case 1 is large but that in Case 2 is small. The reason is presumed to be that the fluctuation of the room temperature is suppressed in Case 2 in accordance with the difference in the behavior of the outlet air temperature of the adjacent zone of inW01. Furthermore, in Fig. 10 it is

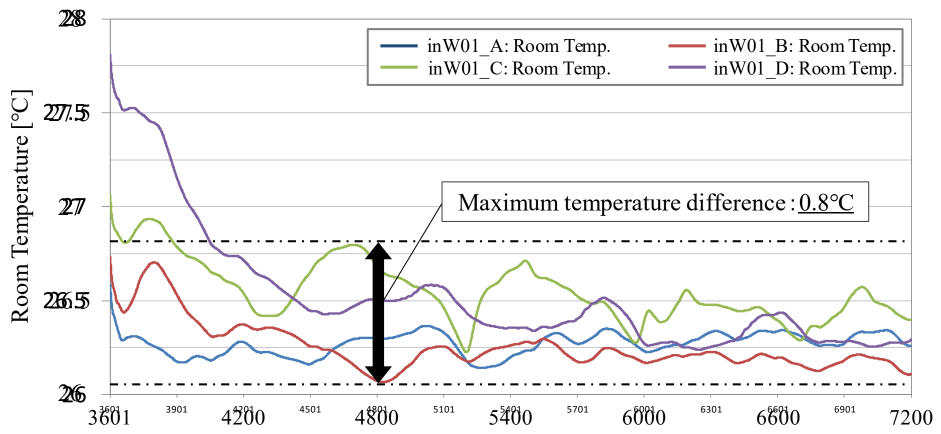


Fig.8 The room temperature (each point) of the inW01 zone in Case1(SISO MPC)

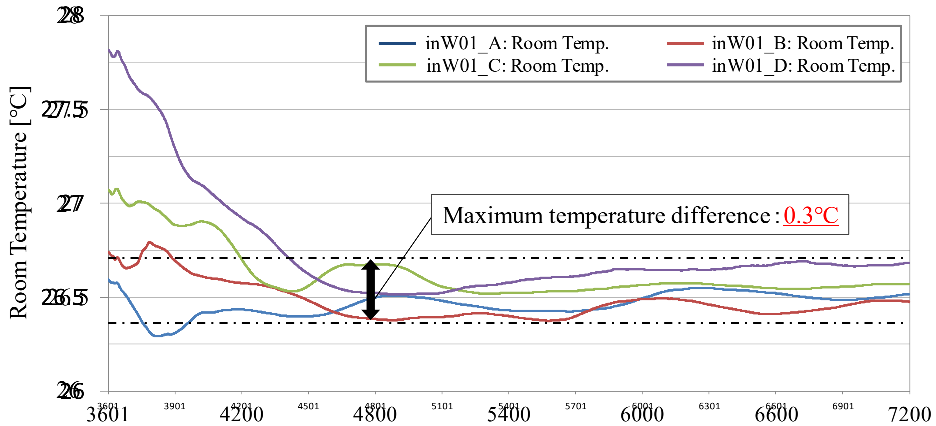


Fig.9 The room temperature (each point) of the inW01 zone in Case2(MIMO MPC)

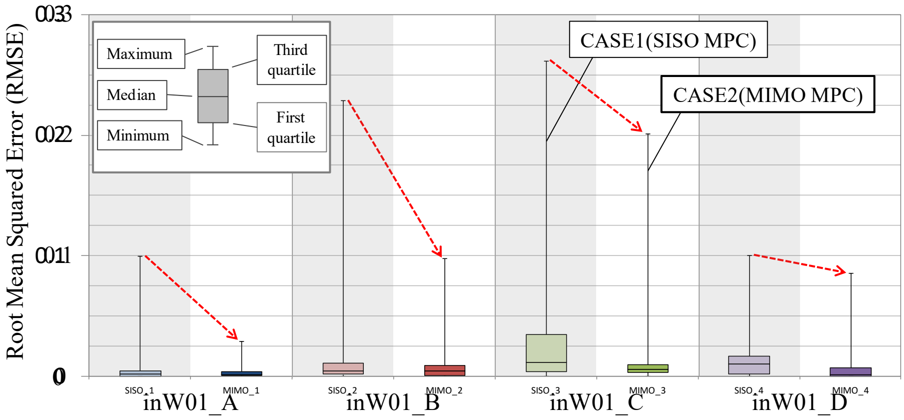
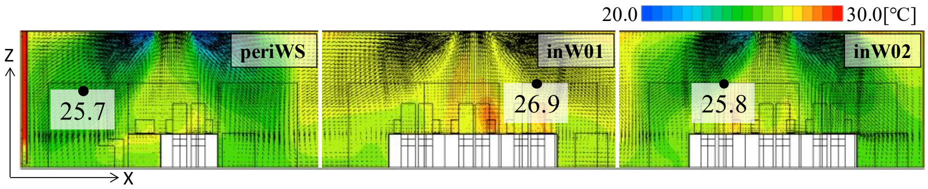
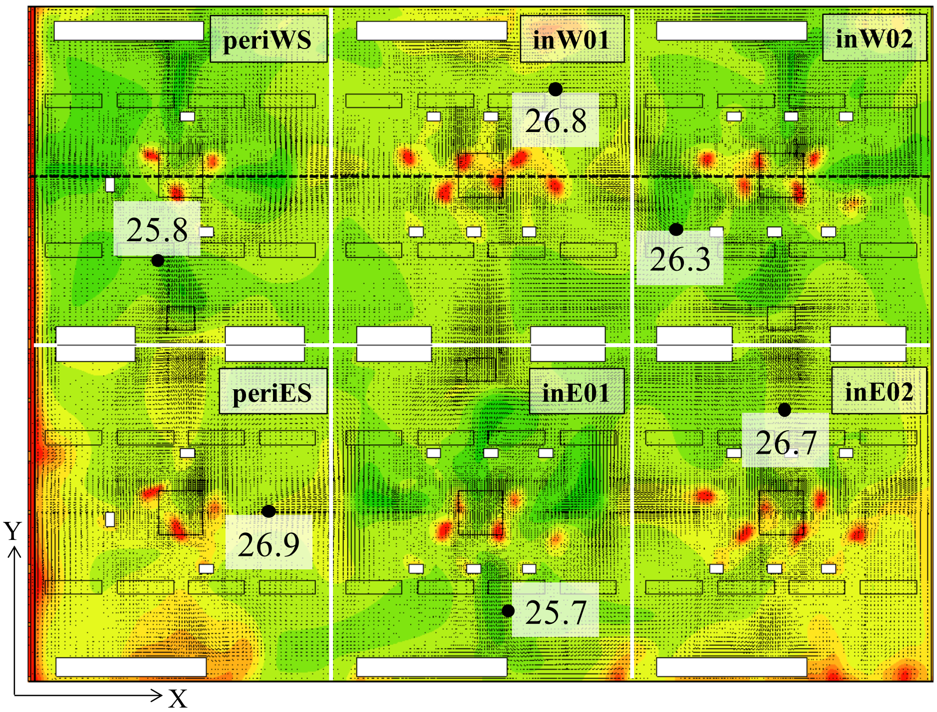


Fig.10 A temperature control error in the average temperature of the room in the inW01 zone



(a) The vertical surface



(b) The horizontal surface

Fig.11 The temperature fields and flow fields at 5,400 s in Case 2 (MIMO MPC)

confirmed that the fluctuation of the room temperature is suppressed at all four points in Case 2. It is also confirmed in Fig. 11 that the temperature of not only each sensor but also the entire office space is generally controlled to the set temperature of each zone. From the above results, the effectiveness of the MIMO MPC proposed in this research is confirmed.

5 CONCLUSION

In this study, we carried out CFD analyses incorporating MIMO MPC that controls each zone while considering the thermal environment between adjacent zones in an office space in which the set temperature differs between zones. Furthermore, we showed the effectiveness of this method by comparing it with SISO MPC. The following results were obtained: 1) when comparing the outlet air temperatures of the respective cases, the fluctuation range of the outlet air temperatures of the periWS and inW02 zones where the set temperature is 26°C is large in Case 1 but small in Case 2. 2) The averaged room air temperature in the zone where the set temperature was 27 °C showed almost the same behavior in both control methods, but comparing the behavior of the occupancy-area sensor temperature at each point, the temperature fluctuation range in SISO MPC was large but that in MIMO MPC was small. The reason is presumed to be that the fluctuation of the room temperature was suppressed in MIMO MPC in accordance with the difference in the behavior of the outlet air temperature of the adjacent zone. From the results of 1) and 2), the improvement of control performance and the reduction effect of mutual interference were confirmed by the introduction of the MIMO MPC for the office space with different set temperatures among each zone.

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