A Numerical Investigation on the Effect of Operation Control of a Multi-Split Air-Conditioning System on Indoor Thermal Environment

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ABSTRACT

In this study, a numerical investigation on the effect of operation control of an air-conditioning system (multi-split air-conditioning system) on the indoor thermal environment during a power-saving period in summer was performed by a coupled analysis of CFD and HVAC system simulations. In the operation control, one of the indoor units was forced to change from a cooling mode to a fan mode. Two different forced operation controls, i.e., a simple/regular rotation control and a lowest reference temperature control, were introduced, and the difference in the effect on the indoor thermal environment was investigated. For creating a more uniform thermal environment, the lowest reference temperature control was better than the regular rotation control.

KEYWORDS

CFD, HVAC system simulation, Multi-split air-conditioning system, Forced operation control, Indoor thermal environment

INTRODUCTION

Especially after the Fukushima nuclear power plant disaster in 2011, high power saving is strongly required in Japan. In office buildings, for instance, thinning out lighting fixtures and cutting standby power consumption are requested to save power. During such a power-saving period, especially in summer, it may be possible to stop or reduce some of air-conditioning due to the reduction of internal heat generation. However, when performing the operation control of air-conditioning, it is necessary to maintain indoor thermal environment without discomfort.

In this study, an operation control of an air-conditioning system in an office during a

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power-saving period in summer, in which one of the indoor units was forced to change from a cooling mode to a fan mode, was introduced, and the effect on the indoor thermal environment was quantitatively investigated by a coupled analysis of computational fluid dynamics (CFD) and heating, ventilation, and air-conditioning (HVAC) system simulations. The air-conditioning system adopted in this study was a multi-split air-conditioning system, which is currently being used in many office buildings. For the forced control, two kinds of operations were introduced. One was to switch the cooling/fan modes of an indoor unit by a simple/regular rotation at a certain time interval. The other was by a manner based on the lowest reference temperature with the same time interval as that of the regular rotation control. Particularly in this study, the effect of the difference in the forced operation control on the indoor thermal environment was evaluated by the coupled analysis of CFD and HVAC system simulations.

OUTLINE OF SIMULATIONS

Target office room and air-conditioning system

Figure 1 shows the typical floor plan of the target office building. The office rooms were arranged in the northern and southern parts of the floor; however, only a room in the southern office area was focused in this study. The size of the target room was 11 m (length; x direction) × 13 m (width; y direction) × 2.9 m (height; z direction). The target period was a power-saving period in summer, and the outdoor air temperature and humidity were set at 34 °C and 0.02 kg/kg(DA), respectively. A multi-split air-conditioning system, in which eight indoor units (hereafter IUs) on the ceiling of the office rooms were connected to an outdoor unit (cf. Figure 1), was adopted in this study. In the target room, four IUs were installed and two total heat exchanger units (hereafter HEXs) were mounted between the IUs, as shown in Figure 2.

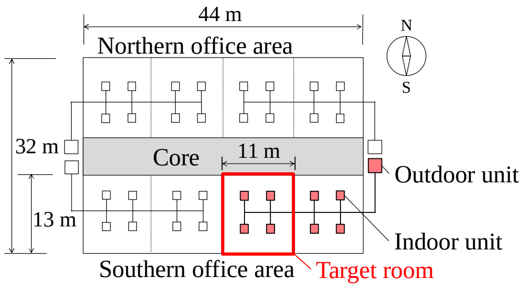


Figure 1. *Typical floor plan of the target office building*

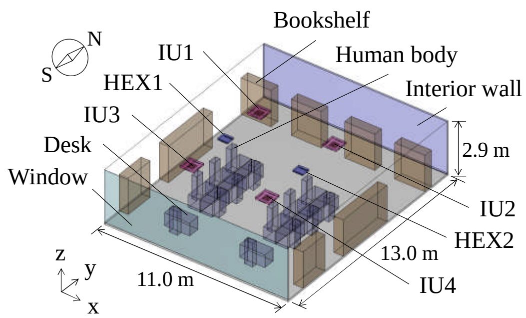


Figure 2. *Target office room*

CFD

For the analysis of thermal and airflow environments as well as the radiation environment in the target room, a commercial CFD software, STREAM ver. 8, was used. The CFD analysis conditions are summarized in Table 1. Each IU had four supply inlets in four directions and all of the supply airs were provided at a 30-degree angle from the ceiling. On the other hand, each HEX had only one supply inlet and the supply air blows at the same angle as those of the IUs. The heat generation from lighting, equipment, and human bodies (rectangular box shape) was considered to be internal heat sources; however, those from lighting and equipment were reduced to 10 W/m^2 and 7 W/m^2, respectively, because a power-saving period was assumed in this study.

Table 1. *CFD analysis conditions*

Domain	11.0 m (x) × 13.0 m (y) × 2.9 m (z)
Grid points	76 (x) × 122 (y) × 24 (z) = 222,528
Scheme for convection terms	QUICK scheme for all governing equations
Turbulence model	RNG k-ε model (high-Reynolds number type)
Inlet boundary conditions	Indoor unit (IU) Velocity : 660 m^3/h Temperature : 16 °C (cooling mode) or Return air temperature + 0.5 °C (fan mode) Humidity : Results from HVAC system simulation (cooling mode) or Return air humidity (fan mode) k : 7.87 × 10^{-2} m^2/s^2 ε : 2.78 × 10^{-1} m^2/s^3
	Total heat exchanger unit (HEX) Velocity : 250 m^3/h Temperature : Return air temperature × 0.5 + Outdoor air temperature × 0.5 Humidity : Return air humidity × 0.5 + Outdoor air humidity × 0.5 k : 5.53 × 10^{-1} m^2/s^2 ε : 1.53 × 10^{-1} m^2/s^3
Outlet boundary conditions	Zero-gradient conditions for all variables
Wall boundary conditions	Velocity : Symmetry boundary condition (for the x direction) Logarithmic law (for other walls) Temperature : Overall heat transfer coefficients for the window, interior wall, and ceiling were 2.080 W/(m^2・K), 0.760 W/(m^2・K), and 0.314 W/(m^2・K), respectively. Adiabatic condition (for other walls) Humidity : Impermeable condition without condensation
Heat generation	Lighting : 10 W/m^2 Equipment : 7 W/m^2 Human body : 55 W/person (sensible) and 63 W/person (latent)

HVAC system simulation

The HVAC system simulation was performed using the life-cycle energy management (LCEM) tool ver. 3.03, which was developed under the supervision of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. Table 2 shows the performances of the outdoor unit, IU, and HEX.

__Table 2.__ Performances of the outdoor unit, indoor unit, and total heat exchanger unit

Outdoor unit	Cooling capacity	: 33.5 kW
	Cooling power consumption	: 10.1 kW
Indoor unit (IU)	Cooling capacity	: 3.6 kW
	Cooling power consumption	: 0.05 kW
Total heat exchanger (HEX)	Sensible heat/Enthalpy exchange efficiency	: 50/50 %
	Power consumption	: 0.097 kW

Coupling method of CFD and HVAC system simulations

The CFD and HVAC system simulations described above were coupled every 30 seconds. In the coupled simulation, the air temperature and humidity at the suction opening, which was attached to each IU, calculated by CFD were given to the HVAC system simulation. The supply air of each IU was controlled by an ON (cooling mode) -OFF (fan mode) control. Here, each IU had one reference temperature for controlling the supply air. The ON-OFF control switched to the cooling mode when the reference temperature reached 27 °C and above, while it changed to the fan mode when the reference temperature reached 25 °C and below. In the cooling mode, the supply air temperature was set at 16 °C, and the supply air humidity obtained by the HVAC system simulation, (in which it was calculated based on the coil surface air temperature and humidity, the coil outlet air temperature, the supply air temperature, and the return air temperature and humidity), was given to CFD as the boundary condition. In the fan mode, the supply air temperature was 0.5 °C higher than that at the suction opening due to the heat generated by the fan, and the supply air humidity was the same as that at the suction opening. For the HEXs, the temperature and humidity at the supply inlet were provided by the CFD results only and as the sum of halves of the air temperature/humidity at the suction opening of each HEX and the outdoor air temperature/humidity. Those values were calculated every one second.

SIMULATED CASES

In this study, a power-saving period in summer was assumed. Under such a circumstance, in addition to the ordinary ON-OFF control described previously, one of the four IUs of the air-conditioning system in the target room (cf. Figures 1 and 2) was forced to change from the cooling mode to the fan mode. For the forced control, two kinds of operations were introduced. One was to switch the cooling/fan modes of an IU by a simple/regular rotation at a certain time interval (900 seconds) in the order of IU1 (northwest), IU2 (northeast), IU3 (southwest), and IU4 (southeast). The other was by a manner based on the lowest reference temperature with the same time interval (900 seconds) as that of the regular rotation control.

A total of 6 cases were studied as listed in Table 3. In addition to the difference in the forced operation control, three locations of the reference temperature points for controlling the supply air of each IU were introduced. The locations were (1) the occupied zone with a height of FL+1.2 m (for IU1: (x, y) = (2.5 m, 9.5 m); for IU2: (x,

y) = (8.0 m, 9.5 m); for IU3: (x, y) = (2.5 m, 2.8 m); for IU4: (x, y) = (8.0 m, 2.8 m)), (2) the vicinity of the walls with a height of FL+1.5 m (for IU1: (x, y) = (0.01 m, 11.0 m); for IU2: (x, y) = (10.99 m, 11.0 m); for IU3: (x, y) = (0.01 m, 0.6 m); for IU4: (x, y) = (10.99 m, 0.6 m)), and (3) the suction opening of each IU. All of the coupled (CFD and HVAC system) simulations were conducted for 7,200 seconds (2 hours). The first half of the simulation (0 to 3,600 seconds) was for a spin-up run and the second half (3,600 to 7,200 seconds) was selected for discussion.

Table 3. *Simulated cases*

	Forced operation control	Reference temperature point
Case 1-1	Regular rotation control	Occupied zone
Case 1-2		Vicinity of the walls
Case 1-3		Suction opening of each IU
Case 2-1	Lowest reference temperature control	Occupied zone
Case 2-2		Vicinity of the walls
Case 2-3		Suction opening of each IU

RESULTS AND DISCUSSION

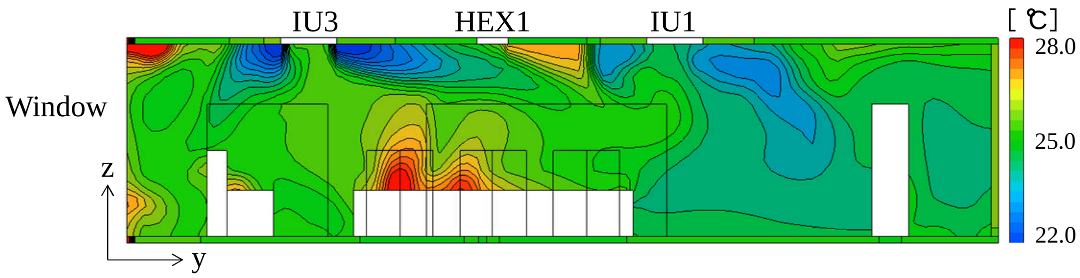
Thermal and airflow environments

As an example, Figure 3 shows the vertical distributions of the air temperature and velocity vectors at x = 3.25 m at 7,200 seconds in Case 1-1. The modes of IUs 1 and 3 are the cooling mode (also see Figure 5), and thus the temperature in the entire room is relatively well mixed due to the cold supply airs from the IUs (Figure 3(1)). On the other hand, the airflow field is complicated, as shown in Figure 3(2). An interference of the supply air from IU1 and that of HEX1, and a short circuit, in which the supply air from IU3 flows directly into the suction opening of HEX1, can be observed.

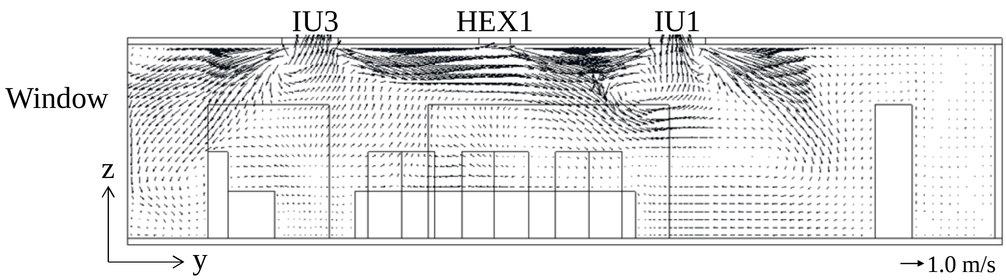
Time histories of the space-averaged air temperature and operation modes

Figure 4 shows the time histories of the space-averaged air temperature of the entire room. The space-averaged air temperatures in all cases fluctuate according to the operation (cooling/fan) modes (cf. Figure 5). The fluctuations in the regular rotation control cases (Cases 1-1 to 1-3) are a bit larger than those in the lowest reference temperature control cases (Cases 2-1 to 2-3). However, the time-averaged (from 3,600 to 7,200 seconds) and space-averaged air temperatures of the entire room are almost the same in all cases, and 26.6 °C (Cases 1-1, 1-2, and 2-1), 26.3 °C (Case 1-3), 26.5 °C (Case 2-2), and 26.4 °C (Case 2-3). With regard to the mean air temperature, there is little difference between the regular rotation control (Cases 1-1 to 1-3) and the lowest reference temperature control (Cases 2-1 to 2-3). Therefore, there is also little difference in the total amount of heat supplied from the IUs into the room in all cases.

Figure 5 shows the time histories of the operation (cooling/fan) modes for IUs 1 to 4 in all cases. In the figure, colors indicate the cooling mode, while white means the fan



(1) Instantaneous air temperature



(2) Instantaneous velocity vectors

Figure 3. *Vertical distributions of the air temperature and velocity vectors in Case 1-1 (x = 3.25 m, 7,200 seconds)*

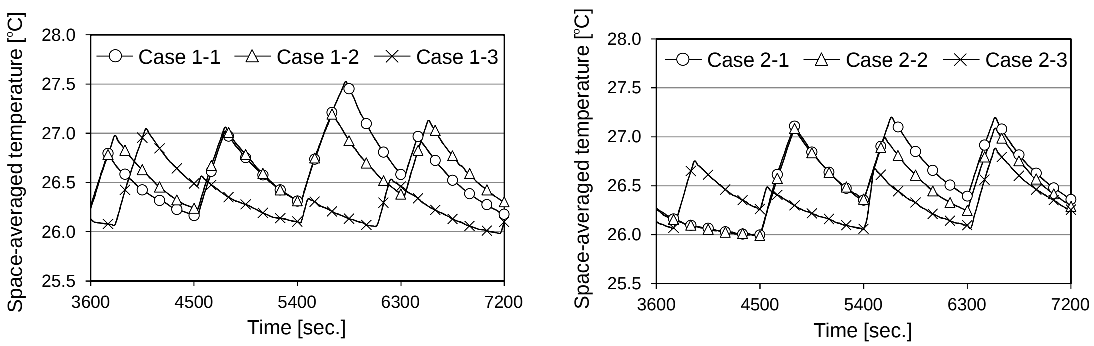


Figure 4. *Time histories of the space-averaged air temperature of the entire room*

mode. In the regular rotation control cases (Cases 1-1 to 1-3), the fan mode appears regularly, although the fan mode by the ordinary ON-OFF control is included in some amount of time. In the lowest reference temperature control cases (Cases 2-1 to 2-3), on the other hand, for IUs 3 and 4, the fan mode does not appear completely (Case 2-1 and 2-2) or appears for a certain time (Case 2-3). This is because IUs 3 and 4 are installed near the window.

Time histories of the reference temperatures

Figure 6 shows the time histories of the temperatures at the reference points for IUs 1 to 4 in all cases. When the four reference points are located in the occupied zone (Cases 1-1 and 2-1), relatively large differences can be seen between the results by the two forced operation controls.

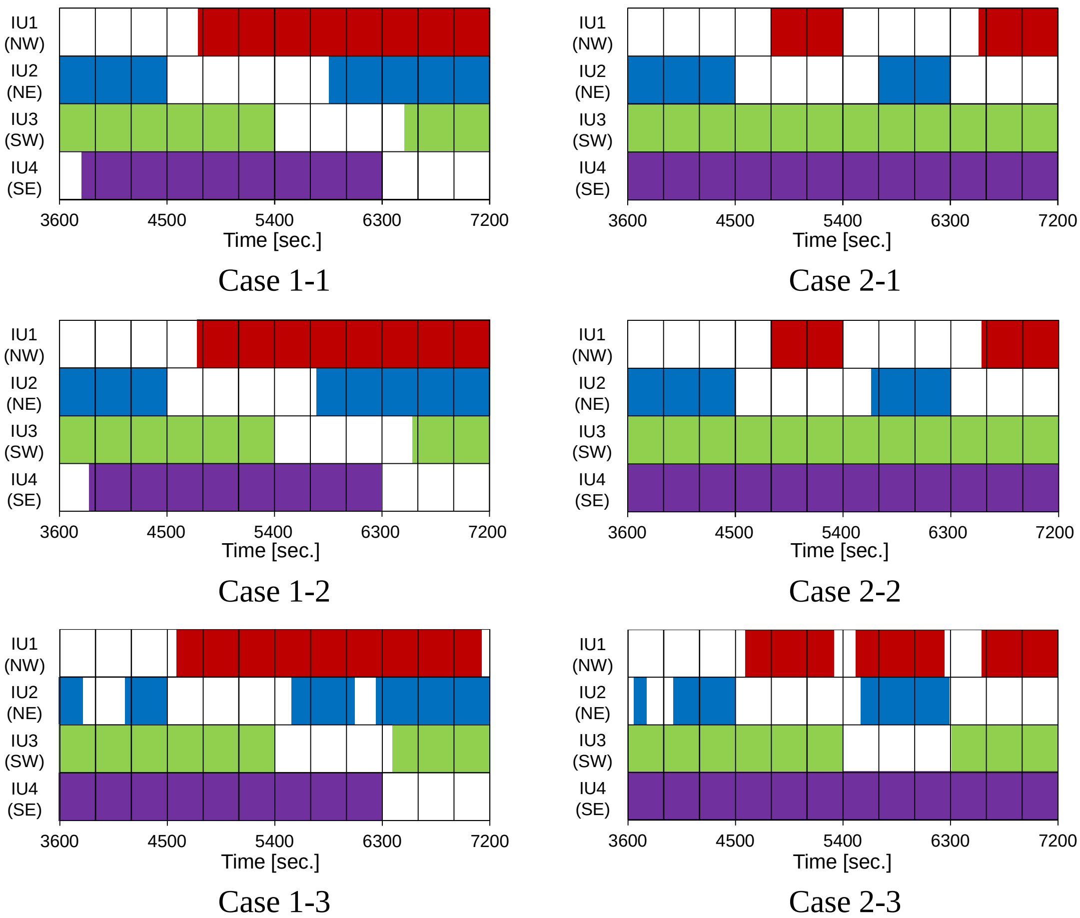


Figure 5. *Time histories of the operation modes for the IUs (colors: cooling mode, white: fan mode)*

In the regular rotation control (Case 1-1), the differences in the temporal fluctuations of the four reference temperatures become larger over time, especially in the second half of the analysis time. In the lowest reference temperature control (Case 2-1), the differences among the four reference temperatures are small. Namely, the lowest reference temperature control (Case 2-1) is better for creating a more uniform thermal environment than the regular rotation control (Case 1-1). This can be also confirmed in Figure 7. On the other hand, when the four reference points are located in the vicinity of the walls or at the suction openings of the IUs, there is little difference in the temporal and horizontal spatial fluctuations of air temperature between the regular rotation control (Case 1-2 or Case 1-3) and the lowest reference temperature control (Case 2-2 or Case 2-3).

CONCLUSIONS

In this study, a numerical investigation on the effect of operation control of a multi-split air-conditioning system in an office on the indoor thermal environment during a power-saving period in summer was performed by a coupled analysis of CFD and HVAC system simulations.

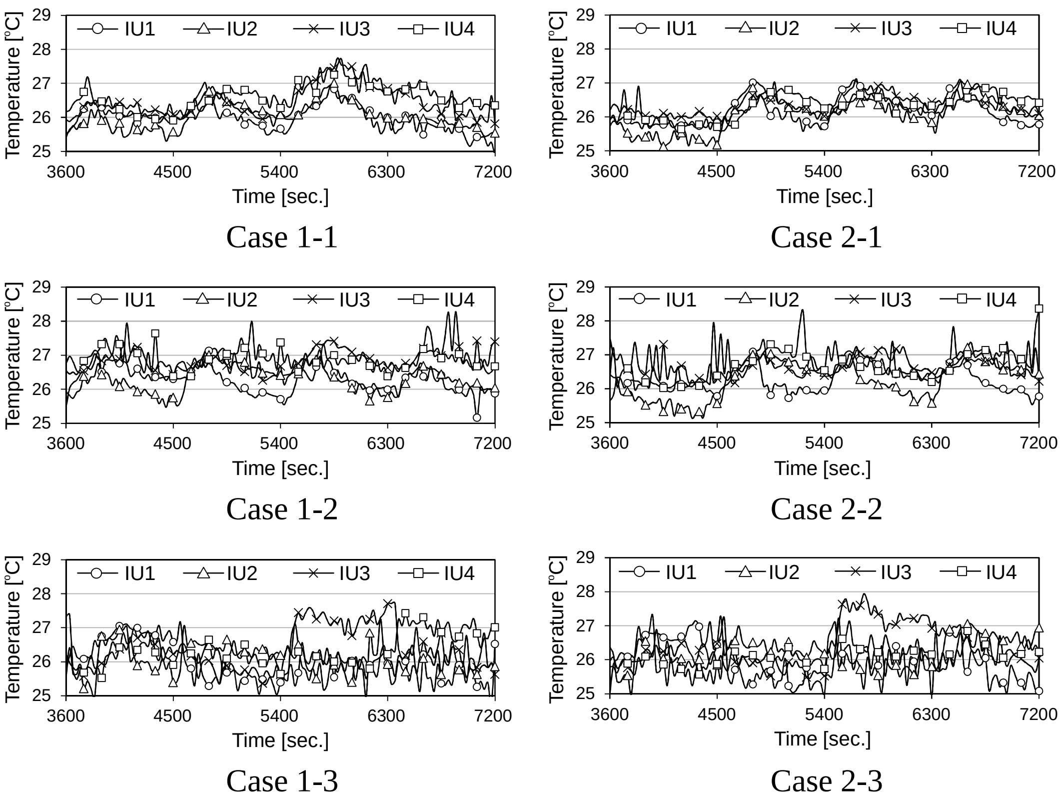
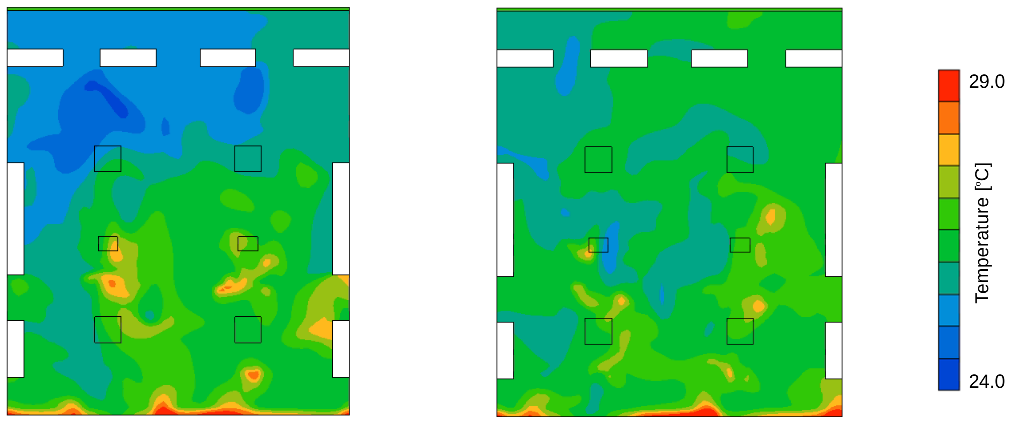


Figure 6. *Time histories of the reference temperatures for IUs 1 to 4*



Case 1-1 Case 2-1

Figure 7. *Horizontal distributions of the air temperature in Cases 1-1 and 2-1 (7,200 seconds, z = 1.5 m)*

In particular, the effect of different forced operation controls (regular rotation control and lowest reference temperature controls) for the indoor units (IUs) on the indoor thermal environment was investigated.

The lowest reference temperature control, by which one of the IUs was changed from a cooling mode to a fan mode, was better for creating a more uniform thermal environment in the target office room than the regular rotation control, especially when the reference temperature points were located in the occupied zone.