Article

A Study on the Status and Thermal Environment Improvement of Ceiling-Embedded Indoor Cooling and Heating Unit

Miae Seong ¹ , Cheolsoo Lim ¹, Jaehyun Lim ^{1,*} and Jaewan Park ²

¹ Climate and Air Quality Research Department, National Institute of Environmental Research, Incheon 22689, Korea; smatina@korea.kr (M.S.); lcs6713@korea.kr (C.L.)

² Research and Development Office, TES Eng, Daejeon 35245, Korea; mil0516@hanmail.net

* Correspondence: dr4earth@korea.kr; Tel.: +82-32-560-7300

Abstract: In this study, a basic study was performed to analyze the seasonal temperature status of a research room in the Global Environment Research Building, where ceiling-embedded indoor units are installed to study the room temperature status of the building, as well as to improve its thermal environment. In addition, a direction for improvement of the indoor thermal environment in the winter was proposed through a CFD (computational fluid dynamics) simulation and was proven by an additional experiment. Through the results of this study, it appeared that if the ceiling-embedded indoor unit was installed in the small indoor space without considering the thermal vulnerability of its perimeter boundary, the air temperature of the upper part was greatly different from that of the bottom part in the winter. Based on the PMV measurement result, the case that used both FCUs and convectors showed 1.33, the biggest maximum and minimum difference, and the case that used all FCUs, convectors and circulating fans showed 0.68, the smallest maximum and minimum difference. Therefore, it was considered that the operating method suggested in the room used in this study would improve not only the temperature stratification but also the thermal comfort. Hence, in this study, as a means to improve the stratification, convectors were installed to minimize the effect of the external thermal environment, and angle-controllable air flowing fans were installed to mitigate the stratification distribution. With such a result, it was intended to present essential data for the improvement of the thermal environment, as well as the conservation of heating energy in the winter, by reviewing the use of the ceiling-embedded indoor units in the future.

Keywords: indoor unit; temperature stratification; predicted mean vote; heating and computational fluid dynamics

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1. Introduction

The ceiling-embedded indoor unit has the advantage of increasing the efficiency of the indoor space since it is possible not only to configure it to the thermal distribution system of various cooling and heating heat sources, such as air conditioners, multi-system air conditioners and heat pump fan coil units but also to embed the indoor unit, the power line, the cooling and heating supply piping and other required materials [1,2]. In addition, in the case of the multi-system air conditioner that mainly uses the ceiling-embedded indoor unit, since it is easy to additionally install in the existing building and the area required to install the system is small, its installation and supply continue to expand not only from small and mid-sized office buildings but also to schools, shops and homes [3].

However, for ceiling-embedded indoor units that are currently commercially available, thermal comfort may partially drop due to cool draft and warm draft effects caused by dropped airflow at the air inlet, and most of all, it has a drawback in that the thermal comfort may become extremely bad due to unbalanced indoor temperature caused by temperature stratification in the winter. In addition, the room heating temperature is usually set to high due to temperature stratification in the winter, which causes increased use of heating energy [4].

As a study on the ceiling used a cooling and heating supply system, Tomas Mikeska et al. conducted a CFD simulation analysis on a new form of cooling and heating supply system combined with a cooling and heating radiation system and a ventilation system [5]. Zhai et al. installed sensors in a lecture room where fans were installed on the ceiling to measure temperature, humidity and airflow, experimented with the room temperature in the summer and studied the level of satisfaction among persons in the room [6]. Chiang et al. conducted a verification experiment on the school research room where a ceiling type radiation cooling panel and ventilation system is installed to study the thermal environment of the ceiling type radiation cooling system, conducted a CFD simulation analysis on the experimental results and analyzed the wall temperature and the room airflow distribution in detail [7]. Chen Zhang et al. built a lab-scale ceiling type radiation cooling system, analyzed the PMV (predicted mean vote), the index that indicated the temperature and the indoor thermal environment by position and height and presented the basic data for the indoor thermal environment of each system [8]. As such, studies on the development of the ceiling type cooling and heating supply system and evaluations on the indoor thermal environment have continued. However, the reality is that studies are lacking on seasonal room temperature states followed by operation of ceiling type embedded cooling and heating systems and improvement of the room temperature deviation caused by temperature stratification in the winter.

Consequently, in this study, with regards to the study object research room in the Global Environment Research Building of the National Institute of Environmental Research, where ceiling type indoor units (FCUs: fan coil units) are installed, the verification analysis was performed on the seasonal temperature difference between the upper and lower parts of the research room and the temperature deviation phenomenon between them due to temperature stratification in the winter. In addition, to derive the plan to reduce the temperature difference between the upper and lower parts caused by temperature stratification in the winter, the air CFD analysis within the research room was conducted, and the plan derived by the CFD analysis was applied to the study object research room in order to analyze the said temperature difference. The purpose of this study was to present the basic data for the improvement of the thermal environment and conservation of heating energy in the winter for buildings currently equipped with ceiling-embedded indoor units.

2. Study Description and Method

2.1. State of Construction of the Relevant Building and Method of Actual experiment

Figure 1 and Table 1 show the full front view and the building overview of the Global Environment Research Building of the National Institute of Environmental Research in Korea. The Global Environment Research Building is located in Gyeongseo-dong, Seo-gu, Incheon, Korea and is composed of 1 basement floor and 2 aboveground floors. When rooms in the Global Environment Research Building are divided into heating system types, the total cooling and heating area is 1677.9 m², the total heating-only area is 45.2 m² and the total area without cooling and heating is 726.1 m². The research room, where the temperature experiment of temperature stratification by height was conducted, is located at the west end of the second floor. In the room, 4 units of ceiling-embedded 4-way indoor units are installed to supply cooling and heating. It is 10,150 mm long, 9980 mm wide and 2700 mm high. The heat source system for the cooling and heating supply is the GSHP (ground source heat pump). Figures 2 and 3 show the floor plan of the research room where the experiment was held and locations where sensors were installed. Temperature sensors were installed at 4 locations near the center, the outer wall and the inner wall. In each location, 5 temperature sensors were installed at a 50 cm interval from the floor to the ceiling.

Figure 1. Front view of the Global Environment Research Building of the National Institute of Environmental Research.

Table 1. Construction overview of Global Environment Research Building.

Floor	Facility	Use	Area (m ²)
Underground floor	Public facility	Machine room, electricity room, generator room, control room	521.6
1st floor	Promotion facility	Exhibition room	280.7
		International conference room	431.4
		Information room, situation room	18.0
		Warehouse	11.3
	Public facility	Rest room	22.6
		Hall	138.3
		EV	28.3
		Wind-proof room	28.3
2nd floor	Research facility	Laboratory	412.1
		Data center	42.7
		Large meeting room	92.0
		Small meeting room	22.8
		Data storage room	56.1
		Lounges (male and female)	30.4
	Public facility	Rest room	22.6
		Hall	153.6
		EV	
		Hallway	164.9
		Staircase	
Total floor area			2449.2

The temperature sensors used were thermocouple T-type (TC) sensors, which were used for most of the building experiment, and HP's 34970A model was used for data acquisition [9]. For the data acquisition program, the LabVIEW 7.1 program from National Instruments was used to build the extra monitoring program for the experiment [10]. For the experiment, data were collected for 24 h a day from 20 April 2014 to 17 May 2015. Data were collected every minute. Therefore, 1440 pieces of data were collected a day. For the data on the operating status, the driving status and the device usage status of the cooling and heating system, data from the monitoring program already installed in the Global Environment Research Building were utilized for analysis [11].

Figure 2. Temperature sensor-installed locations of the research room.

Figure 3. Images displaying how temperature sensors were installed in the research room.

2.2. CFD Analysis Conditions to Derive Improvement Plan for Thermal Environment in the Winter

To derive the improvement plan for the thermal environment in the winter of the research room in the Global Environment Research Building of the National Institute of Environmental Research, the CFD analysis program was applied to the actual research room size to analyze temperature stratification on 3 modeling cases. The 3 cases used in the CFD analysis are as follows: Case 1, in which only the ceiling-embedded fan coil units were operated; Case 2, in which both ceiling-embedded fan coil units and convectors were operated; and Case 3, in which both ceiling-embedded fan coil units and convectors were operated and mini fans were operated at the same time to circulate the air of the research room. Figures 4 and 5 illustrate conceptual drawings for the 3 cases applied for the CFD analysis to derive the improvement plan for the thermal environment [12]. Table 2 lists the equipment capacity for each study.

CASE 1	CASE 2	CASE 3
- Fan-Coil Unit	- Fan-Coil Unit - Convector	- Fan-Coil Unit - Convector - Mini Fan

Figure 4. CFD analysis concept to derive the improvement plan for the thermal environment.

Figure 5. Modeling cases for CFD analysis, Case (1) Ceiling Mounted Fan Coil Units Case (2) Ceiling Mounted Fan Coil Units + Convector Case (3) Ceiling Mounted Fan Coil Units + Convector + Mini-Fan.

Table 2. Equipment capacity for each case study.

Item	Equipment	Heating/Cooling Capacity (W)	Quantity	Total Capacity (kW)
Case 1	Ceiling Mounted Fan Coil Units	Cooling: 3614 heating: 3372	4	Cooling: 14.45 heating: 13.48
Case 2	Ceiling Mounted Fan Coil Units	Cooling: 3614 heating: 3372	4	Cooling: 14.45 heating: 16.48
	Convactor	heating: 1000	3	
Case 3	Ceiling Mounted Fan Coil Units	Cooling: 3614 heating: 3372	4	Cooling: 14.45 heating: 16.62
	Convactor	heating: 1000	3	
	Mini-Fan	12	12	

For analyzing the conditions of the 3 cases used in the CFD analysis, the analysis modeling work was conducted on the room conditions as shown in Figure 4, based on the site visit to the Global Environment Research Building, construction documents and construction specifications. The room size was set to 10.2 m long, 10 m wide and 2.7 m high. The ceiling-embedded FCU used in the CFD analysis had a 3000 kcal/h cooling capacity, 2900 kcal/h heating capacity and the 4-way outlet had a supply flow rate of 12 m³/min. Figure 5 illustrates the 3 modeling cases used in the CFD analysis. Table 3 lists the envelope boundary conditions for the CFD analysis.

Table 3. Envelope boundary conditions of the study object research room.

Item	Convective Heat Transfer Coefficient (W/m ² K)	Outer Wall Temperature (K)	Wall Thickness (m)
Window	20	273.15	0.043
Left Wall	10	293.15	0.1
Right Wall	10	293.15	0.1
Corridor Wall	10	295.15	0.006
Ceiling	10	293.15	0.1
Floor	10	286.15	0.1

3. Results and Discussion

3.1. Actual Experiment Results on Room Temperature by Season and Height

3.1.1. Summer Temperature Status and Result Analysis

Figure 6 illustrates the room temperature distribution for a week from 25 August (Monday) to 31 August (Sunday) 2014. Note that the cooling system was not operated in the afternoon according to the governmental guidelines on cooling energy conservation.

It appeared that the temperature repeatedly increased and decreased during the week of working hours between 8 A.M. and 6 P.M. as the air-conditioner turned on and off. The set room temperature was 28 °C and the system operated according to the governmental guidelines for energy conservation [13]. The highest temperature in the upper part during the week appeared at 5:40 P.M., 28 August, and was 30.2 °C at the 230 cm high point of the number ③ location (Figure 2). At this moment, the temperature at its lowest point (50 cm high) was 29.1 °C. It was analyzed that there was an insignificant difference of about 1.1 °C between the highest and the lowest temperatures in the experiment period. Note that all room temperatures kept decreasing very slowly from midnight to sunrise and kept rising until sunset on holidays, Fridays and Sundays.

Figure 6. Cont.

Figure 6. Summer weekly temperature distribution (25–31 August 2014): (a) Temp. sensor location ①; (b) Temp. sensor location ②; (c) Temp. sensor location ③; (d) Temp. sensor location ④.

3.1.2. Intermediate Season (Fall) Temperature Status and Analysis

Figure 7 illustrates the room temperature distribution during the intermediate season between 20 October (Monday) and 26 October (Sunday), 2014. Note that the temperature kept decreasing until the office opening hour of 8:30 A.M., and then increased upon the attendance of room users. The highest temperature during the week appeared at 1:16 P.M., 20 October and was 25.4 °C at the number ① location. At this moment, the lowest temperature was 22.7 °C. It appeared that there was a temperature difference of 2.7 °C. There were two reasons why the temperature increased, even if it was a period without any cooling and heating. One was the solar radiation effect as what appeared in the summer analysis, and the other was because of the internal load generated by actual room use of occupants, that is, the human body temperature and the heat generated from lighting and plugs in the room. Overall, the room temperature showed the temperature distribution to be approximately 5 °C or above higher than that of the summer. It was analyzed that the temperature deviation was generated between the upper and the lower parts as the temperature dropped. In addition, during the holidays of the intermediate season, 25–26 October 2014, the temperature increase pattern due to solar radiation was similar to that in the summer, and the gradual drop pattern was shown since no internal heating was generated as there were no room users.

3.1.3. Winter Temperature Status and Analysis

Figure 8 shows the temperature distribution of the research room in the Global Environment Research Building of the National Institute of Environmental Research during a week during winter between 19 and 25 January 2015. Note that the temperature decreased until 8:30 A.M. while no workers were present in the room, and it increased from the time when heating started. The set heating temperature during the winter used in this study was operated at 20 °C according to the governmental guidelines of energy conservation. During the measurement period, the highest temperature appeared at 3:21 P.M., 22 January 2015, and was 30.1 °C at the 250 cm high point of the number ③ location. At this moment, the temperature of the lowest layer (50 cm) was 20.4 °C. It appeared that a deviation of 9.7 °C temperature had occurred. In the winter, it occurred that the temperature difference between the upper part and the lower part of the building was greatest during office hours while heating was in operation. In particular, it appeared that the temperature deviation was bigger below 1 m where occupants sat and worked. It was considered that the indoor

thermal environment would be very vulnerable even if the average room temperature reached the set temperature level by the nature of the research room where occupants spent most of their time sitting.

Figure 7. Cont.

Figure 7. Intermediate season's weekly temperature distribution (20–26 October 2014): (a) Temp. sensor location ①; (b) Temp. sensor location ②; (c) Temp. sensor location ③; (d) Temp. sensor location ④.

Figure 8. Cont.

Figure 8. Winter weekly temperature distribution (19–25 January 2015): (a) Temp. sensor location ①; (b) Temp. sensor location ②; (c) Temp. sensor location ③; (d) Temp. sensor location ④.

3.2. Result of CFD Analysis to Derive an Improvement Plan for Thermal Environment in the Winter

In this study, for the analysis of the room temperature deviation due to temperature stratification in the winter and derivation of the improvement plan of the thermal environment, the CFD program was utilized to study the room temperature deviation for three cases before the verification experiment.

There are various causes for the room temperature deviation between the upper and lower parts of the building due to temperature stratification in the winter, including condensation generated on the outer walls, the roof and the windowpanes, the Cold Bridge, the thermal loss and the blow rate of the ceiling-embedded indoor unit while heating in the winter. Accordingly, in this study, various conditions were applied for the CFD analysis.

Figure 9 illustrates the temperature distribution of the Case 1 analysis result in the research room by axes x , y and z . Based on the CFD analysis result, it is possible to note that the temperature near the windows was relatively lower. This is the phenomenon that occurs because the overall heat transmission coefficient of the window is relatively low. For the research room used in the CFD analysis, it was possible to identify that a cold draft phenomenon occurred on the window glass. In addition, for the reason why the floor temperature was relatively low, it appeared that heat loss occurred significantly on the floor due to the outer air because the research room was in a piloti structure where the floor outside was exposed to the outer air. In addition, it was possible to note that the temperature gradient of each zone changed depending on the location of the ceiling-embedded indoor unit.

Figure 10 shows the analysis result of Case 2, which installed three 1 kW convectors under the glass of the curtain wall, which was exposed to the outside, in order to mitigate the cold draft phenomenon occurring on the glass. As shown in Table 4, it is possible to note on the x -axis temperature distribution that the temperature declining phenomenon had decreased. It appeared that while the cold draft phenomenon partially disappeared from the glass as the radiation heat of the convector increased, the small convector capacity was not enough to mitigate the heat loss from the entire glass surface. Therefore, the low temperature diffused beyond a certain height. The temperature drop phenomenon was expected to improve throughout the glass if a convector of a bigger capacity was installed. However, the drawback of the installation of a convector of a bigger capacity is increased energy consumption.

Figure 9. Result of CFD analysis in Case 1.

Table 4. Conditions of verification experiment for thermal environment improvement.

Item	Equipment Operation	Remark
Case 1	Existing FCU only	
Case 2	FCU + convector	
Case 3-1	FCU + convector + circulating fan	90 degrees of the circulating fan angle
Case 3-2	FCU + convector + circulating fan	120 degrees of the circulating fan angle

Figure 11 shows the analysis result of Case 3, which additionally installed the circulating fan (mini fan) on the convector to mitigate the cold draft phenomenon generated on the glass and to solve low-temperature airflow stagnation in the lower section. Based on the CFD analysis result, it was identified that the overall temperature distribution was uniform in Case 3. In particular, it was possible to note that the installation of the circulating fan removed flow stagnation from the lower section and the overall room temperature gradient became low except for the outlet surroundings of the ceiling-embedded indoor unit (FCU).

Figure 10. Result of CFD analysis in Case 2.

Figure 11. Result of CFD Analysis in Case 3.

Figure 12 shows the temperature distribution by height for the three cases. It appeared that the temperature stratification was the greatest in Case 1. It was possible to note that the temperature stratification of the convector + fan installed in Case 3 improved compared to that of Case 1. For the average temperature, it was 19.7 °C for Case 1, 24.2 °C for only the convector installed in Case 2 and 25.2 °C for the convector + fan installed in Case 3. The average temperature increased as convectors and circulating fans were additionally installed, and it was considered that it would be helpful for the indoor thermal environment accordingly.

Figure 12. CFD simulated temperature analysis by height, Case (1) Ceiling Mounted Fan Coil Units Case (2) Ceiling Mounted Fan Coil Units + Convector Case (3) Ceiling Mounted Fan Coil Units + Convector + Mini-Fan.

3.3. Result of Verification Experiment Applied with Thermal Environment Improvement Plan

In this study, based on the result derived from the CFD analysis, a verification experiment was performed to improve the thermal environment due to temperature stratification by applying Case 3 CFD analysis conditions, i.e., installing convectors and circulating fans in the research room in the Global Environment Research Building of the National Institute of Environmental Research. Three sets of 1 kW convectors and nine units of 50 mm circulating fans were used in the CFD analysis, but only six sets of 0.5 kW convectors were installed instead because the 1 kW convector was not commercially available. In addition, 60 mm wide fans and 120 mm wide fans were installed on each convector for comparative experiments. The angle controllable rotating fin was added to the circulating fan for the angular experiment. Figure 13 shows convectors and circulating fans installed in the research room.

Figure 13. Installation view of equipment system with added convector + circulating fan.

Locations of temperature sensors installed for the verification experiment of the thermal environment improvement plan due to temperature stratification in the winter were as shown in Figure 2. The verification experiment was conducted from 6 March 2015 to 17 March 2015, and experiment conditions were set on each day for the verification experiment. Table 4 lists the verification experiment conditions. The experiment was conducted by cases considering the equipment operation and the table layout. In addition, to measure the thermal environment, PMVs were measured by height each day in the AM and PM. The device used for measurement was the AM-101 model PMV tester from KEM (Kyoto Electronics Manufacturing). The clothing (Clo) and the metabolic activity (Met), which are classified as subjective factors, were calculated based on the ISO 7730 [14] standard and were measured based on the input clothing of 0.91 and the input metabolic activity of 1.2.

Figure 14 illustrates the temperature distribution by height in the research room from the result of the verification experiment in Case 1. Based on the experiment result, for five locations between 2 and 3 P.M., the temperature distribution was 30.45–27.39 °C at the 250 cm height and 27.6–24.7 °C at 50 cm above the floor. The difference between the highest temperature at the 250 cm height and the average temperature at the 50 cm height was 2.8 °C. This indicated that it was lower than the average of the maximum and minimum differences exhibited in the results of the previous experiments. As shown in the outdoor temperature distribution graph, it was analyzed that it was due to the low-temperature difference between the room and the outside since the outdoor temperature was higher than previous experiments during the additional experiment period. In addition, by the result compared to the temperatures at the outer wall and the glass exposed to the outdoor air, it was possible to note that the temperature distribution on the glass was higher than that of the outer wall due to the effect of solar radiation penetrating through the window during the heating operated time.

Figure 15 illustrates the temperature distribution in the research room from the result of the verification experiment in Case 2. For Case 2, which used both FCUs and convectors, for five locations between 2 and 3 P.M., the temperature distribution was 28.9–25.1 °C at the 250 cm height and 25.6–24.6 °C at 50 cm above the floor. The average difference was 2.7 °C, which was a slight improvement compared to Case 1, but it was analyzed that its effect was insignificant. Even though the temperature stratification was partially improved at Locations ③ and ④, as shown in the locational temperature distribution, it was considered that it did not affect the average temperature difference significantly because it did not significantly affect the rest of the locations that were far from the convectors.

Figure 14. Temperature distribution in research room in Case 1 experiment: (A) Temp. sensor location ①; (B) Temp. sensor location ②; (C) Temp. sensor location ③; (D) Temp. sensor location ④.

Figure 15. Temperature distribution in research room in Case 2 experiment: (A) Temp. sensor location ①; (B) Temp. sensor location ②; (C) Temp. sensor location ③; (D) Temp. sensor location ④.

Figures 16 and 17 illustrate the temperature distributions in the research room from the result of the verification experiments in Case 3-1 and Case 3-2, respectively. In Case 3, FCUs, convectors and internal circulating fans were used at the same time, and the outlet angle of each internal circulating fan was controlled to analyze the temperature distribution with respect to the fan installation angle. Based on the experiment result of Case 3-1, which kept the fan outlet angle to 90 degrees, the temperature deviation by height was 2.0 °C, which meant that the temperature deviation in the inventory research room was reduced. In the graph indicated as (A) in Figure 16, it appeared that the temperature deviation by height at location ①, which was farthest from the circulating fan, was 2.0 °C at best. Since the number ① temperature measurement location was located relatively farther from the circulating fan than other temperature measurement locations, its temperature deviation was greater than other locations due to reduced airflow from the circulating fan.

In Case 3-2, which kept the fan outlet angle to 120 degrees, the average temperature difference in the inventory research room was 2.45 °C, which appeared to have increased compared to Case 3-1. It was considered that the lower air in the inventory research room was not well circulated as the outlet angle of the circulating fan was raised from 90 degrees to 120 degrees. Therefore, it was considered that it would be possible to improve the stratification of the room temperature by deriving the optimal condition for smooth upper and lower air circulation when the circulating fan was used.

Figure 18 illustrates the averages of the maximum and minimum temperature differences between 14:00 and 16:00 by cases. Based on the verification experiment results of the four cases, it appeared that the temperature difference by internal height was the lowest in Case 3-1, which used all of the FCUs, convectors and circulating fans, and the circulating fan angle was set to 90 degrees.

Figure 16. Temperature distribution in the research room in Case 3-1 experiment: (A) Temp. sensor location ①; (B) Temp. sensor location ②; (C) Temp. sensor location ③; (D) Temp. sensor location ④.

Figure 17. Temperature distribution in the research room in Case 3-2 experiment: (A) Temp. sensor location ①; (B) Temp. sensor location ②; (C) Temp. sensor location ③; (D) Temp. sensor location ④.

Figure 18. Temperature difference by cases.

3.4. Indoor PMV Experiment and Analysis

PMV is a technique to analyze the thermal environment of the building as well as the energy consumption and the thermal environment for the air conditioning system. Fanger suggested the predicted mean vote (PMV) that can digitize the indoor thermal environment in terms of how humans feel, and it is utilized as ISO (International Standard Organization) Standard 7730 [15]. PMV calculated by the six factors as follows is shown in Equation 1, which is the average of what a large group of people evaluated on the thermal environment: air temperature (T), air velocity (v), relative humidity (RH), mean radiant temperature (MRT), clothing (Clo) and metabolic activity (Met).

$$PMV = (0.303exp - 0.0336M + 0.28) \times \{(M - W) - 3.5 \times 10 - 3[5733 - 6.99(M - W) - pa] - 0.42(M - 58.5) - 1.7 \times 10 - 5 \times M(5867 - pa) - 0.0014M(34 - ta) - 3.96 \times 10 - fcl[(tcl + 273)4 - (tr + 374)4] - fcl \times hc(tcl - ta)\} \quad (1)$$

where M is the metabolism rate, W , the external work, pa , the partial water vapor pressure, ta , the air temperature, tcl , the surface temperature of clothing and tr , the radiant temperature. The PMV thermal environment is divided from -3 to $+3$ and when it is 0 , it is the most comfortable thermal environment state. Table 5, as follows, indicates the indoor thermal environment indices suggested by PMV. ASHRAE [16] suggested scales from -0.5 to $+0.5$ as the optimal condition.

Table 5. Thermal sensation on the PMV scale.

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

In this study, PMV values were measured on a total of four case verification experiments to analyze thermal comfort. The device used to measure the PMV was AM-101, which provides the PMV according to the surrounding environment level when Clo and Met are entered. To measure the indoor thermal comfort, it was measured in the AM and PM during the period when the experiments for the cases were performed. Table 6 lists the experimental results measured for each case. Based on the measurement result, the minimum was -0.76 and the maximum was 1.06 . It appeared that the thermal comfort varies significantly by height.

Table 6. PMV measurement results by case.

Height	Case 1		Case 2		Case 3-1		Case 3-2	
	AM	PM	AM	PM	AM	PM	AM	PM
50 cm	-0.76	0.11	-0.5	0.23	-0.21	0.38	-0.18	0.34
100 cm	0.02	0.41	0.31	0.43	0.15	0.67	0.18	0.53
150 cm	0.18	0.48	0.56	0.81	0.35	0.73	0.65	0.74
200 cm	0.24	0.7	0.75	1	0.44	0.83	0.8	1
250 cm	0.37	0.78	0.83	1.05	0.47	0.87	0.84	1.06

Figure 19 illustrates differences of maximum and minimum PMV results by the four cases. Based on the PMV measurement result, Case 2, which used both FCUs and convectors, showed 1.33 , the biggest maximum and minimum difference, and Case 3-1, which used all FCUs, convectors and circulating fans, showed 0.68 , the smallest maximum and minimum difference. Therefore, it was considered that the operating method of Case 3-1 suggested that improvement of the temperature stratification in the room used in this study would improve not only the temperature stratification but also the thermal comfort.

Figure 19. Average differences of PMV measurement results by case.

4. Conclusions

In this study, the verification analysis on seasonal stratification was performed on the research room, where ceiling-embedded indoor units (FCUs) are installed in the Global Environment Research Building of the National Institute of Environmental Research, and the plan to solve the winter temperature stratification was presented. The study results are summarized as follows:

- Seasonal temperature status of the Global Environment Research Building according to the ceiling-embedded indoor units.

Based on the result that the room temperature was measured by seasons, it appeared that the higher and lower temperature difference was about 1.1 °C in the summer season, and it appeared that there was a temperature difference of 2.7 °C in the intermediate season without both cooling and heating that was an insignificant difference. However, in a season when heating is required, such as winter, the highest temperature that appeared was 30.1 °C at the 250 cm high point. At this moment, the temperature of the lowest layer (50 cm) was 20.4 °C. It appeared that a deviation of 9.7 °C had occurred. It was analyzed that the lower the outdoor temperature was, the larger the temperature difference was between the upper and lower parts. In particular, it was analyzed that the temperature difference was extremely high below the 1 m height where building occupants mostly sit mostly working.

- Winter CFD simulation analysis and search for temperature stratification improvement plan.

Based on the CFD simulation analysis result, the average room temperature increased as equipment was added from 19.7 °C for the basic model to 24.2 °C for the model convectors that were installed and 25.2 °C for the model convectors and fans that were installed. When convectors and fans were installed, it appeared that the temperature stratification was improved. It was considered that it would also help the indoor thermal environment, and thus the temperature stratification improvement plan was presented.

- Verification experiment analysis on the improvement plan.

In this study, it was found that the existing average temperature difference decreased from 3.4 to 2.3 °C and based on the PMV measurement result, the case that used both FCUs and convectors showed 1.33, the biggest maximum and minimum difference, and the case that used all FCUs, convectors and circulating fans showed 0.68, the smallest maximum and minimum difference. However, it was analyzed that the furniture layout affected the room

air circulation for temperature stratification improvement. It appeared that temperature stratification would be intensified if the furniture density increased according to the nature of each room. In addition, it was analyzed that the outlet angle of the circulating fan, which generated forced airflow, affected temperature stratification.

Finally, it was analyzed that the temperature stratification improvement was the most effective, regardless of furniture layout, if operated in a basic heating system operation + convectors + circulating fans at 90 degrees.

As above, the indoor thermal environment improvement plan was presented here based on the energy modeling data and experimental data for the Global Environment Research Building.

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