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A Study on Establishing Thermal Output Conditions of Radiant Ceiling Heating Panels for Improving Thermal Comfort of Perimeter Zone in Buildings

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Abstract: Amid concerns over airflow-induced transmission of the COVID-19 virus in buildings frequented by large numbers of people, such as offices, the necessity for radiant ceiling heating panels has increased. This is due to the concern that the airflows emitted from the convection heating systems installed near the ceiling or windows for winter heating may be a major cause of COVID-19 transmission. In this study, we aim to evaluate thermal comfort under various indoor and outdoor environmental conditions of a building and present the thermal output conditions of the radiant ceiling heating panel that can replace the convection heating system while ensuring comfort in the perimeter zone and handling the heating load. As a result, we were able to present, in a chart format, the thermal output conditions that can secure thermal comfort by analyzing the indoor airflow distribution depending on the surface temperature of the radiant ceiling heating panel, the interior surface temperature of the window, and the influence of internal heat generation. Moreover, through derived empirical formulas, we were able to determine the heating conditions of the panel that can secure the necessary heat dissipation while minimizing discomfort, such as downdrafts, even for indoor and outdoor conditions that were not evaluated in this study.

Keywords: radiant ceiling heating panel; thermal comfort; thermal output; data analysis; simulation

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1. Introduction

1.1. Background and Purpose

As diverse lifestyles emerge in modern society, which was once dominated by mass consumption, people's interests have shifted from quantity to quality, resulting in a heightened demand for improved quality of life. This includes a higher level of thermal comfort within buildings [1]. Consequently, radiant heating systems are being adopted as an alternative to address the discomfort caused by air currents discharged from convective heating systems during the winter period. In particular, with the advent of COVID-19, there is an increased sensitivity about the transmission of the virus due to air currents in buildings used by an unspecified number of people, such as offices [2,3]. The air currents discharged from convective heating systems installed near ceilings or windows for winter heating are now considered a primary cause of COVID-19 transmission, further emphasizing the need for radiant heating systems. In this context, the demand for radiant ceiling heating panels is growing [4,5].

In order to replace convective heating systems with radiant ceiling heating panels, it is essential to rapidly respond to external load fluctuations, prevent discomfort such as downdraft, and maintain adequate thermal output to handle the heating load in the perimeter zone [6]. However, despite the application of panel forms to address external load fluctuations, there is a scarcity of data regarding the necessary thermal output, corresponding heating surface area, and surface temperature for perimeter zone applications. Therefore, when implementing a radiant ceiling heating panel, it is important to establish

appropriate thermal conditions, such as heating surface area and surface temperature, that can manage the heating load in perimeter zones while preventing downdraft [7]. In this study, our objective is to assess thermal comfort under various indoor and outdoor environmental conditions in buildings and propose thermal conditions for radiant ceiling heating panels that can be applied to perimeter zones, ensuring both comfort and the ability to handle the heating load.

1.2. Scope and Method

In this study, we examined the indoor and outdoor environmental conditions affecting the building perimeter zones and the thermal characteristics of radiant ceiling heating panels and, based on these, constructed a simulation model capable of deriving generalized results. Then, we performed thermal comfort evaluation simulations to collect data for setting appropriate thermal conditions for the radiant ceiling heating panel and, through the analysis of the collected data, presented the optimal thermal conditions to ensure thermal comfort of perimeter zones using radiant ceiling heating panels.

The optimal thermal conditions suggested in this study were presented in the form of a thermal output chart based on the data analysis results, allowing for the generalized use of the findings (Figure 1).

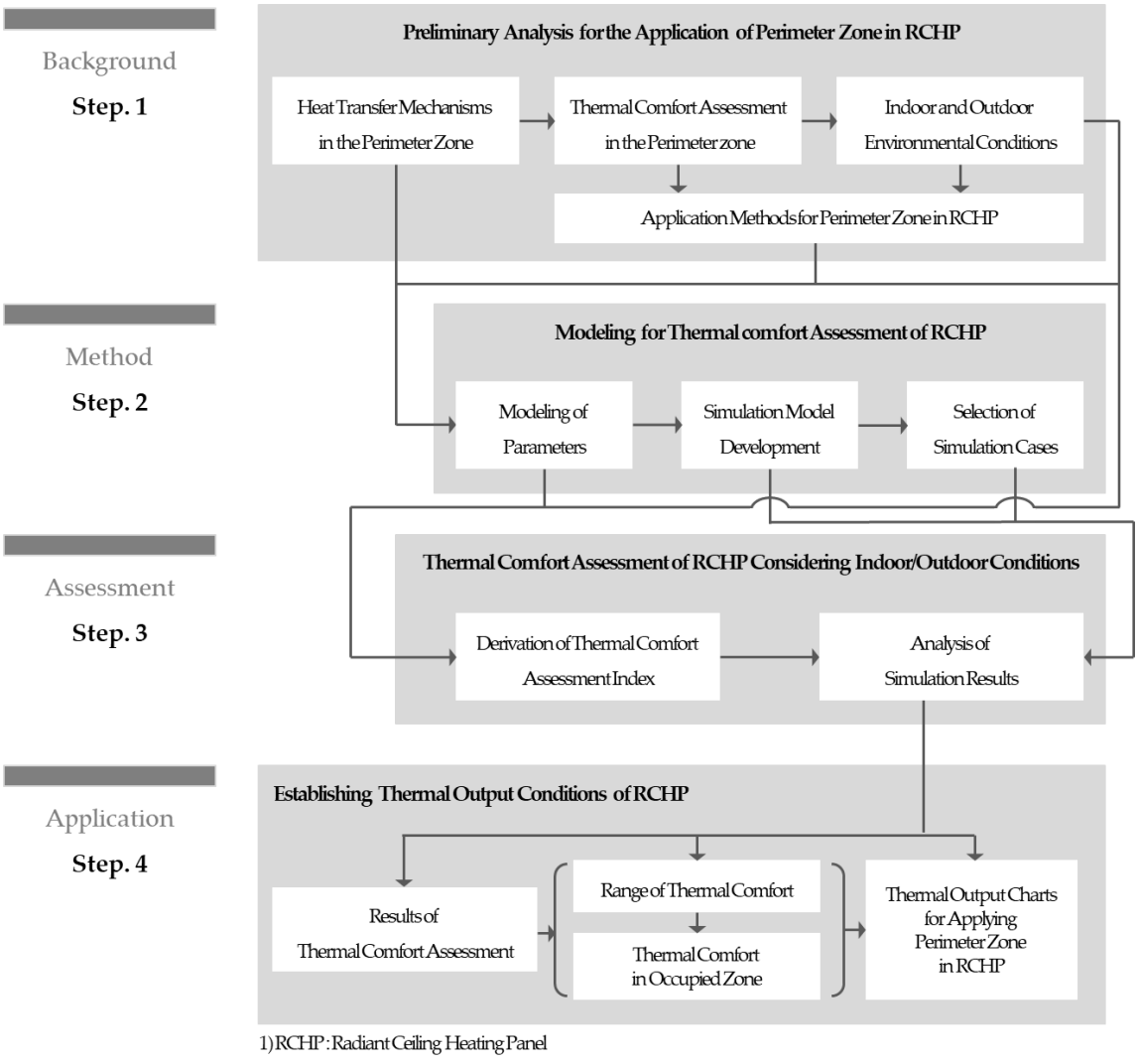


Figure 1. Flow chart of this study.

2. Preliminary Study

2.1. Review of Preliminary Studies on Thermal Comfort Assessment of Radiant Ceiling Heating Panel

The thermal comfort assessment of a building's perimeter zone with radiant ceiling heating panels can be conducted through experiments or simulations [8].

In the case of assessment through experiments, Olsesen [9] calculated the maximum air velocity for downdraft evaluation and suggested a range of acceptable maximum air velocities by deriving a formula that combines window height and window U-value in a space. However, it did not take into account the temperature of the air, failing to reflect the aspect of 'cold drafts'. To improve this, Heiselberg [10] conducted experiments in an insulated space with an outdoor and indoor area on either side of a door and analyzed the distribution of maximum air velocities of the descending drafts formed depending on the window surface temperature to evaluate the occurrence of downdraft and visualize the flow of cold drafts in the boundary layer. Based on Heiselberg's research, Manz [11] performed a downdraft evaluation when there are heat-emitting elements indoors, deriving research results that the warm drafts generated from the heat-emitting body rise, travel along the ceiling surface towards the window side and then descend, increasing the air velocity, and applied a weighting factor of 1.5 to Helselberg's formula to derive the maximum air velocity in cases with indoor heat-emitting elements. On the other hand, Larsson [12] focused on the window itself and analyzed the flow of descending drafts depending on the window's insulation properties, the width of the window sill, etc., in an experimental space with a window applied to the upper part of one wall. These experimental studies were conducted under-insulated conditions, so they did not reflect various external environmental parameters affecting downdraft and only evaluated the impact of indoor airflow caused by internal heat generation, a major factor in indoor environmental conditions. Therefore, they did not consider the discomfort of occupants due to indoor thermal imbalance and overheating caused by internal heat generation and Radiant Asymmetry.

To overcome the limitations of thermal comfort assessment experiments, Schellen [13] analyzed air velocity and draft rate according to window height and surface temperature using CFD simulations, while Jurelionis [14] simulated the occurrence of downdraft through the distribution of PPD (Predicted Percentage Dissatisfied) in the indoor environment and compared the results with those of Heiselberg and Manz. Additionally, Myhren [15] analyzed indoor air velocity distribution depending on various heating methods to evaluate the degree of downdraft reduction through the heating of cooled air, and Mustakallio [16] analyzed the thermal environment in an office building with a CBRP (chilled beam having an integrated radiant panel) for heating. Maxime Tye-Gingras [17] analyzed indoor airflow based on the radiative heat exchange effect between the radiant system and the window or surrounding walls, as well as the convective heat transfer effect with the surrounding air layer. Catalina [18] derived vertical temperature distribution in spaces with radiant panels, panel surface temperature, PMW, and PPD. Although thermal comfort assessment through simulations such as these enabled precise analysis reflecting various indoor and outdoor environmental conditions and the application of radiant systems, they did not consider the temperature deviation on the window surface due to the descending drafts or the temperature rise effect on the window caused by radiative heat exchange, as they treated the window surface temperature as a fixed condition.

Therefore, in this study, we aim to evaluate the thermal comfort in a building's perimeter zone by overcoming the limitations of existing research, considering the changes in the indoor thermal environment due to differences in external environmental conditions, the influence of indoor environmental parameters, and the applicability of the radiant heating system. Furthermore, we intend to analyze the temperature profile based on the effect of window heating by radiant heat from the radiant heating system and temperature distribution caused by the influence of outdoor air, as well as reflecting the natural convection effect depending on the building's indoor and outdoor environmental conditions.

2.2. Parameters Affecting Thermal Comfort in Indoor and Outdoor Environments

In winter, the perimeter zones of a building experience heat loss to the colder outdoor air, causing the air near the windows to cool down and descend due to the influence of the cold windows. When the cooled air descends from the window side and directly reaches the occupants, it can cause discomfort called downdraft.

The building's perimeter zones, which face the outdoors, are affected by heat loss to the outside and solar radiation. However, they are also influenced by internal heat gains from occupants, lighting, and equipment. The combined impact of these indoor and outdoor environmental parameters influences the thermal comfort of the occupants as shown in Figure 2. Furthermore, the warm air generated by internal heat gains rises due to its relatively low fluid density, flows along the ceiling towards the window side, and descends, a phenomenon known as the ceiling effect or Coanda effect. This effect can amplify the descending airflows near the windows and exacerbate downdraft. Moreover, the cold air infiltration in buildings can also affect occupant comfort.

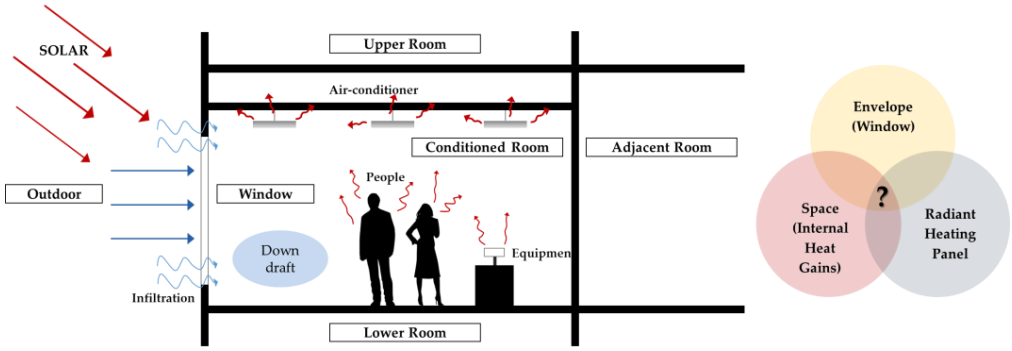


Figure 2. Thermal environment in building space.

As shown in Figure 3, based on the heating period, indoor and outdoor environmental parameters can be divided into parameters that positively affect the thermal comfort of the building's perimeter zone and parameters that negatively affect it. Parameters that positively affect thermal comfort are related to heat gain in the building, including solar heat gain and internal heat gain. Solar heat gain comes from the outside, and internal heat gain provides heat to the interior and occupants from the inside. Both of these parameters not only have high importance in terms of building heat gain but also can improve occupants' thermal comfort during periods with low outdoor temperatures, such as the heating season. However, in the case of internal heat gain, it can also negatively affect the thermal comfort of the perimeter zone due to the Coanda effect, which may amplify the downward air currents near the window and intensify the occurrence of downdraft.

2.3. Parameters for Assessing Thermal Comfort of Radiant Ceiling Heating Panel

To address the heating load of a building's perimeter using a radiant ceiling heating panel, either a zoned heating approach similar to convection heating systems must be applied, handling only the perimeter load, or the panel should be installed across the entire ceiling to address both the interior and perimeter loads [19]. The thermal output of a radiant ceiling heating panel depends on the panel's surface temperature and the heated surface area [20]. Therefore, to apply a radiant heating panel to the perimeter, the required heat output for removing the heating load and the corresponding surface temperature and heated surface area must be considered. As shown in Figure 4, an assessment that takes into account the indoor thermal environment changes due to differences in external environmental conditions, the influence of indoor environmental parameters, and the heat output required by the radiant heating system for removing the heating load and ensuring thermal comfort is necessary. Additionally, it is essential to establish heating conditions that do not negatively affect occupant comfort due to the Coanda effect or mixing loss.

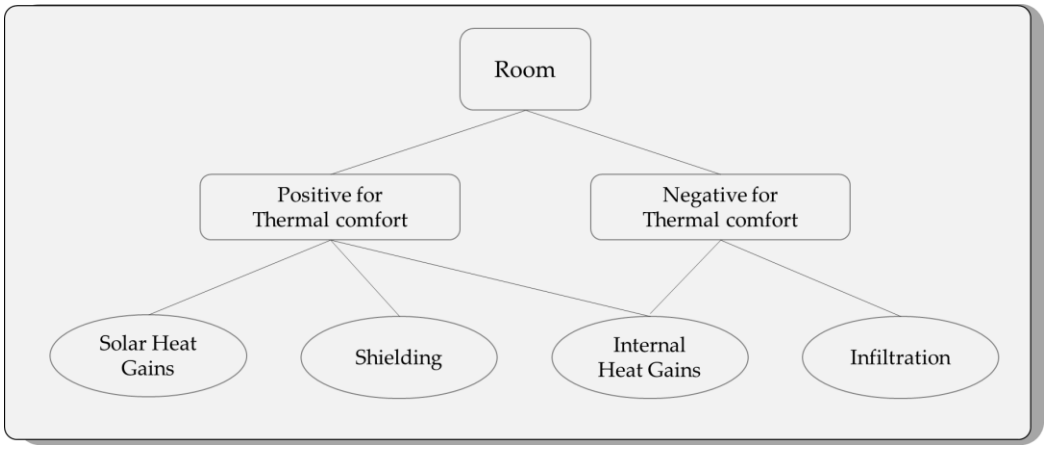


Figure 3. Indoor parameters for thermal comfort assessment.

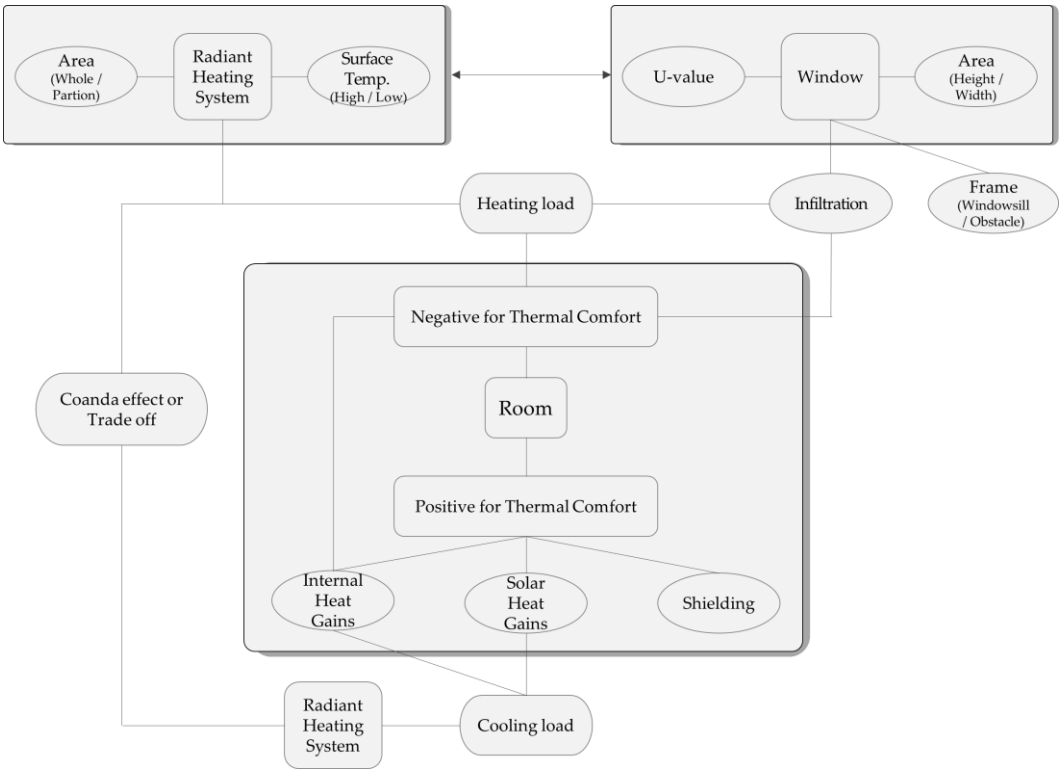


Figure 4. Parameters for thermal comfort assessment of radiant ceiling heating panel.

2.4. Mechanism of Preventing Downdraft

Radiant ceiling heating panels cater to the 'cold air' established near chilled windows through the principles of natural convection. In scenarios where a high-temperature fluid coexists with a comparatively low-temperature fluid, the fluids engage in movement due to density variations induced by temperature disparities. The phenomenon of fluid density propagating with velocity can be denoted as kinetic energy per unit volume. This adheres to the law of energy conservation, signifying the transformation of potential energy held by the fluid into a different energy form. As vertical distance progresses, the potential energy between the lesser-density fluid at the boundary layer and the fluid of relatively larger density is represented by Equation (1). Correspondingly, the velocity induced by natural convection is as presented in Equation (2).

$$\mathrm{pv2} \approx \mathrm{g}\Delta\mathrm{pL} \tag{1}$$

$$\mathrm{v} = \sqrt{\frac{\Delta p}{p} gL} \tag{2}$$

where p is the fluid density, v is the fluid velocity, g is the magnitude of the acceleration due to gravity, delta p is the characteristic density difference between the boundary layer fluid and that which is far away, and L is over a vertical distance.

This can be defined as Equation (3) when represented in terms of the Reynolds Number, where Equation (3) primarily refers to the Grashof Number, a dimensionless group predominantly occurring in natural convection phenomena. Consequently, this can be resolved as per Equation (4).

$$Re_L^2 = \frac{\frac{\Delta p}{p} gL^3}{a^2} \tag{3}$$

$$\mathrm{Gr} = \frac{\beta \Delta T g L^3}{a^2} \tag{4}$$

where Re_L is the Reynolds number for the fluid, a is the kinematic viscosity of the fluid, Gr is the Grashof number for the fluid, β is the coefficient of volumetric expansion of a fluid, and delta T is the temperature difference between the surface temperature of the cold wall and the fluid outside the thermal boundary layer.

Accordingly, the fluid's velocity augments proportional to the inter-fluid temperature differential, with an accentuated effect when a radiant heating panel is applied. The fluid velocity near the panel's radiating surface escalates as the surface temperature increases, resulting in a greater temperature disparity between the fluid adjacent to the radiating surface and that which is near the window.

When a chilled draft, engendered by a cold window surface, descends and infiltrates the occupied area within a space facilitated with a ceiling radiant heating panel, it is endowed with heat, triggering an 'elevation in temperature.' Concurrently, the warm draft emanating from the ceiling radiant heating panel forms an ascending current, serving to 'inhibit the indoor influx of the cold draft.'

As depicted in Figure 5, when the panel is implemented within a limited area at a high surface temperature, it deters the indoor entry of the chilled draft, engendering elevated air temperature proximal to the interior floor surface. This escalation of the temperature difference between the cold air navigating along the floor and the warm air originating from the panel's surface intensifies the floor's current velocity. Correspondingly, the velocity of the descending current in the vicinity of the window also increases.

Conversely, as shown in Figure 6, expanding the radiant surface area of the ceiling radiant heating panel to equilibrate the required heat dissipation indoors leads to a relative reduction in the radiant surface's temperature. Hence, the air temperature proximate to the floor surface forms at relatively lower values as compared to the scenario depicted in Figure 5. Nonetheless, this configuration can form a sufficient air temperature to prevent the onset of downdrafts. It also facilitates a reduction in floor current velocity by decreasing the temperature disparity between the warm floor surface temperature and the cold window surface temperature. The intensity of downdrafts is exacerbated as the air temperature decreases and the current velocity increases.

Therefore, in a space equipped with a ceiling radiant heating panel, to alleviate downdrafts, the panel should be capable of substantially elevating the temperature of the cold air formed at the window side. This can be achieved by fostering an appropriate surface temperature when the panel is installed near the window, all while avoiding an increase in current velocity due to high-temperature differences in the process of supplying heat to the cold current.

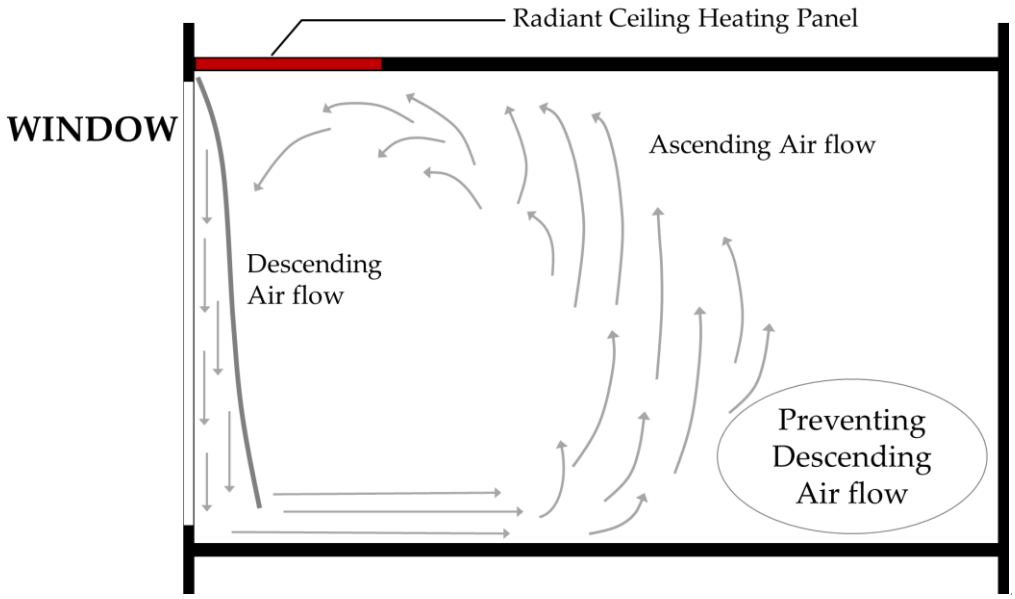


Figure 5. Airflow by application of radiant ceiling heating panel (narrow area/high surface temp.).

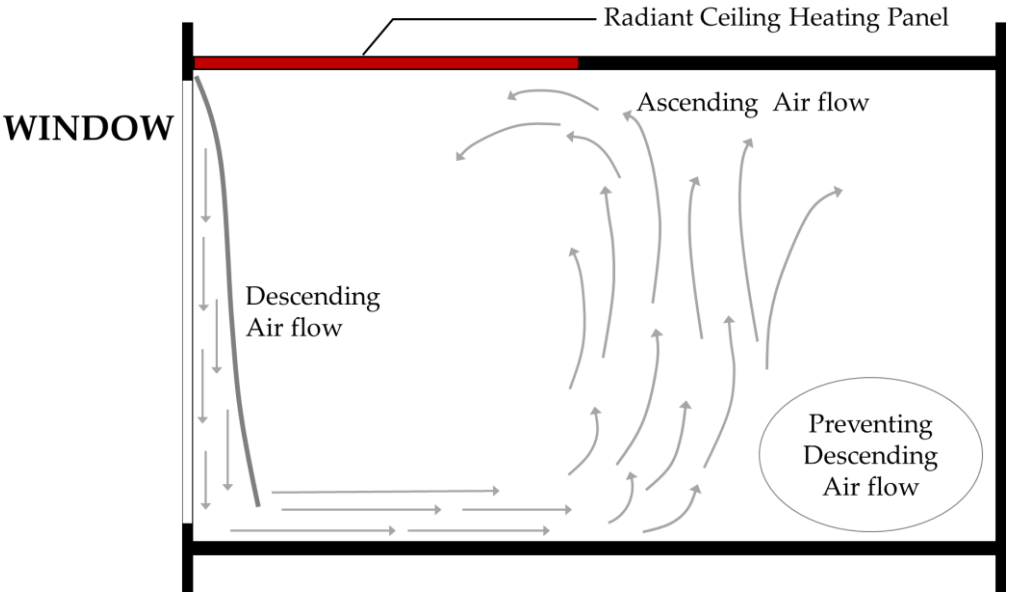


Figure 6. Airflow by application of radiant ceiling heating panel (wide area/low surface temp.).

3. Developing a Model for Evaluating the Thermal Comfort of Radiant Ceiling Heating Panel

3.1. Modeling Parameters for Evaluating the Thermal Comfort of Radiant Ceiling Heating Panel

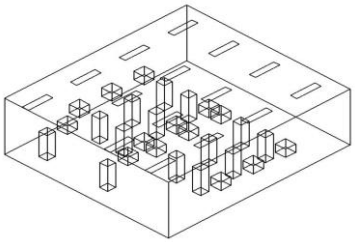
To ensure that the thermal comfort assessment results and heat dissipation conditions of a building perimeter zone with radiant ceiling heating panels applied can have value as generally applicable data, we derived the average spatial range of office buildings in Seoul, as shown in Table 1 and set a specific shared office area of 8.1 m × 9 m × 2.7 m (w × d × h) within this range as the target space [21]. Additionally, to improve the accuracy of the thermal comfort assessment model and to reflect the temperature deviation on the window surface and the resulting temperature distribution, we modeled the outdoor environment and set the heat exchange conditions with the building envelope. In this case, we set the window-to-floor area ratio to 100%, as the possibility of discomfort caused by cold windows is high, and if the radiant ceiling heating panel can ensure occupants' comfort in

such situations, no discomfort would occur in better conditions. The detailed information about the physical properties of the simulation model is as shown in Table 2.

Table 1. Average space range of office buildings.

Classification	Description
Ceiling height	2.7 m~3.3 m
Depth of space	Maximum 12 m
Unit model (structure module by column)	9 m × 12 m
Occupation density	0.1 person/m^2~0.2 person/m^2

Table 2. Input value of internal heat gains.

Classification		Description	
		Value	Reference
People		70 W	Seated, very light work, Sensible Heat (2021 ASHRAE Handbook)
Lighting		54.675 W	The value obtained by converting the total heat gain of lighting in the target office, which is 12 W/m^2, into a value per unit area.
Equipment	Computer	95 W	Conservative value, Including monitor (2021 ASHRAE Handbook)
	Printer	110 W	Conservative value (2021 ASHRAE Handbook)
Shape		Integrated model	

3.2. Setting Simulation Conditions for Thermal Comfort Assessment

The thermal comfort assessment of the radiant ceiling heating panel should be presented as data generally applicable to external environmental conditions, such as outdoor temperature and window insulation, and the corresponding heat dissipation conditions. In general, heating loads in buildings are significantly influenced by external temperature, heat transfer coefficient, and the surface area of the building envelope. Since the area refers to the window-to-floor area ratio, which was set based on 100%, the external environmental conditions ultimately depend on how they change with the outdoor temperature and the heat transfer coefficient of the windows. According to the heat transfer mechanism analyzed earlier in the building perimeter zone, the outdoor temperature and the heat transfer coefficient of windows affect the interior surface temperature of windows, leading to the formation of cold air and downward currents. Thus, the interior surface temperature of windows can be considered a representative of the impact of external environmental conditions on the indoor environment.

In this study, we set the range of window interior surface temperatures as the basis for the changing patterns of external environmental conditions and established the required input values for modeling external environments in future simulation cases based on each range. The interior surface temperature of the windows can be calculated using Equation (5), and the interior surface temperature of the windows decreases steadily with the heat transfer coefficient. By linear regression analysis and generalization, Equation (6) can be derived, through which the difference in outdoor temperature according to the heat transfer coefficient of the windows can be obtained.

$$t_{i,sur} - t_{o,sur} = (t_i - t_o) \times (R_{cond}/R_T) \quad (5)$$

$$\Delta t_o = -0.0356U^2{}_{glaz} + 0.0934_{Uglaz} - 1.16\ (R^2 = 0.9923) \quad (6)$$

where $t_{i,sur}$ is the interior surface temperature of the window, $t_{o,sur}$ is the perimeter zone surface temperature of the window, t_i is the indoor temperature, t_o is the outdoor temperature, R_{cond} is the thermal resistance of the window, R_T is the overall thermal resistance of the facade, and U_{glaz} is the heat transfer coefficient of the window. Outdoor temperature was selected based on the maximum heating load calculation during temperate and cold climates, excluding extreme climates (too cold or too hot) from Köppen's climate classification and the average outdoor temperature during winter. Furthermore, the heat transfer coefficient of windows was chosen based on the most commonly applied low-e glass heat transfer coefficient in newly constructed or remodeled buildings over the past three years, as well as the recommended heat transfer coefficient for window insulation in buildings [22]. The results are shown in Table 3.

Table 3. Inner surface temperature of window by outdoor conditions.

Classification	1.75 W/m^2 °C	1.15 W/m^2 °C	Index
−16.7 °C	10.559 °C	13.796 °C	Tisw * 10.5
−11.3 °C	11.968 °C	14.709 °C	Tisw 12.0
−5.9 °C	13.477 °C	15.622 °C	Tisw 13.5
−0.2 °C	14.926 °C	16.585 °C	Tisw 15.0

* Term: isw means Indoor Surface Temperature of Window.

The heat dissipation of the ceiling radiant heating panel can be expressed in terms of the panel's heat dissipation area and the heat supply per unit area, which is represented by the panel surface temperature. The panel surface temperature is provided in the ASHRAE [23] and EN [24] standards based on the analysis of the heating characteristics of ceiling radiant heating panels. In cases where the panel's heat dissipation is assessed by calculating the surface temperature, EN's formula is advantageous for calculating the surface temperature, so Equation (7) was used for the calculation.

$$q_p = 6(t_{rsurf} - t_i) \quad (7)$$

where q_p represents the heat dissipation of the ceiling radiant heating panel, t_{rsurf} refers to the surface temperature of the panel, and t_i is the indoor temperature.

3.3. Numerical Model of Simulation

For the assessment of thermal comfort, the modeled space comprises a radiant panel and a window that perform heat exchange with the wall and exterior. The convective heat transfer on the interior side of the window occurs via conduction due to the radiant ceiling heating panel's thermal output conditions and convective cooling, as well as internal environmental factors. Density differences between air with different temperatures cause thermal flow within the space. Additionally, radiative energy exchange occurs in the form of radiation between the radiant panel, window, internal environmental elements, and the surface of the space.

Hence, we utilized STAR-CCM+, one of the most validated CFD (Computational Fluid Dynamics) simulation programs, to calculate such airflow and energy exchange. To evaluate the indoor thermal environment distribution and the associated thermal comfort, an appropriate calculation model must be chosen (red font). In this study, we selected the calculation model, as shown in Figure 7, to perform the simulation.

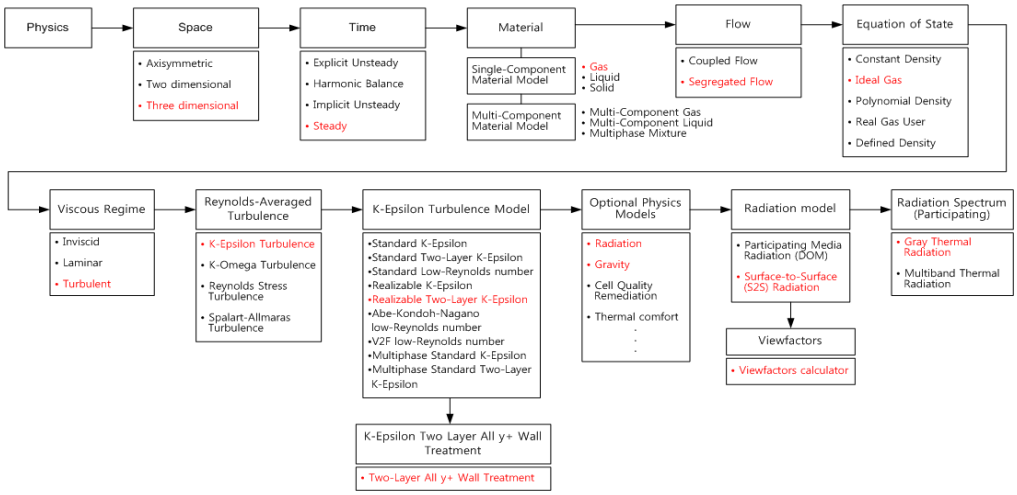


Figure 7. The numerical models of the CFD simulation.

3.4. Simulation Cases

In this study, according to the process shown in Figure 8, simulation cases were selected. These cases were derived from analyzing the relationship between the air near the windows, the windows themselves, and the heat dissipation conditions of the ceiling radiant heating panel applied to the perimeter zone to derive the basic heat dissipation conditions that can secure thermal comfort. Additionally, an internal heat generation model was implemented to reflect the impact of indoor environmental parameters on the assessment.

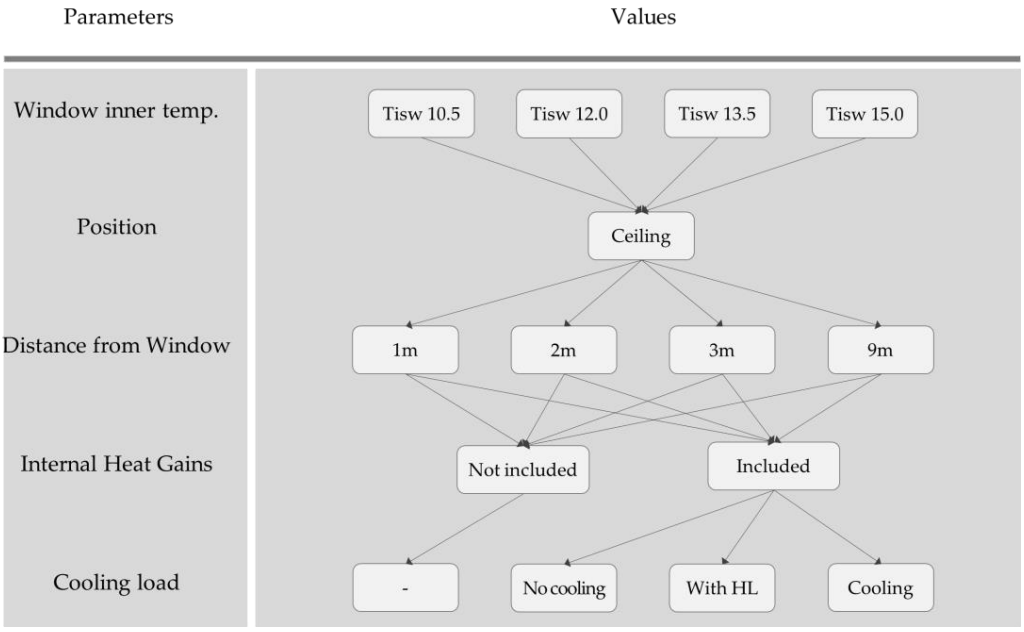


Figure 8. Process of simulation case selection.

Internal heat generation can positively affect occupant comfort as it supplies heat to the indoor environment, but it may also have negative effects due to indoor overheating and ceiling effects. Therefore, a clear criterion for acceptable internal heat generation in terms of thermal comfort must be provided. Accordingly, cases were selected to evaluate how the thermal comfort of occupants changes as the cooling load gradually decreases, based on the highest cooling load due to internal heat generation. Additionally, simulations were performed to determine whether thermal comfort can be secured even when the heat

dissipation of the ceiling radiant heating panel decreases due to the cooling load generated by internal heat generation. The detailed simulation cases are shown in Table 4.

Table 4. Thermal output conditions and load ratio of Cases.

Case	Outdoor Conditions		Cooling Load with IHG [W]	Thermal Output Conditions		Heating Load with IHG [-]
	Tisw [-]	Heating Load [W]		Heating Area [m^2]	Surface Temp. [°C]	
A_01	10.5	1786.25	N/A	8.1 (1)	56.75	N/A
A_02				16.2 (2)	38.38	
A_03				24.3 (3)	32.25	
A_04				72.9 (9)	24.08	
A_05	12.0	1332.35	N/A	8.1 (1)	47.41	
A_06				16.2 (2)	33.71	
A_07				24.3 (3)	29.14	
A_08				72.9 (9)	23.05	
A_09	13.5	761.25	N/A	8.1 (1)	35.66	
A_10				16.2 (2)	27.83	
A_11				24.3 (3)	25.22	
A_12				72.9 (9)	21.74	
A_13	15.0	510.32	N/A	8.1 (1)	30.50	
A_14				16.2 (2)	25.25	
A_15				24.3 (3)	23.50	
A_16				72.9 (9)	21.17	
B_01	12.0	1332.35	1980	8.1 (1)	47.41	
B_02				16.2 (2)	33.71	
B_03				24.3 (3)	29.14	
B_04				72.9 (9)	23.05	
B_05	13.5	761.25		8.1 (1)	35.66	
B_06				16.2 (2)	27.83	
B_07				24.3 (3)	25.22	
B_08				72.9 (9)	21.74	
B_09	12.0	1332.35	1080	8.1 (1)	47.41	
B_10				16.2 (2)	33.71	
B_11				24.3 (3)	29.14	
B_12				72.9 (9)	23.05	
B_13	13.5	761.25		8.1 (1)	35.66	
B_14				16.2 (2)	27.83	
B_15				24.3 (3)	25.22	
B_16				72.9 (9)	21.74	
C-01	12.0	1332.35	1080	8.1 (1)	25.19	Including
C-02				16.2 (2)	22.60	
C-03				24.3 (3)	21.73	
C-04				72.9 (9)	20.58	

3.5. Validation of Simulation

Prior to the downdraft evaluation in the context of the radiant ceiling heating panel application, the simulation model was validated using Heiselberg's experimental setup [12]. This experiment assessed the degree of downdraft by analyzing the peak velocity of the descending airflow distribution, which was shaped based on the window surface

temperature. A comparative analysis was subsequently performed between the maximum velocity of the airflow distribution derived from Heiselberg's experiment and that observed at an equivalent location within the simulation target space.

The peak airflow velocity distribution within the simulation exhibited a similar trend to the maximum airflow velocity derived from Heiselberg's experiment, as demonstrated in Figure 9. The relative error spanned from a minimum of 0.01% to a maximum of 13.32%, with an average error of 6.36% and a standard deviation of 3.42%. As shown in Figure 10, the draft rate comparison yielded a minimum error of 0.01% and a maximum error of 13.33%, with an average error of 6.05% and a standard deviation of 3.32%. Both the relative error of the air velocity and the draft rate escalated as the distance from the window augmented. This error is attributed to the fixed value evaluation starting from 2 m away from the window during the experimental phase. The high error near the window was discerned as a discrepancy introduced by the differences in window temperature distribution between Heiselberg's experiment and the current simulation.

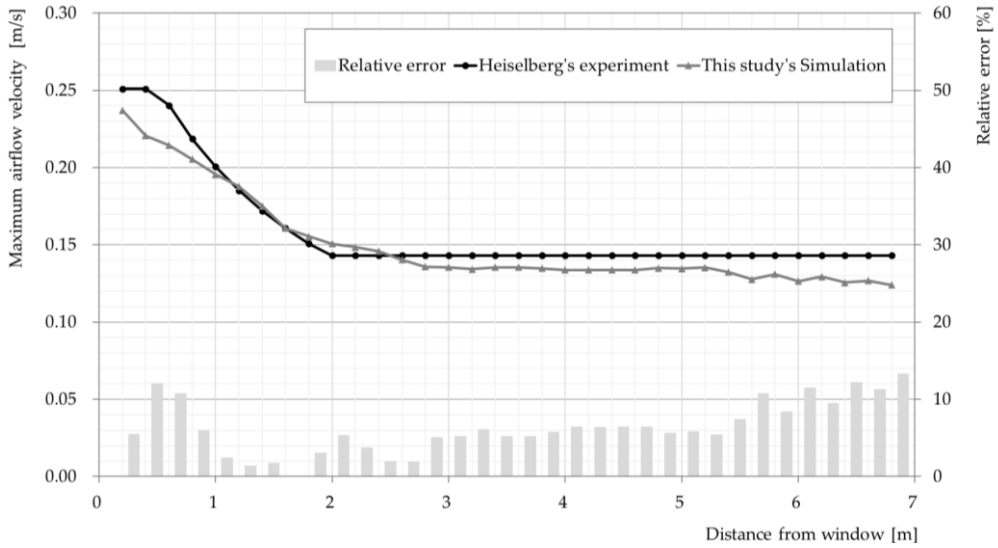


Figure 9. Results of maximum airflow velocity comparison.

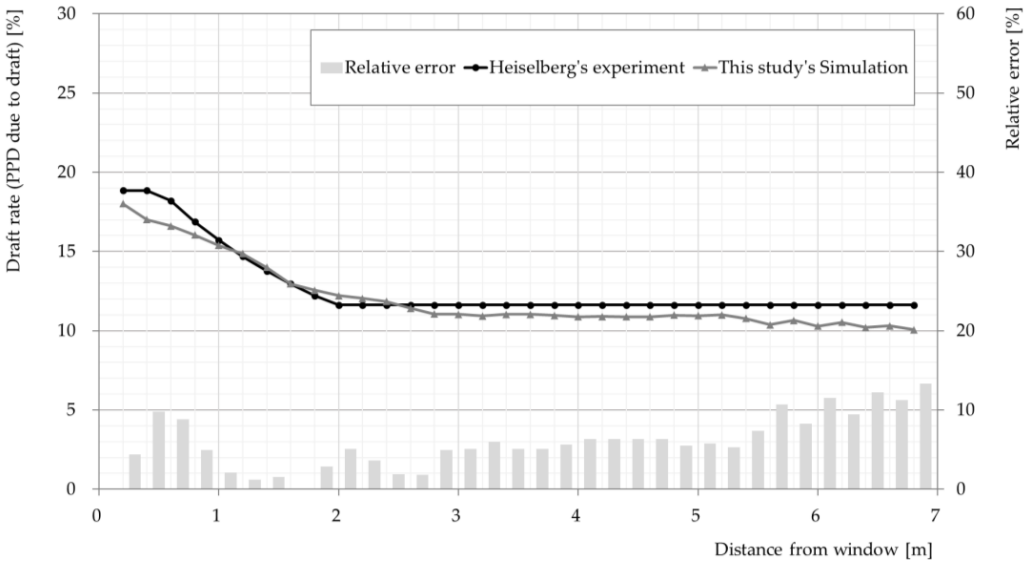


Figure 10. Results of draft rate comparison.

Thus, the validation results suggest that the simulation model upholds an average reliability of 6.20% and a standard deviation of 3.35%, inclusive of the total error of the air velocity and draft rate.

4. Thermal Comfort Assessment of Radiant Ceiling Heating Panel in Perimeter Zone

4.1. Criteria of Thermal Comfort Assessment

Thermal comfort in the building perimeter can be evaluated using discomfort due to downdraft and radiant discomfort (Radiant Asymmetry Temperature, RAT) caused by heat exchange between the heating panel surface and cold windows and occupants [25]. In this study, the draft rate was used to evaluate downdraft, which calculates the proportion of people feeling discomfort due to air currents [26].

The draft rate is influenced by temperature, air velocity, and turbulence intensity and is calculated using Equation (8).

$$\text{Draft rate (DR)} = \{(34 - t_a) \times (v - 0.05)^{0.62}\} \times \{(0.37 \times v \times Tu) + 3.14\} \quad (8)$$

where DR represents the proportion of people who feel discomfort due to downdraft, t_a is the indoor temperature, v is the air velocity, and Tu is the turbulence intensity. Additionally, to evaluate radiant asymmetry that can reflect the influence of the radiant surface and radiant area of ceiling radiant heating panel, as well as cold window surfaces, Equation (9) was used, which utilizes the shape factor between surfaces where radiant heat exchange occurs, as proposed by Wang Z et al. [27].

$$T_{\text{radiant temperature asymmetry}} = MRT_{\text{upper0.6m}} - MRT_{\text{below0.6m}} = (T_{\text{upperenclosure}} \times Vf_{\text{upperenclosure}} + T_{\text{upperwall}} \times Vf_{\text{upperwall}}) - (T_{\text{floor}} \times Vf_{\text{floor}} + T_{\text{wall-0.6m}} \times Vf_{\text{wall-0.6m}}) \quad (9)$$

where T represents the temperature of a specific surface, MRT is the mean radiant temperature of a specific area, and Vf is the shape factor of a particular surface.

4.2. Simulation Results

The simulation results are detailed in Table 5. To evaluate the thermal comfort of a radiant ceiling heating panel applied to building perimeters and establish thermal output conditions that can ensure occupant comfort, the panel's thermal conditions were assessed.

Assessment is carried out based on the draft rate at the initiation point of the occupied area (1 m from the window) and at the location where the draft rate drops below the criterion range proposed by ISO [28] (Class A standard), which are deemed to provide satisfactory thermal comfort. Furthermore, localized discomfort, such as downdraft, transpires when cool air currents directly impinge upon occupants' skin, inducing a cooling effect due to heat dissipation from the skin. Consequently, evaluation points were selected at the ankle level (0.1 m) and neck level (1.2 m), which are exposed regions when occupants are seated and engaged in activities. To scrutinize thermal comfort due to the elevated surface temperatures of radiant ceiling heating panels, radiative discomfort indices were also computed.

Examining the results of simulation Case A, which evaluates the downdraft of a radiant ceiling heating panel depending on external environmental conditions, the draft rate at a point 1 m from the window exceeded the reference point, and the point where the downdraft fell below the reference point occurred deep inside the room. Furthermore, a high draft rate was observed when the panel provided heating at a high temperature in a narrow area. When considering the similarity in values at H 0.1 m and H 1.1 m, it is inferred that this occurred due to the ceiling effect, where air currents re-entered near the window, causing cold air to infiltrate the room at a relatively high velocity.

In contrast, when the entire ceiling surface was heated, the draft rate fell below the reference point deep within the room (8.2 m, 7.6 m). Based on these results, it can be inferred that providing heating at a high temperature in a relatively large area is more advantageous in reducing downdraft under adverse external environmental conditions.

Additionally, when the radiant area (or depth) is relatively the largest, the low surface temperature results in a relatively small amount of thermal output per unit area, insufficiently supplying heat to the cold air currents near the window, leading to the highest draft rate values.

Table 5. Results of simulation.

Case	Draft Rate (1) [%]		Position (2) [m]		RAT (3) [°C]
	H 0.1	H 1.1	H 0.1	H 1.1	
A_01	20.89	20.14	6.0	5.6	1.28
A_02	18.89	17.89	6.2	5.8	1.26
A_03	19.48	18.58	6.2	5.8	1.25
A_04	22.08	21.13	8.2	7.6	1.24
A_05	17.19	16.48	3.4	3.2	0.95
A_06	17.01	16.34	3.2	3.2	0.93
A_07	17.68	16.71	3.6	3.4	0.93
A_08	18.51	17.65	5.4	5.0	0.92
A_09	14.48	13.22	2.2	2.0	0.44
A_10	14.72	13.44	2.2	1.8	0.43
A_11	14.77	13.88	2.0	1.4	0.43
A_12	15.03	14.21	2.4	1.6	0.43
A_13	11.55	10.25	1.2	1.0	0.25
A_14	11.54	10.21	1.4	1.2	0.25
A_15	11.57	10.47	1.2	1.2	0.25
A_16	11.59	10.57	1.2	1.2	0.25
B_01	12.27	11.89	1.8	1.6	0.89
B_02	12.57	12.25	1.8	1.6	0.88
B_03	12.79	12.33	1.8	1.8	0.88
B_04	13.55	13.17	2.2	2.0	0.87
B_05	9.89	9.62	0.8	0.8	0.37
B_06	10.02	9.79	1.2	1.0	0.37
B_07	10.12	9.88	1.2	1.0	0.37
B_08	10.47	10.03	1.2	1.2	0.36
B_09	14.55	14.01	2.2	2.0	0.88
B_10	14.58	14.12	2.4	2.0	0.88
B_11	14.98	14.56	2.4	2.2	0.88
B_12	15.54	15.02	2.8	2.6	0.87
B_13	11.75	11.47	1.8	1.6	0.37
B_14	11.85	11.55	1.6	1.4	0.37
B_15	11.95	11.63	1.6	1.6	0.37
B_16	12.17	11.82	2.0	1.8	0.36
C-01	22.78	22.42	2.8	2.6	0.26
C-02	22.45	22.32	2.8	2.4	0.27
C-03	22.98	22.85	3.0	2.6	0.27
C-04	25.25	24.98	4.4	4.0	0.28

(1) Value of draft rate when the occupation area is starting; (2) Distance from window when the draft rate falls below class A; (3) Radiant Asymmetry Temperature.

On the other hand, when external environmental conditions are typical (i.e., the outdoor temperature is higher or window insulation performance is improved), the lowest draft rate was observed when a radiant ceiling heating panel provided heating at a high temperature in a narrow area. This, similar to the previous case, is believed to be a result of the cold air near the window mixing with the warm air released from the radiant ceiling heating panel, causing the air current velocity to increase but raising the temperature of the air entering the room as it descends near the window, leading to a lower draft rate value. In examining the results of simulation Case B, which takes into account the impact of internal heat generation, the internal heat acted as a heat source within the room, raising the air temperature and reducing discomfort caused by downdraft. It was assumed that the air currents generated by internal heat could flow from the ceiling to the window side,

increasing the air current velocity and amplifying the flow of cold air currents. However, based on the simulation results, the effect of heating the air or providing heat was greater than the increase in air current velocity, so the impact of internal heat generation can be considered positive from the occupants' comfort perspective.

Furthermore, as seen in the results of simulation Case C, when the cooling load of the room is included in the heating load, insufficient heat supply near the window results in high draft rate values that can cause discomfort due to air cooling phenomena and downward air currents near the window. Looking at the RAT results, they were lower than the standard in most cases. In particular, it was predicted that discomfort due to radiant asymmetry would be severe when radiant ceiling heating panels are applied to the perimeter zone at high surface temperatures in a small area, but the simulation results did not match the prediction.

These results can be attributed to the fact that even if the radiant ceiling heating panel is applied at high temperatures, the radiant area is not large and is installed near the cold window. As a result, the occupants are influenced by both the cold window and the warm radiant ceiling heating panel, offsetting the discomfort caused by the panel's high temperature. Moreover, in the case of a radiant ceiling heating panel, the shape factor of the ceiling surface is small, so even if the temperature is high, the radiant heat exchange effect between the occupants and the panel is not significant, preventing discomfort due to radiant asymmetry.

5. Establishing Thermal Output Conditions of Radiant Ceiling Heating Panel

5.1. Optimal Thermal Output Conditions for Radiant Ceiling Heating Panel Considering Thermal Comfort

According to the thermal comfort evaluation simulation results, indoor parameters of a building, such as internal heat generation and the application of radiant cooling panels, positively influence the thermal comfort of occupants.

Therefore, since the relationship between external environmental conditions and the thermal output conditions of radiant ceiling heating panels is fundamental, the relationship between cold windows affected by external environments and the thermal output conditions of radiant ceiling heating panels has been analyzed.

The points where it is determined that downdraft does not occur in spaces with radiant ceiling heating panel applied are shown in Figure 11, and the distribution of draft rate at the starting point of the occupant area, which is 1 m away from the window, is shown in Figure 12.

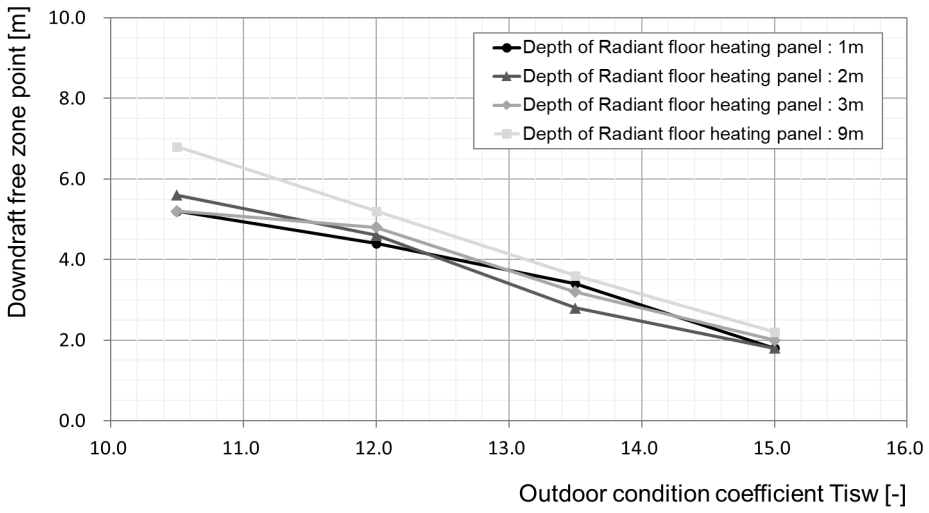


Figure 11. The relationship between ceiling panel and outdoor conditions (the point when the draft rate falls below class A).

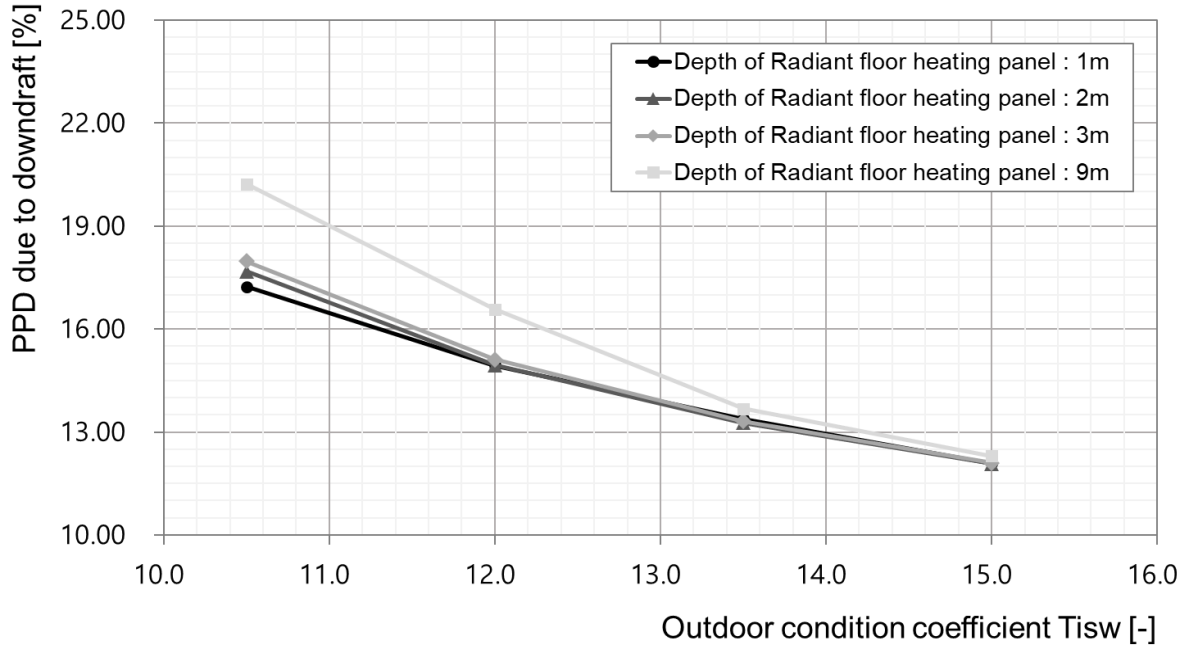


Figure 12. The relationship between ceiling panel and outdoor conditions (the same as above).

Partially applying a radiant ceiling heating panel is advantageous from a thermal comfort perspective, regardless of external environmental conditions. If external environmental conditions are maintained at an average level, it is also possible to apply radiant ceiling heating panels to the entire ceiling surface. However, the comparison of the heating surface area is only a relative evaluation. In harsh external environmental conditions, the downdraft value is high near the windows, so the downdraft-free zone, i.e., the point where occupants' discomfort due to downdraft is below the threshold, appears in the deeper interior of the room. This can be attributed to the warm air currents emitted from the ceiling, amplifying the descending currents generated by the windows, increasing the air current velocity, and intensifying the occurrence of downdraft. However, if the heating surface is partially applied, sufficient heat is supplied to the cold air currents near the window, so even if the descending air current velocity increases, it is not the cold air that descends but relatively less cold or warm air that descends and infiltrates the occupant area, resulting in occupants not experiencing discomfort due to the infiltrated air currents.

5.2. Thermal Output Charts of Radiant Ceiling Heating Panel in Perimeter Zone

When applying a radiant ceiling heating panel to the perimeter zone, the appropriate thermal output range for the panel can be determined by the point at which they can heat the air near the windows through radiation from the ceiling at a relatively high surface temperature. To achieve this, it is advantageous to set the thermal output conditions by gradually increasing the radiating area in the direction of a narrow area and high surface temperature. In other words, as the surface temperature and heating load increase, the temperature difference between the panel and the window increases, amplifying the air current speed and increasing the likelihood of downdraft. Therefore, the thermal output conditions should be designed based on the relationship between the representative inner surface temperature of the window and the surface temperature of the radiant heating panel.

$$\mathrm{DR} = 0.0105\Delta t^2 - 0.6635\Delta t + 29.074\left(R^2 = 0.9931\right) T_{isw} 10.5 \tag{10}$$

$$\mathrm{DR} = 0.058\Delta t^2 - 0.3264\Delta t + 21.453\left(R^2 = 0.9820\right) T_{isw} 12.0 \tag{11}$$

$$\mathrm{DR} = 0.002\Delta t^2 - 0.0989\Delta t + 15.698\left(R^2 = 0.9812\right) T_{isw}13.5 \quad (12)$$

$$\mathrm{DR} = 0.0013\Delta t^2 - 0.0323\Delta t + 11.745\left(R^2 = 0.9628\right) T_{isw}15.0 \quad (13)$$

$$\mathrm{DR} = \frac{\Delta \mathrm{DR}\left(T_{isw_{reference}} - T_{isw_{target}}\right)}{1.5} \quad (14)$$

To provide thermal output conditions that ensure thermal comfort for the radiant heating panel applied to the perimeter zone, these conditions are presented in the form of a chart. The thermal output conditions of the radiant heating panel depending on the external environmental conditions are shown in Figure 13 and Equations (10)–(14), and the thermal output conditions of the panel change as shown in Figure 14 when the effects of internal heat generation are reflected in the external environmental conditions. The equations presented in these findings, derived from empirical formulas, allow for the calculation of the draft rate value and the ensuing thermal comfort under specific circumstances by inserting indoor environmental conditions, such as outdoor temperature and internal heat generation, and the radiant conditions of the radiant ceiling heating panel.

When the radiant ceiling heating panel is applied to the perimeter zone, the draft rate tends to decrease uniformly with the amount of internal heat generation, regardless of the panel's placement. This means that the draft rate can be consistently reduced by the amount of heat supplied due to internal heat generation, regardless of the heating load or external environmental conditions. However, when the internal heat generation is considered as a heat supply in calculating the heating load and setting the thermal output of the radiant ceiling heating panel, the draft rate at the starting point of the occupied area shows a constant trend.

This can be attributed to the panel's insufficient heat supply, resulting in the occupant's thermal comfort being determined by the cold air currents from the windows and the amount of internal heat generation.

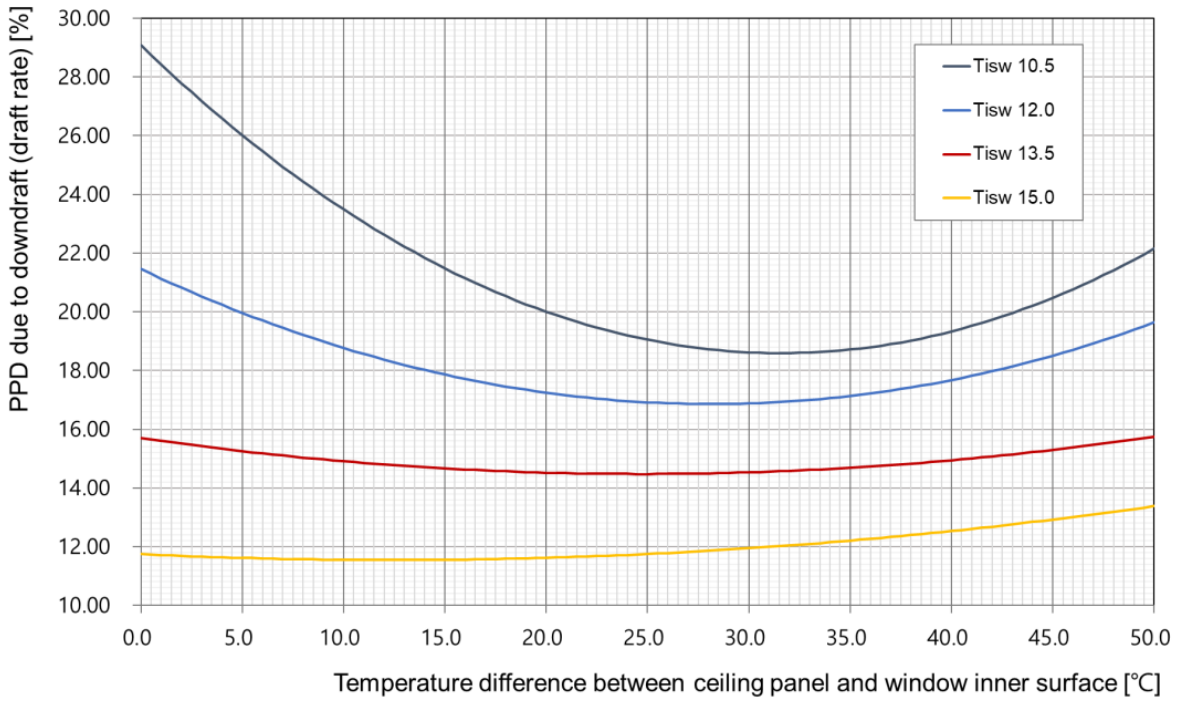


Figure 13. Draft rate by thermal output conditions of ceiling panel.

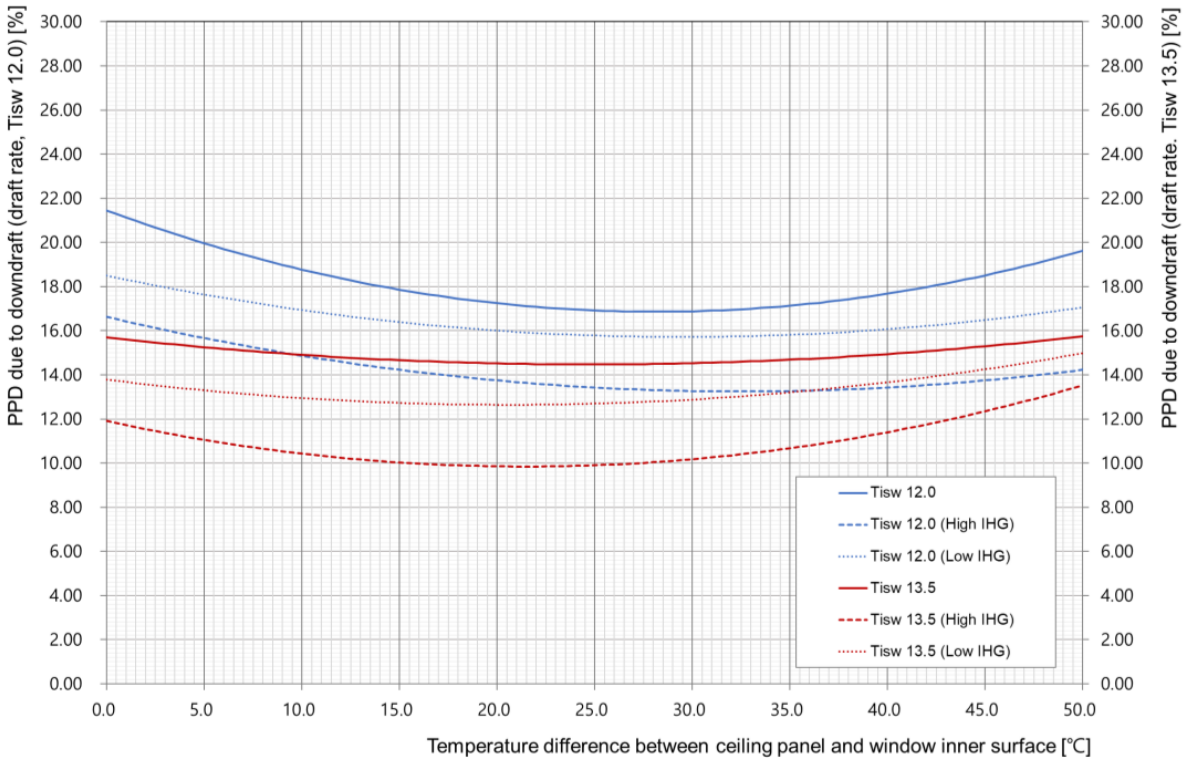


Figure 14. Draft rate by thermal output conditions of ceiling panel with internal heat gains.

6. Conclusions

This research aimed to evaluate the suitability of radiant ceiling heating panels in a building's perimeter zone from a thermal comfort perspective. This was accomplished by studying the patterns of air current mixing under external environmental conditions leading to heat loss during winter and indoor environmental conditions acting as heat gain sources such as internal heat generation. We proposed optimal heat dissipation conditions for radiant ceiling heating panels. The main findings of this study are as follows:

(1) As the stringency of external environmental criteria was eased, the temperature difference between the interior surface of the window and the radiant ceiling heating panel surface decreased, resulting in a reduced draft rate in the occupied area with relatively smaller heat dissipation per unit area. This can be attributed to the fact that an increased temperature difference between the window surface and the panel's heat dissipation surface raises the per unit area heat supply but also accelerates the speed of downward air currents. Consequently, relatively cooler air currents penetrate deeper into the occupied area.

(2) Radiant asymmetry is not strictly a function of temperature alone; the area of the heat dissipation surface corresponding to the temperature also plays a significant role. Even if the radiant ceiling heating panels were operated at high temperatures, the heat dissipation area was not sufficiently large to induce discomfort due to radiant asymmetry. Therefore, discomfort resulting from high surface temperatures of the radiant ceiling heating panel did not occur.

(3) In cases where radiant ceiling heating panels were applied without any internal heat generation, the draft rate at a point 1 m away from the window was approximately 20% when the external environment was in poor condition and about 10% when the external environmental conditions were relaxed. When internal heat generation was applied, the draft rate fell below the standard value in all cases. These findings suggest that thermal discomfort due to downdraft is more influenced by temperature than air velocity. Therefore, applying radiant ceiling heating panels at higher temperatures proves advantageous for reducing downdraft.

(4) We introduced a chart that categorizes the heat dissipation conditions of radiant ceiling heating panels based on the influence of internal heat generation, considering the temperature difference between the radiant ceiling heating panel surface temperature and the representative temperature of the window's indoor surface as external environmental conditions change. Using the draft rate graph in this chart, which considers the influence of indoor and outdoor environmental parameters in △t, the appropriate heat dissipation range for radiant ceiling heating panels can be determined, and conditions not evaluated in this study can be extrapolated.

(5) Utilizing the heat dissipation chart presented in this study, the representative value of the indoor surface temperature of the window can be calculated according to the window's heat transfer rate and outdoor design temperature for the target space where radiant ceiling heating panels are to be implemented. After selecting the range in accordance with the representative value, the heating load can be calculated, and the external environmental conditions can be set. Moreover, it becomes possible to calculate the perimeter zone application area of the radiant ceiling heating panels to be installed, as well as the panel's heat dissipation capacity and surface temperature. With the external environmental conditions and panel area established, the heat dissipation conditions of the panel can be derived, ensuring the necessary heat dissipation while minimizing discomforts such as downdraft when the radiant ceiling heating panels are applied to the building's perimeter zone.

The limitation of this study lies in its basis on simulation results. Therefore, further research is planned to explore the applicability of radiant ceiling heating panels through experimental verification and extensive data analysis on thermal comfort. Additionally, a comparative evaluation for scenarios with cooling systems applied is deemed necessary.

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