

Article

Thermal Comfort Assessment of the Perimeter Zones by Using CFD Simulation

Taesub Lim ¹ and Daeung Danny Kim ^{2,*} 

¹ Department of Architectural Engineering, Seoul University, Seoul 02192, Republic of Korea

² Architectural Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

* Correspondence: dkim@kfupm.edu.sa

Abstract: Most perimeter zones are thermally susceptible to the variation of outdoor conditions, especially due to a large amount of heat gain through glazing. To reduce heat gain, spandrel panels are generally installed in curtain walls of commercial buildings. For the present study, thermal performance in an office located in the perimeter zone was investigated using Computational Fluid Dynamics (CFD) simulation. By varying the spandrel panel heights, thermal comfort was assessed quantitatively. The findings suggest that when the spandrel panel height was 0 m, the highest temperature was observed in all cases. As the height of the spandrel panel was increased, the temperature decreased. For thermal comfort evaluation, Predicted Mean Vote (PMV) values at 1.5 m from the floor in all cases were larger than zero. PMV values in all cases were within the range of slightly cool to warm. When the spandrel panel height was 0 m, the highest thermal sensation (warm) among the cases was observed, which may cause thermal dissatisfaction for occupants. In addition, thermal comfort was deemed satisfactory based on the criteria of ASHRAE standard 55, when the height of the spandrel panel was higher than 0.6 m.

Keywords: thermal comfort; perimeter zone; spandrel panel; office building



Citation: Lim, T.; Kim, D.D. Thermal Comfort Assessment of the Perimeter Zones by Using CFD Simulation.

Sustainability **2022**, *14*, 15647.

<https://doi.org/10.3390/su142315647>

su142315647

Academic Editor: Wenjie Ji

Received: 9 October 2022

Accepted: 21 November 2022

Published: 24 November 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Noticeably, about 30% of the total energy consumption accounts for a significant increase in CO₂ emissions in commercial buildings [1–3]. In addition, energy consumption by buildings is still increasing and much attention has been paid to reduce building energy consumption [4,5]. In South Korea (hereafter Korea), approximately 30% of the total building energy consumption is attributed to commercial buildings [6]. According to the “Energy Statistics Handbook in 2020” provided by Korea Energy Agency, a significant amount of energy was consumed by commercial buildings [7]. In addition, around 50% of the total energy consumption of commercial buildings was used for operating mechanical systems for thermal comfort [8]. As can be shown, most building energy is used for heating and cooling. Thus, it is important to find ways to improve thermal comfort in commercial buildings to contribute to the reduction of building energy consumption.

Among building components of commercial buildings, the main contributor to heat gain and loss is window systems [9–11]. The thermal load caused by sunlight can be maximized in a perimeter zone through the window systems, compared with that in the core of office buildings [12,13]. While the use of advanced window systems shows improvement in thermal performance, there are still issues such as cost and durability [14,15]. Another suggested solution is the use of internal and external shading devices for sunlight penetration through window systems [16,17]. Some studies demonstrate the effectiveness of shading devices for reducing cooling demand in buildings [18–21]. Thus, it is imperative to use shading devices to maintain thermal comfort in buildings by absorbing or reflecting the sun’s radiation. However, in the case of glazed buildings, the use of external shading devices is limited due to esthetic concern. Fully glazed façades are preferred on most office

buildings [22,23]. Even with the development of glass materials and dematerialization of the façade system, glazed façades are significantly associated with indoor thermal comfort levels [22,24,25].

While many studies have revealed thermal and daylight performance with various shading devices, it still requires much effort for the optimization of their application and control to building facades [26–29]. Moreover, with improper use of shading devices, it is difficult to satisfy visual comfort as well as achieve proper daylighting performance [28,30,31]. In general, building envelope systems of most high-rise office buildings are composed of a steel frame with spandrel panels [32]. According to several studies, these spandrel panels lead to little daylight to the indoor thermal performance in office buildings [33,34]. In the present study, thermal performance of the perimeter zone with spandrel panels in an office building was investigated through Computational Fluid Dynamics (CFD) simulation. CFD simulations are generally used to assess thermal performance or contaminant migration [35–37]. By varying the heights of the spandrel panel, thermal comfort in an office located in the perimeter zone was quantitatively analyzed by CFD simulation. A numerical model was established using the software STAR CCM+ 9.02 and was calibrated against the data obtained by Lim et al. [13]. In addition, the data were used for the Predicted Mean Vote (PMV) equation. The effects of various heights of the spandrel panel were examined using the PMV values.

2. The Spandrel Panels

Typically, a large glazing area in curtain walls in commercial buildings has shown low thermal performance [38]. Even the perimeter zone in these buildings is more susceptible to the variation of outdoor weather conditions [39]. Therefore, Lam et al. insisted that the interaction among the façade design variables, climatic conditions, human behaviors, and building operation parameters should be taken into account [38]. To reduce daylight levels in the perimeter zone, advanced systems were used. As shown in the measurement performed by Konis, daylight levels were significantly reduced by implementing highly visible and light transmittance glazing. However, occupants in the perimeter zone still complained about thermal discomfort due to daylight availability [40]. Excessive sunlight levels vary with orientations. Zhang et al. investigated energy consumption for different building orientations [12]. In their results, cooling energy consumption increased in the east- and west-facing perimeter zones because of the most solar-heat gain and glare. This was also pointed out by Zhang et al. [41]. They mentioned that poorly designed window systems could affect the thermal sensation of occupants in the perimeter zones. Moreover, the interaction between solar-heat gain and air-conditioning system resulted in thermal stratification in the perimeter zone [42]. Even though the heat gain caused by sunlight could be reduced by internal or external shading devices, the daylight in the perimeter zone was important for occupants for visual comfort as well as artificial energy saving [43–45]. Therefore, it is important to consider the thermal comfort of occupants in the perimeter zone as well as visual comfort.

In general, the façades of high-rise office buildings are curtain-wall systems, which are non-structural cladding systems [33,46,47]. A curtain wall is a prefabricated exterior façade composed of glass and panels that are wrapped wholly or partially by metallic grids; it is different from a conventional window system [48]. Typically, the sections of a curtain wall can be classified into the top, middle, and bottom parts. Daylight is admitted through the top and middle parts, while the bottom is opaque [49]. Based on the construction types, spandrel panels can be assembled piece by piece, or used as a system composed of pre-assembled glass panels [50,51].

Due to a large amount of heat gain and loss through fenestrations, many studies performed investigations into the use of high-performance glazing, window systems, such as frames and inert gases in curtain walls [52–55]. However, published work on the thermal and energy performance of spandrel panels is inadequate although the spandrel areas play an important role in building façade systems. According to several studies, the spandrel

area is thermally susceptible, caused by heat flow through the spandrel panel [56–58]. Other studies pointed out the ratio of visible to opaque parts of building façades because heating and cooling energy consumption is highly related to the admitted daylight. Even though the spandrel area is fully insulated, some issues, such as thermal parameters and designs of spandrel panels, still exist [56,59]. Thus, the height of the spandrel panel from the floor is important, which varies from 0 m to 1.0 m [38,49,60,61].

3. Methodology

To evaluate the thermal performance in the perimeter zone in an office building in relation to the height of spandrel panels, CFD simulation was used. A typical office building located in Korea was chosen as a reference building. By varying the heights of spandrel panels, thermal behaviors were predicted using CFD simulation. For the validation of CFD simulation, the measured data at the reference building were utilized. In addition, Predicted Mean Vote (PMV) was used to quantify thermal performance in the perimeter zone with different heights of spandrel panels.

3.1. Building Description

The study selected an office building located in Seoul in Republic of Korea, and the building is located at the latitude and longitude of 37.5665° N and 126.9780° E, respectively. The annual mean air temperature and insolation in the building site were 12.5°C and 4125 MJ/m^2 , respectively [62,63]. The gross floor area of the selected building is $72,718\text{ m}^2$ which has 21 floors above ground and 7 basement floors. The main façade faces West and is covered by glass. Due to window-to-wall ratio (WWR) of 70% of the façades, a large quantity of solar radiation is expected. The main façade descriptions of the office building are presented in Figure 1 and Table 1.



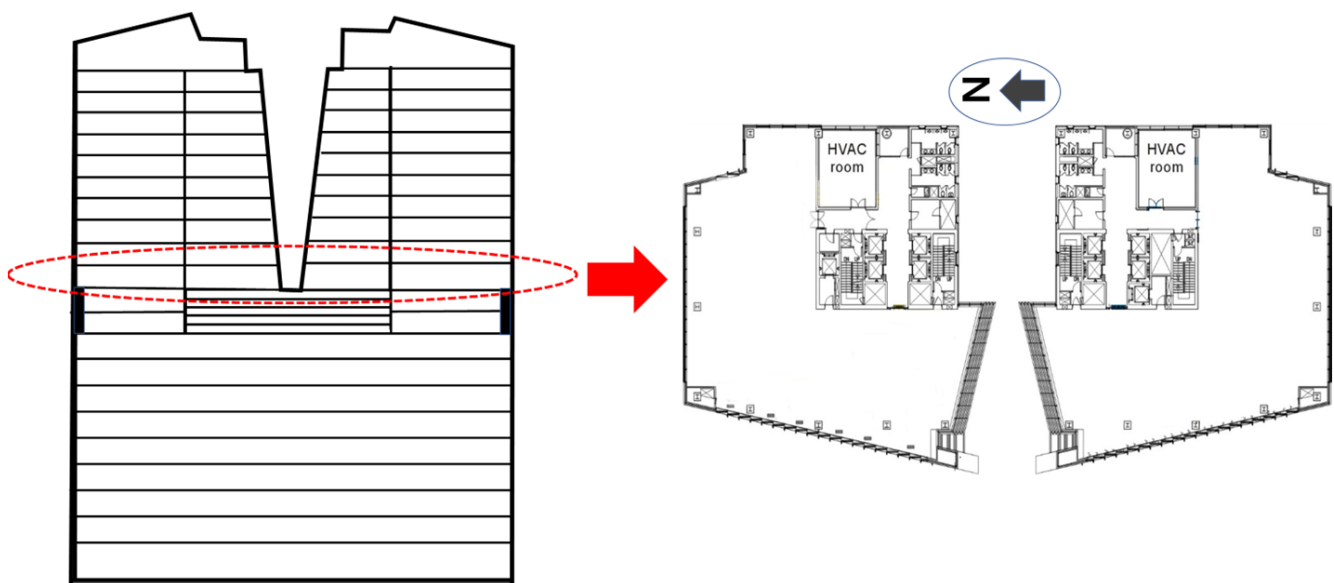
Figure 1. The west façade of the reference building [13].

Table 1. Description of the reference building [13].

Building	Description
Location	Seoul, Republic of Korea
Floor	21 floors above ground and 7 basement floors
Usage	Office: 1st–21st floor, 2nd basement floor Parking: 1st basement floor, 4th–7th basement floor Exhibition: 3rd basement floor
Year the building was built	2007
Building envelopes and structure	Low-e double glazing with reinforced concrete & steel-framed structure
Gross floor area	72,718 m ²
Heating, Ventilation, and Air-conditioning systems (HVAC)	Screw chillers, turbo refrigerators, steam boilers, packaged heat pump and air barrier systems

3.2. CFD Simulation

This study investigated the thermal performance in the perimeter zone of an office building. For CFD simulation, an office area located in the perimeter zone was selected (Figure 2). As shown in Figure 2, the 10th floor of the reference building was selected. According to Lim et al., most heat is gained in the west façade through the glazing in the reference building [13]. Thus, the office area in the perimeter zone facing west was chosen. The size of the model is 10 m wide, 7 m deep, and 2.7 m high. Figure 3 shows the model for the CFD simulation. Based on the measured temperature data obtained in Lim et al., the amount of solar gain was about 132.96 W/m² at the glazing [13]. In addition, three different spandrel panel heights, namely 0.3 m, 0.6 m, and 0.9 m, were designed, which were compared with 0 m (Figure 4). For internal gain, people, lighting, and equipment were considered, based on ASHRAE Fundamental [64] (Table 2). Indoor air temperature of the office was set at 26 °C and supply air (SA) was set as 0.5 m/s, which was 7 air changes per hour.

**Figure 2.** The west-facing office in the reference building.

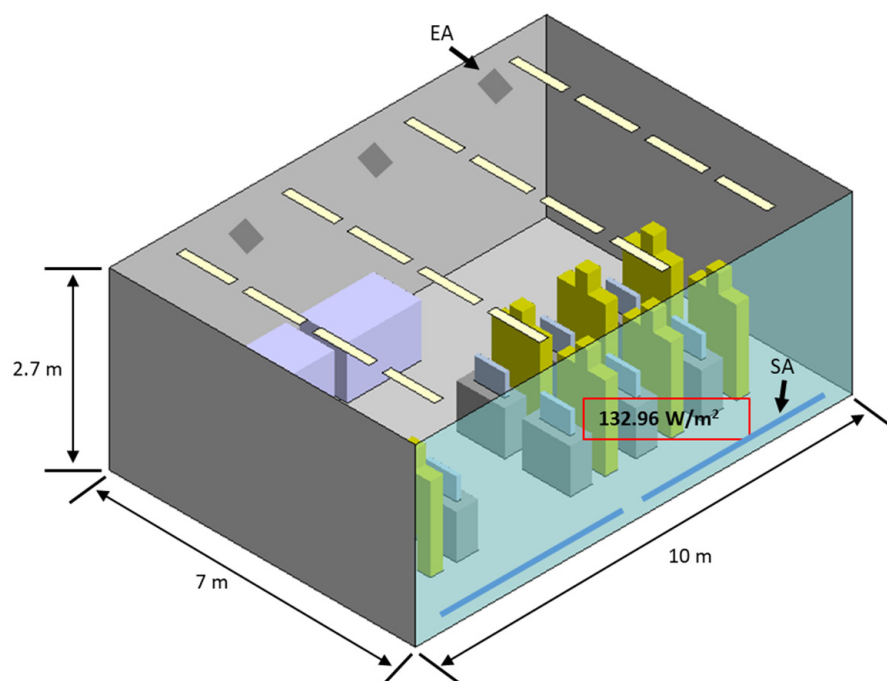


Figure 3. CFD simulation model.

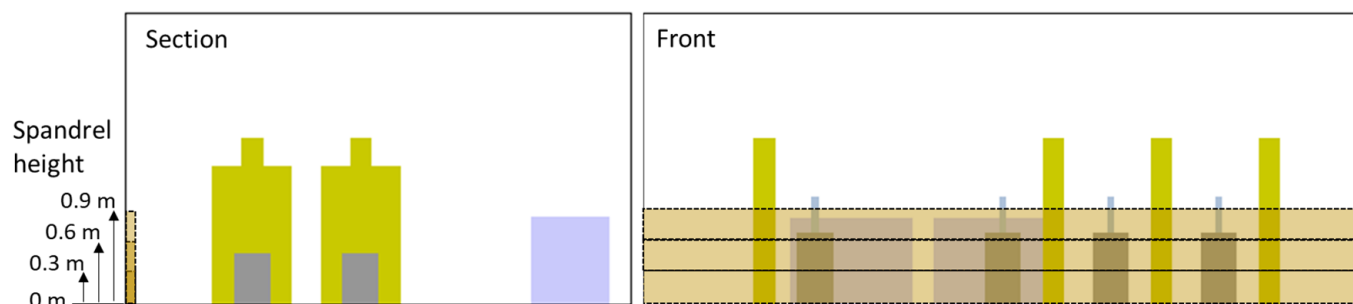


Figure 4. Spandrel panel heights.

Table 2. Internal heat gain sources.

Internal Heat Source		Heat Gain
7 People		785 W
Lighting		13.33 W/m ²
Equipment	2 Printers	60 W
	7 Computers	343 W
	7 Monitors	140 W

In the study, all numerical simulations were performed with the software STAR CCM+ 9.02, which calculates the steady-state Reynolds-averaged Navier–Stokes Equations and utilizes Boussinesq approximation to create the buoyancy effect. This commercial software has been used for the design and analysis of acceptable thermal comfort. The geometries and meshes of the model were built with a design modeler and a meshing tool of STAR CCM+ 9.02. Since airflow has a low velocity and the change of pressure is small in buildings, the fluid flow in numerical simulations is incompressible. Moreover, the three-dimensional, steady-state flows with heat-transfer continuity, momentum, and energy equations were below:

$$\frac{\partial U_i}{\partial x_i} \quad (1)$$

$$\rho U_i \frac{\partial U_i}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i} \left[\mu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] \quad (2)$$

$$\rho c_p U_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\lambda \frac{\partial T}{\partial x_j} - \rho c_p \overline{u'_i T'} \right] \quad (3)$$

$$p = \rho RT \quad (4)$$

where U_i is the time-averaged velocity and T is temperature. ρ , λ , p , and μ are density, thermal diffusivity, static pressure, and viscosity, respectively. In addition, R is gas constant. Moreover, $u'_i, u'_j, T', \rho \overline{u'_i u'_j}, \rho c_p \overline{u'_i T'}$ are fluctuating velocities, temperature, the average Reynolds stresses, and turbulent heat fluxes, respectively. As the most reputable turbulence model for flow problems that requires a low computational cost, the k- ϵ turbulence model was selected [65]. Specifically, the Realizable k- ϵ turbulence model was chosen among various k- ϵ turbulence models due to its accuracy [66,67]. The SIMPLE algorithm was implemented for pressure-velocity coupling, and first-order upwind discretization scheme was employed for pressure, momentum, turbulent kinetic energy, turbulent dissipation energy, and energy equations. When all the residuals of continuity, momentum, turbulence, and energy were less than 10^{-4} , the numerical solutions were assumed to be converged. To validate the numerical solutions, the data obtained from the measurements performed by Lim et al. were used, which is shown in Section 4.2 [13]. After validation, airflow and temperature distributions with three different heights of spandrel panes in the perimeter zone were predicted.

3.3. Thermal Comfort Assessment

To evaluate thermal comfort, Predicted Mean Vote (PMV) was used [68]. Compared with a single evaluation, such as temperature and velocity, PMV is a more comprehensive evaluation method for thermal comfort [69]. The PMV equation is expressed as:

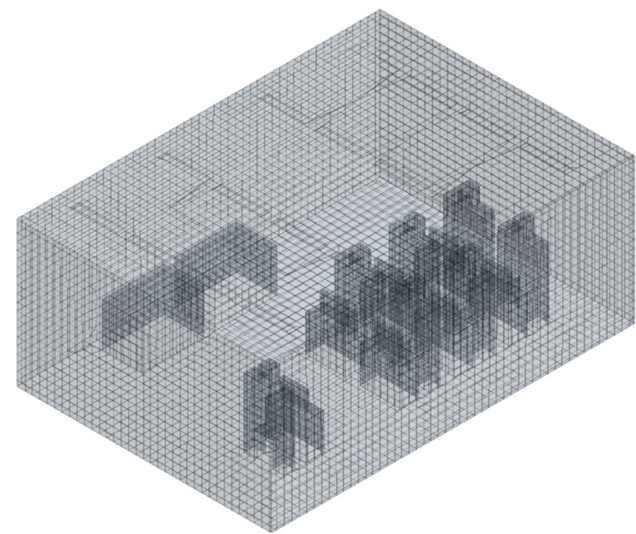
$$\begin{aligned} \text{PMV} = & (0.303 e^{-0.0336M} + 0.028) \\ & \times \{ (M - W) - 0.42 [(M - W) - 58.15] - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a] \\ & - 1.7 \times 10^{-5} M(5867 - P_a) - 0.0014M(34 - t_a) \\ & - 3.96 \times 10^{-8} f_{cl} \times [(t_{cl} \times 274)^4 - (t_r + 273)^4] - f_{cl} \times h_c(t_{cl} - t_a) \} \end{aligned} \quad (5)$$

where M is the human metabolic rate (W/m^2) and W is the external work made by the person (W/m^2). In addition, t_r is the average radiation temperature ($^{\circ}\text{C}$); t_a is the air temperature ($^{\circ}\text{C}$); f_{cl} is the ratio of the surface area of a dressed human body to the surface area exposed; I_{cl} is the thermal resistance of the clothes (clo); t_{cl} is the surface temperature of the clothes ($^{\circ}\text{C}$); P_a is the steam partial pressure that is related to air relative humidity (KPa).

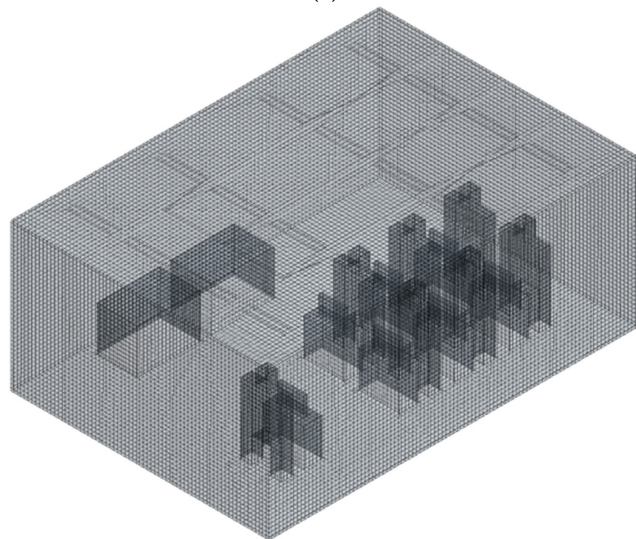
4. Result

4.1. Grid Sensitivity Study

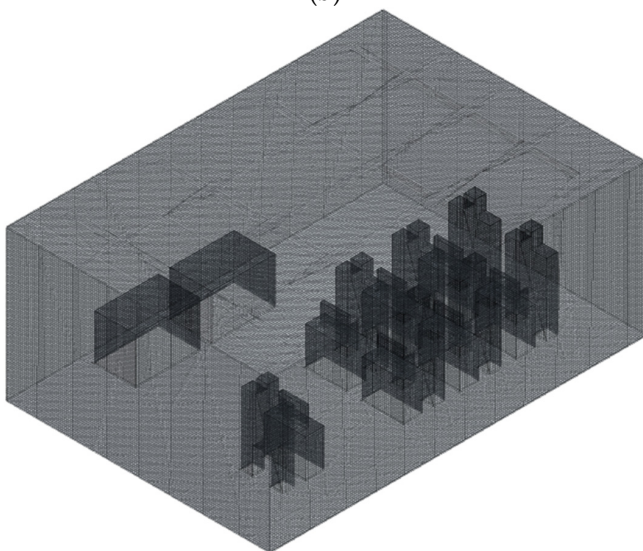
Computational meshes for the CFD simulation were constructed with the dimensions of the office. As shown in Figure 5, three cells (38,515, 151,758, and 616,389) were used to check the mesh quality. The refinement of the mesh was set as 1.3 [70]. As shown in Figure 6, the horizontal velocity distributions of the three cells were obtained along the center of the office. The air velocity profiles of two meshes (151,758 and 616,389 cells) had approximately the same value. Therefore, the meshes of 151,758 cells were recommended to conduct the present study for accurate simulations and less computational resources.



(a)



(b)



(c)

Figure 5. Three different mesh generations. (a) 38,515 cells; (b) 151,758 cells; (c) 616,389 cells.

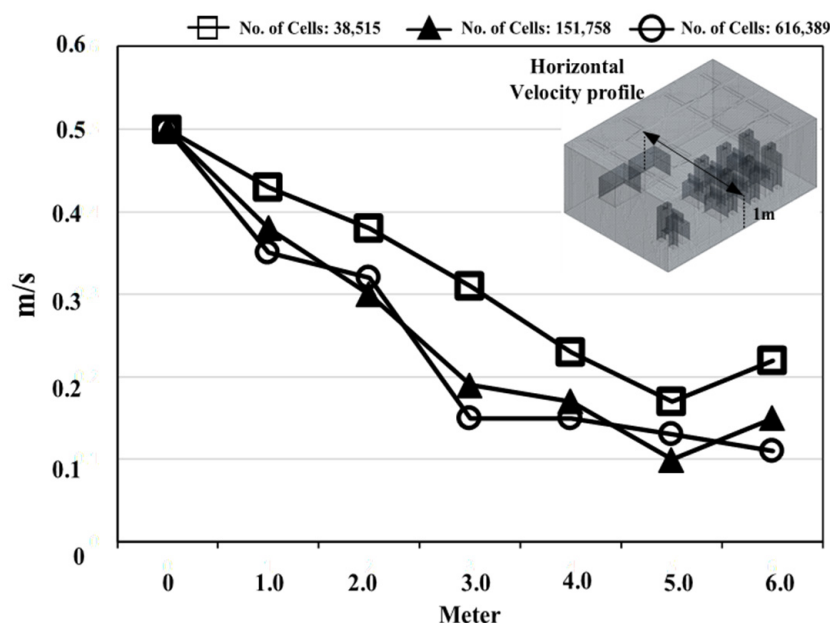


Figure 6. Horizontal velocity distributions of three different cells.

4.2. CFD Model Validation

To investigate the thermal performance of the office in the perimeter zone, it is necessary to validate CFD models. For the validation, temperature data obtained from the measurement of Lim et al. were utilized [13]. CFD model validation was achieved by comparing the vertical temperature distribution at the glazing between the measured data and the CFD simulation. As shown in Figure 7, the numerical results obtained from the CFD provided adequate agreement with the measurement data. However, the temperature profile obtained by CFD above 1.8 m was 20% higher than the measured data. Even though little difference between the measured data and CFD results were observed, this can be considered to be an experimental uncertainty.

4.3. Analysis of the Temperature Distribution by Different Heights of the Spandrel Panel

Figures 8 and 9 show temperature and airflow distributions in the symmetrically vertical section (a-a' section) of the office with several spandrel heights. Incidental solar radiation of 132.96 W/m^2 was assumed at the glazing of the office. The temperature distribution ranged from 24°C to 30°C in all cases. When the spandrel panel height was 0 m, the highest temperature was observed in all cases. The temperature difference between the upper and lower parts, in this case, was about $2\text{--}3^\circ\text{C}$. This could be caused by a larger glazing area than that of the other cases. In the case when the spandrel panel height was 0.3 m, the temperature ranged from 26°C to 29°C . Even though this was lower than the case when the spandrel panel height was 0 m, it was still hotter than the setpoint temperature (26°C). When the spandrel panel height was 0.6 m, the temperature ranged from 25.5°C to 28°C , which was about 1°C lower than the cases when spandrel panel heights were 0 m and 0.3 m, respectively. The lowest temperature distribution ($25\text{--}27^\circ\text{C}$) was observed when the spandrel panel height was 0.6 m, which was close to the setpoint temperature. Temperature decreased as the height of the spandrel panel increased. For airflow distribution (Figure 9), the velocity in these models ranged from 0.0 m/s to 0.45 m/s . In addition, irregular velocity patterns were observed in all cases. This can be seen that slow airflow was influenced by the heat generated by equipment in the office.

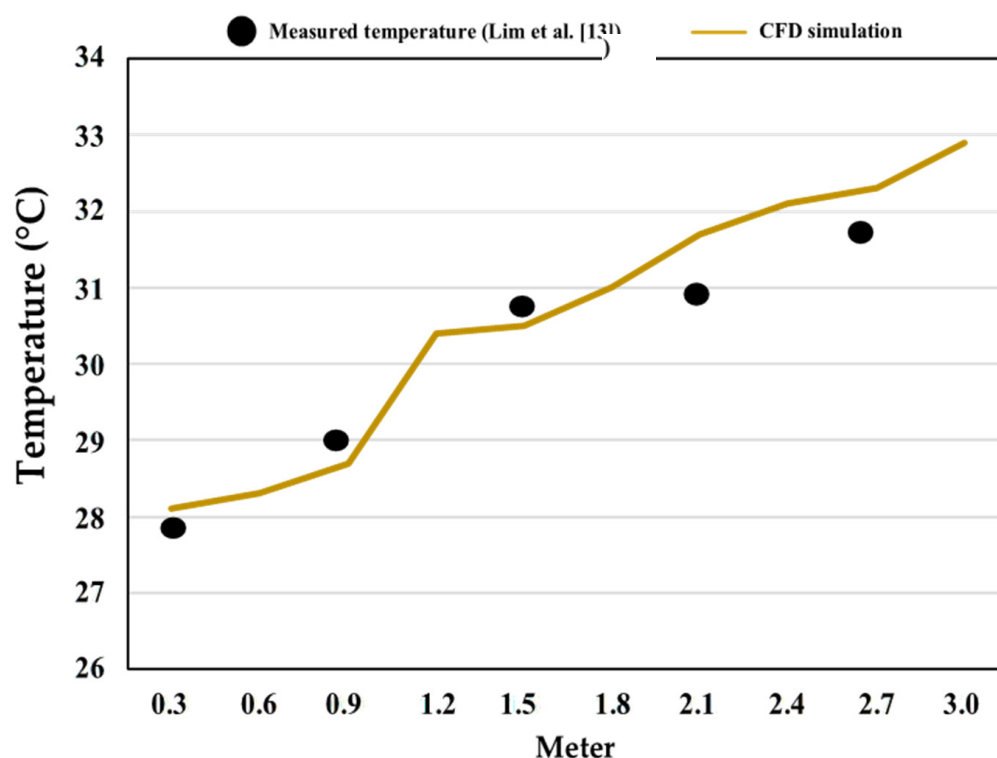


Figure 7. Comparison of vertical temperature profile at the glazing between the experimental data of (Lim et al., 2022) [13] and CFD simulation.

4.4. Effects on the PMV

Figure 10 presents the contours of the PMV values at 1.5 m from the floor with different spandrel panel heights. To quantify the PMV values, PMV equation was calculated using the under-defined function of STAR CCM+ 9.02. For the input parameters of the PMV equation, metabolic rate and clothing insulation were set at 123 W/m^2 and 0.57 clo, respectively. Relative humidity was set at 50%. Based on the results of CFD simulation, air velocity and indoor air temperature were applied. To calculate the mean radiant temperature (MRT), data obtained from Lim et al. were used for the cases [13].

As shown in the figure, the PMV values at 1.5 m from the floor in all cases were larger than zero, because of heat gained by equipment and occupants. For the case of 0 m of spandrel panel height, MRT and air velocity were $30.94 \text{ }^\circ\text{C}$ and 0.2 m/s , respectively. PMV values ranged from 0.9 to 1.5, in which thermal sensation was from slightly warm to warm. This can cause thermal discomfort for occupants. When the spandrel panel height was 0.3 m, MRT was $30.46 \text{ }^\circ\text{C}$ and air velocity was 0.2 m/s . Based on the PMV values (0.6–1.0), thermal sensation was from neutral to slightly warm. As for the case of 0.6 m of spandrel panel height, MRT and air velocity were $29.95 \text{ }^\circ\text{C}$ and 0.2 m/s , respectively. PMV ranged from 0.4 to 0.7, with thermal sensation ranging from neutral to slightly warm. This showed a slight decrease in the degree of thermal comfort than that of the 0.3-m spandrel panel. When the spandrel panel height was 0.9 m, MRT was $29.15 \text{ }^\circ\text{C}$ and air velocity was 0.2 m/s . In this case, the PMV values at 1.5 m were below 0.5. In addition, the PMV values were close to zero near the glazing because it was the smallest glazing area among the cases. Moreover, the supply air from the underfloor air distribution system was the least influenced by solar radiation among the cases, which demonstrated effective removal of heat gain.

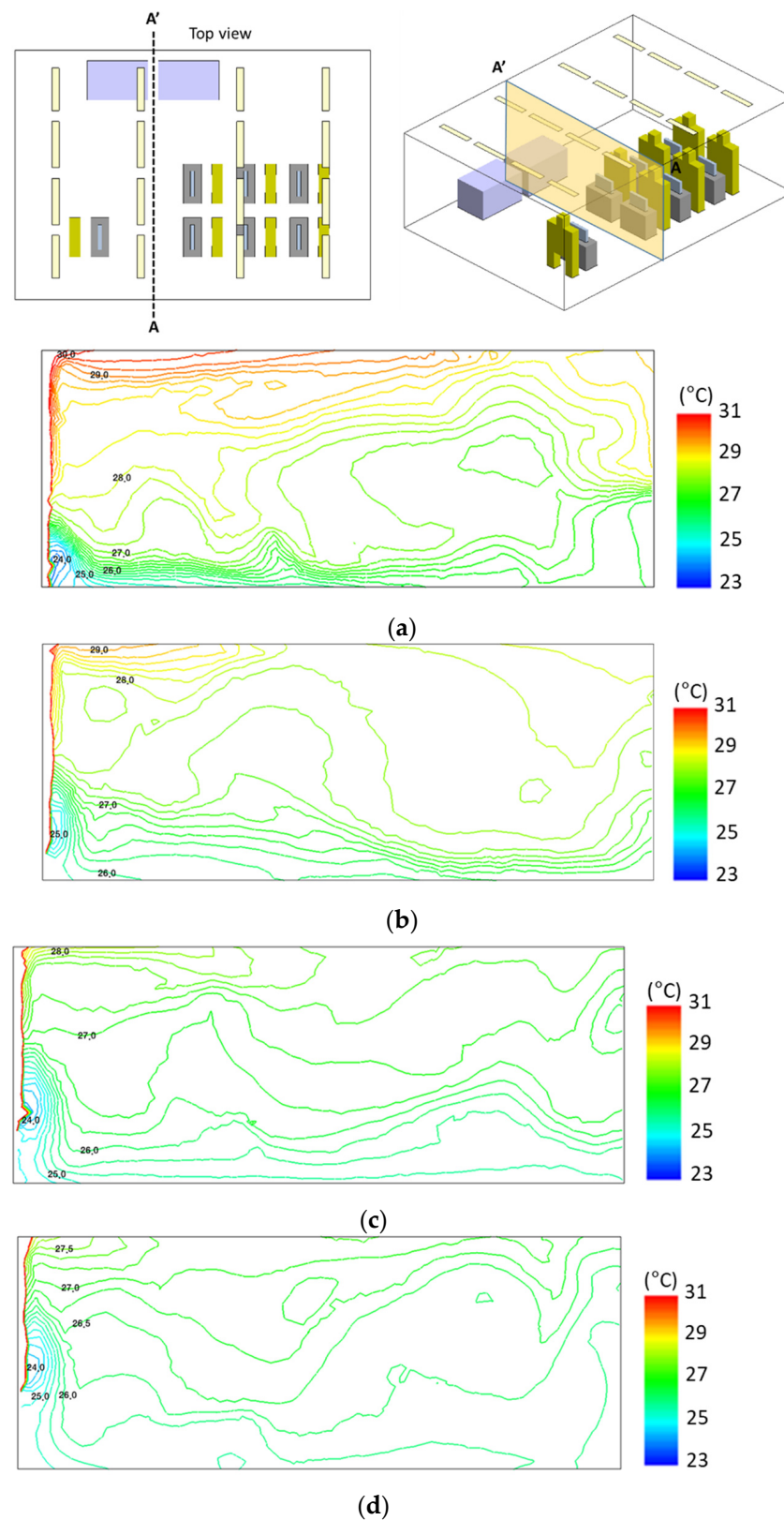


Figure 8. Vertical temperature distribution with different heights of the spandrel panel. (a) Spandrel panel height: 0 m; (b) Spandrel panel height: 0.3 m; (c) Spandrel panel height: 0.6 m; (d) Spandrel panel height: 0.9 m.

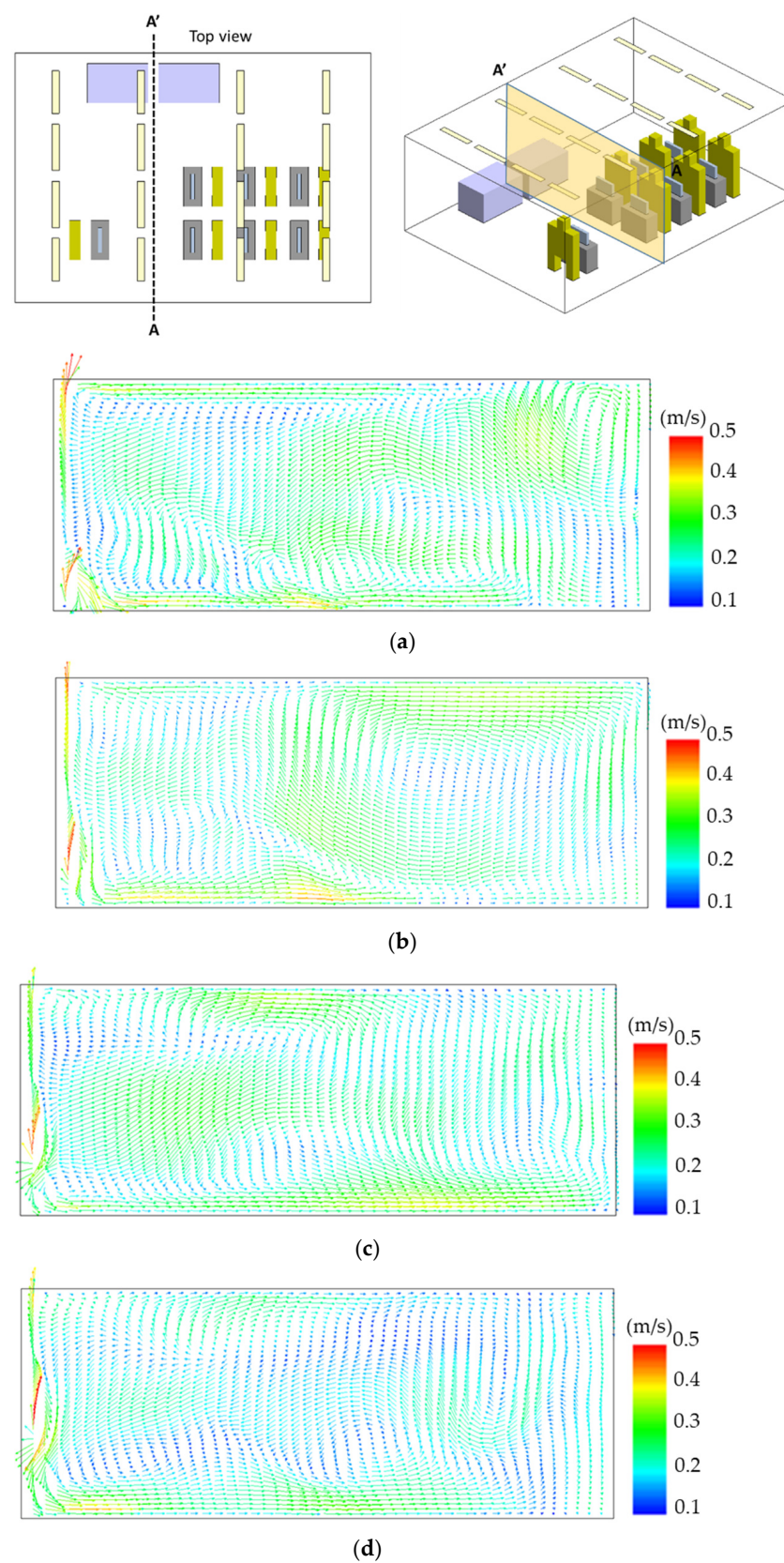


Figure 9. Vertical airflow distribution with different heights of the spandrel panel. (a) Spandrel panel height: 0 m; (b) Spandrel panel height: 0.3 m; (c) Spandrel panel height: 0.6 m; (d) Spandrel panel height: 0.9 m.

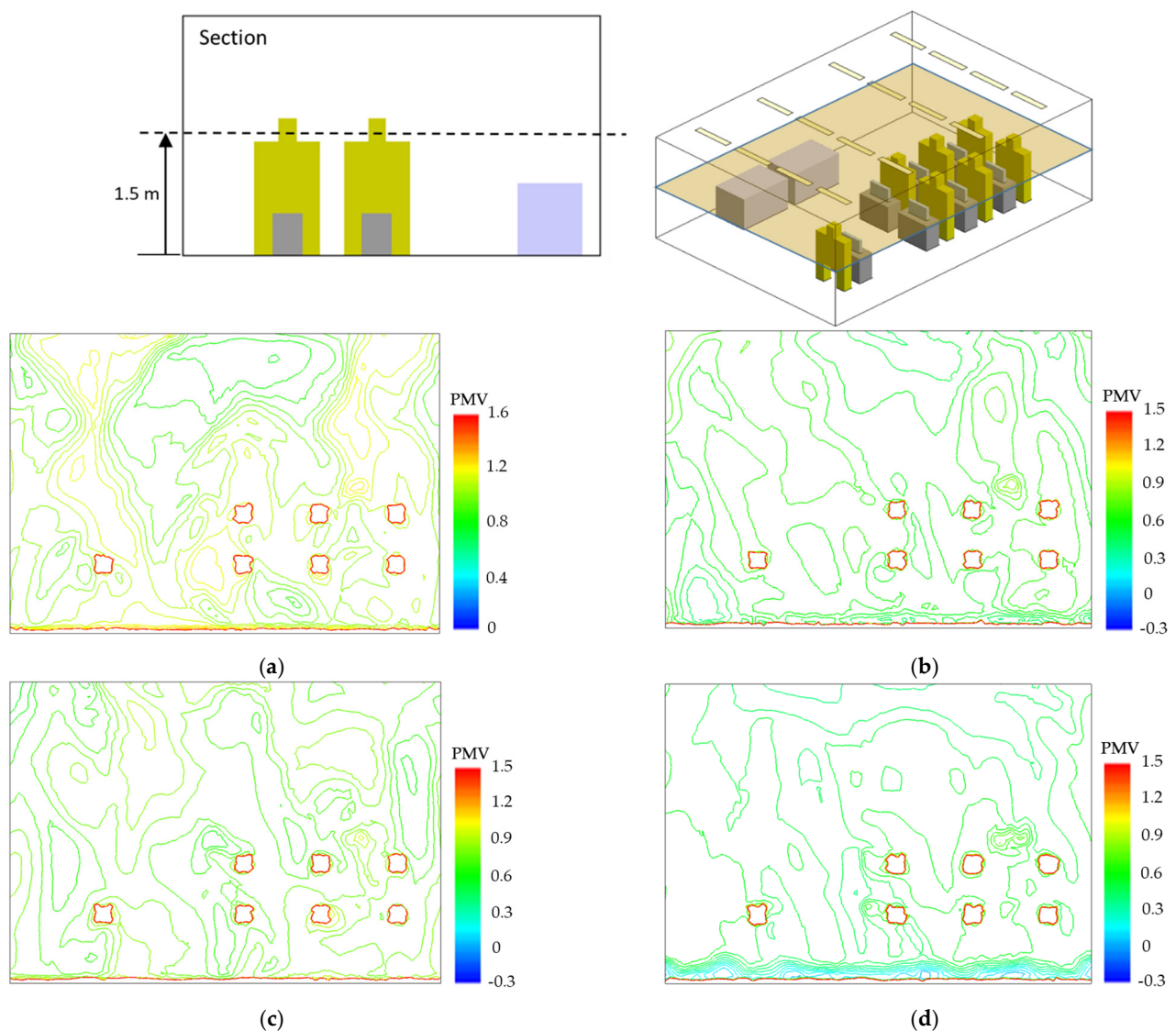


Figure 10. PMV contours of different heights of the spandrel panel. (a) Spandrel panel height: 0 m; (b) Spandrel panel height: 0.3 m (c) Spandrel panel height: 0.6 m; (d) Spandrel panel height: 0.9 m.

5. Discussion

Generally, in curtain walls, the façade is composed of transparent and non-transparent materials to achieve a balance between view and thermal comfort by reducing unwanted heat gain. As discussed in several studies, the largest cooling load is required in the perimeter zone and it can cause thermal discomfort for occupants [71,72]. To reduce heat gain through the glazing, various façade design variables were applied in these studies. By this point, the present study investigated thermal sensation in an office located in the perimeter zone with different spandrel panel heights. Using the ventilation rates of the reference building, airflow and temperature distributions were predicted by CFD simulation. As shown in the results, airflow showed irregular patterns caused by equipment and furniture. However, average air velocity was 0.2 m/s in all cases, which satisfied the criteria for occupants' thermal comfort, as defined by ASHRAE standard 55 [73]. In addition, thermal stratification was identified when the spandrel panel height was zero, which was about a 4 °C difference between the upper and lower parts of the office. This did not meet the criteria of thermal comfort by ASHRAE standard 55, in which vertical temperature difference (0.1 m–1.7 m) should be less than 3 °C [73]. As the spandrel panel height increased, thermal stratification decreased. In the case of 0.3 m of spandrel panel height,

vertical temperature difference was about 2 °C, which satisfied the criteria of ASHRAE standard 55. However, this was 1 °C higher than the setpoint temperature, which caused thermal discomfort to occupants. The other cases satisfied the criteria of thermal comfort by ASHRAE standard 55. Therefore, the cooling system was not effective in reducing the heat gain caused by solar radiation when spandrel panel height was below 0.3 m.

Moreover, to evaluate thermal comfort quantitatively, PMV was calculated by varying the heights of the spandrel panel based on the data obtained in Lim et al. and CFD simulation of the current study [13]. As shown in the results, PMV values observed in the cases of 0 m and 0.3 m of spandrel panel heights were warmer and slightly warmer at 1.5 m from the floor, while better perceived thermal comfort was demonstrated in the other cases when the spandrel panel height was above 0.3 m. According to several studies, PMV and Predicted Percentage of Dissatisfied (PPD) indices are used to assess thermal comfort [74–76]. However, for the current study, only PMV was considered for the evaluation of thermal comfort. For this study, the only variable for the thermal comfort evaluation was the variation of the glazing area by spandrel panel heights. This created little temperature difference among the cases in that PMV values in all cases were within the range of slightly cool to warm. Since PPD was calculated by using PMV values, it also showed little difference among the cases. Thus, PPD assessments were excluded from the study.

6. Conclusions

Most perimeter zones are thermally susceptible to the variation of outdoor conditions, especially due to a large amount of heat gain through the glazing. To reduce heat gain by solar radiation, spandrel systems are employed in curtain walls in commercial buildings. For the present study, thermal performance in an office area located in the perimeter zone was investigated using CFD simulation. By varying the spandrel panel heights, PMV values were obtained to assess thermal comfort quantitatively.

The outcomes of the study were as follows:

- a. When the spandrel panel height was 0 m, the highest temperature was observed in all cases, while the lowest temperature distribution was observed when spandrel panel height was 0.9 m. The temperature difference when the spandrel panel heights were from 0 m to 0.9 m was about 1–3 °C, which was caused by the variation of the glazing area. In addition, the cooling system could not effectively reduce heat gain when the spandrel panel height was zero. In addition, temperature distributions when spandrel panel heights were 0.6 m and 0.9, respectively, were close to or below the setpoint temperature.
- b. For thermal comfort evaluation, PMV values at 1.5 m from the floor in all cases were larger than zero. PMV values in all cases were within the range of slightly cool to warm. When spandrel panel height was 0 m, the highest thermal sensation (warm) among the cases was observed, which may cause thermal dissatisfaction for occupants. When the spandrel panel height was 0.3 m, the thermal sensation ranged from neutral to slightly warm. As for the spandrel panel height of 0.6 m, a slight decrease in the degree of thermal comfort was observed, when compared to that of the 0.3-m spandrel panel. For the case of 0.9 m of spandrel panel height, PMV values were below 0.5 and close to zero near the glazing, it had the smallest glazing area among the cases.

Considering the outcome of the present study, properly designed spandrel panel has the potential to reduce solar-heat gain through the glazing as well as provide better perceived thermal comfort for occupants in the perimeter zone. Moreover, the obtained results can be used for the development of design guidelines for more effective spandrel panels in building envelopes in the aspect of thermal performance. For further study, various design options of spandrel panels in curtain walls can be included in the assessment of thermal comfort, and PPD can be used for a more accurate thermal comfort evaluation. Overall, proper spandrel panel design can contribute to better indoor thermal performance

and lower energy consumption for maintaining thermal comfort in buildings, promoting building sustainability.

Author Contributions: T.L. designed and performed the simulation and collected the data; D.D.K. wrote the manuscript and analyzed the data. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Oh, M.; Jang, K.M.; Kim, Y. Empirical analysis of building energy consumption and urban form in a large city: A case of seoul, south korea. *Energy Build.* **2021**, *245*, 111046. [CrossRef]
- Lei, L.; Chen, W.; Wu, B.; Chen, C.; Liu, W. A building energy consumption prediction model based on rough set theory and deep learning algorithms. *Energy Build.* **2021**, *240*, 110886. [CrossRef]
- Pi, Z.X.; Li, X.H.; Ding, Y.M.; Zhao, M.; Liu, Z.X. Demand response scheduling algorithm of the economic energy consumption in buildings for considering comfortable working time and user target price. *Energy Build.* **2021**, *250*, 111252. [CrossRef]
- Ding, Y.; Fan, L.; Liu, X. Analysis of feature matrix in machine learning algorithms to predict energy consumption of public buildings. *Energy Build.* **2021**, *249*, 111208. [CrossRef]
- Li, L.; Wang, Y.; Wang, M.; Hu, W.; Sun, Y. Impacts of multiple factors on energy consumption of aging residential buildings based on a system dynamics model—taking northwest china as an example. *J. Build. Eng.* **2021**, *44*, 102595. [CrossRef]
- The Annual Energy Consumption in 2017, Korea Energy Agency. Available online: https://www.Energy.Or.Kr/renew_eng/main/main.aspx (accessed on 30 June 2022).
- Agency, K.E. Energy Statistics Handbook. 2020. Available online: https://www.Energy.Or.Kr/web/kem_home_new/new_main.Asp (accessed on 4 August 2022).
- Kim, D.-B.; Kim, D.D.; Kim, T. Energy performance assessment of hvac commissioning using long-term monitoring data: A case study of the newly built office building in south korea. *Energy Build.* **2019**, *204*, 109465. [CrossRef]
- Leung, C.K.; Lu, L.; Liu, Y.; Cheng, H.S.; Tse, J.H. Optical and thermal performance analysis of aerogel glazing technology in a commercial building of hong kong. *Energy Built Environ.* **2020**, *1*, 215–223. [CrossRef]
- Kiran Kumar, G.; Saboor, S.; Ashok Babu, T.P. Investigation of various wall and window glass material buildings in different climatic zones of india for energy efficient building construction. *Mater. Today Proc.* **2018**, *5*, 23224–23234. [CrossRef]
- Lu, S.; Li, Z.; Zhao, Q.; Jiang, F. Modified calculation of solar heat gain coefficient in glazing façade buildings. *Energy Procedia* **2017**, *122*, 151–156. [CrossRef]
- Zhang, Y.; Tennakoon, T.; Chan, Y.H.; Chan, K.C.; Fu, S.C.; Tso, C.Y.; Yu, K.M.; Huang, B.L.; Yao, S.H.; Qiu, H.H.; et al. Energy consumption modelling of a passive hybrid system for office buildings in different climates. *Energy* **2022**, *239*, 121914. [CrossRef]
- Lim, T.; Yim, W.-S.; Kim, D.-D. Analysis of the thermal and cooling energy performance of the perimeter zones in an office building. *Buildings* **2022**, *12*, 141. [CrossRef]
- Berardi, U.; Kisilewicz, T.; Kim, S.; Lechowska, A.; Paulos, J.; Schnotale, J. Experimental and numerical investigation of the thermal transmittance of pvc window frames with silica aerogel. *J. Build. Eng.* **2020**, *32*, 101665. [CrossRef]
- Paulos, J.; Berardi, U. Optimizing the thermal performance of window frames through aerogel-enhancements. *Applied Energy* **2020**, *266*, 114776. [CrossRef]
- Sghiouri, H.; Mezhab, A.; Karkri, M.; Naji, H. Shading devices optimization to enhance thermal comfort and energy performance of a residential building in morocco. *J. Build. Eng.* **2018**, *18*, 292–302. [CrossRef]
- Huang, Y.; Niu, J.-L.; Chung, T.-M. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. *Appl. Energy* **2014**, *134*, 215–228. [CrossRef]
- Liu, S.; Kwok, Y.T.; Lau, K.K.-L.; Chan, P.W.; Ng, E. Investigating the energy saving potential of applying shading panels on opaque façades: A case study for residential buildings in hong kong. *Energy Build.* **2019**, *193*, 78–91. [CrossRef]
- Alhuwayil, W.K.; Abdul Mujeebu, M.; Algarny, A.M.M. Impact of external shading strategy on energy performance of multi-story hotel building in hot-humid climate. *Energy* **2019**, *169*, 1166–1174. [CrossRef]
- Huo, H.; Xu, W.; Li, A.; Cui, G.; Wu, Y.; Liu, C. Field comparison test study of external shading effect on thermal-optical performance of ultralow-energy buildings in cold regions of china. *Build. Environ.* **2020**, *180*, 106926. [CrossRef]
- Chan, A.L.S. Effect of adjacent shading on the energy and environmental performance of photovoltaic glazing system in building application. *Energy* **2019**, *187*, 115939. [CrossRef]
- La Ferla, G.; Acha Román, C.A.; Roset Calzada, J. Radiant glass façade technology: Thermal and comfort performance based on experimental monitoring of outdoor test cells. *Build. Environ.* **2020**, *182*, 107075. [CrossRef]

23. Danis, J.; Mishra, S.; Rempel, A.R. Direct heat flux sensing for window shading control in passive cooling systems. *Energy Build.* **2022**, *261*, 111950. [\[CrossRef\]](#)
24. Pereira Tavares, M.C.; Perdigão Gonçalves, H.J.; de Faria Corrêa Bastos, J.N.T. The glazing area in residential buildings in temperate climate: The thermal-energetic performance of housing units in lisbon. *Energy Build.* **2017**, *140*, 280–294. [\[CrossRef\]](#)
25. Lau, A.K.K.; Salleh, E.; Lim, C.H.; Sulaiman, M.Y. Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: The case of malaysia. *Int. J. Sustain. Built Environ.* **2016**, *5*, 387–399. [\[CrossRef\]](#)
26. de Almeida Rocha, A.P.; Reynoso-Meza, G.; Oliveira, R.C.L.F.; Mendes, N. A pixel counting based method for designing shading devices in buildings considering energy efficiency, daylight use and fading protection. *Appl. Energy* **2020**, *262*, 114497. [\[CrossRef\]](#)
27. Luo, Z.; Sun, C.; Dong, Q.; Yu, J. An innovative shading controller for blinds in an open-plan office using machine learning. *Build. Environ.* **2021**, *189*, 107529. [\[CrossRef\]](#)
28. Atzeri, A.; Cappelletti, F.; Gasparella, A. Internal versus external shading devices performance in office buildings. *Energy Procedia* **2014**, *45*, 463–472. [\[CrossRef\]](#)
29. Bunning, M.E.; Crawford, R.H. Directionally selective shading control in maritime sub-tropical and temperate climates: Life cycle energy implications for office buildings. *Build. Environ.* **2016**, *104*, 275–285. [\[CrossRef\]](#)
30. Khidmat, R.P.; Fukuda, H.; Kustiani; Paramita, B.; Qingsong, M.; Hariyadi, A. Investigation into the daylight performance of expanded-metal shading through parametric design and multi-objective optimisation in japan. *J. Build. Eng.* **2022**, *51*, 104241. [\[CrossRef\]](#)
31. de Vries, S.B.; Loonen, R.C.G.M.; Hensen, J.L.M. Multi-state vertical-blinds solar shading—Performance assessment and recommended development directions. *J. Build. Eng.* **2021**, *40*, 102743. [\[CrossRef\]](#)
32. Khamma, T.R.; Zhang, Y.; Guerrier, S.; Boubekri, M. Generalized additive models: An efficient method for short-term energy prediction in office buildings. *Energy* **2020**, *213*, 118834. [\[CrossRef\]](#)
33. Kapsis, K.; Dermardiros, V.; Athienitis, A.K. Daylight performance of perimeter office façades utilizing semi-transparent photovoltaic windows: A simulation study. *Energy Procedia* **2015**, *78*, 334–339. [\[CrossRef\]](#)
34. Assem, E.O.; Al-Mumin, A.A. Code compliance of fully glazed tall office buildings in hot climate. *Energy Build.* **2010**, *42*, 1100–1105. [\[CrossRef\]](#)
35. Mu, D.; Gao, N.; Zhu, T. Cfd investigation on the effects of wind and thermal wall-flow on pollutant transmission in a high-rise building. *Build. Environ.* **2018**, *137*, 185–197. [\[CrossRef\]](#)
36. Li, A.; Zhang, W.; Gao, M. Field test and cfd modeling for flow characteristics in central cooking exhaust shaft of a high-rise residential building. *Energy Build.* **2017**, *147*, 210–223. [\[CrossRef\]](#)
37. Ascione, F.; De Masi, R.F.; Mastellone, M.; Vanoli, G.P. The design of safe classrooms of educational buildings for facing contagions and transmission of diseases: A novel approach combining audits, calibrated energy models, building performance (bps) and computational fluid dynamic (cfd) simulations. *Energy Build.* **2021**, *230*, 110533. [\[CrossRef\]](#)
38. Lam, T.C.; Ge, H.; Fazio, P. Impact of curtain wall configurations on building energy performance in the perimeter zone for a cold climate. *Energy Procedia* **2015**, *78*, 352–357. [\[CrossRef\]](#)
39. Poirazis, H.; Blomsterberg, Å.; Wall, M. Energy simulations for glazed office buildings in sweden. *Energy Build.* **2008**, *40*, 1161–1170. [\[CrossRef\]](#)
40. Konis, K. Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in san francisco, california. *Build. Environ.* **2013**, *59*, 662–677. [\[CrossRef\]](#)
41. Zhang, S.; Fine, J.P.; Touchie, M.F.; O'Brien, W. A simulation framework for predicting occupant thermal sensation in perimeter zones of buildings considering direct solar radiation and ankle draft. *Build. Environ.* **2020**, *183*, 107096. [\[CrossRef\]](#)
42. Schiavon, S.; Webster, T.; Dickerhoff, D.; Bauman, F. Stratification prediction model for perimeter zone ufad diffusers based on laboratory testing with solar simulator. *Energy Build.* **2014**, *82*, 786–794. [\[CrossRef\]](#)
43. Sadeghi, S.A.; Lee, S.; Karava, P.; Bilonis, I.; Tzempelikos, A. Bayesian classification and inference of occupant visual preferences in daylight perimeter private offices. *Energy Build.* **2018**, *166*, 505–524. [\[CrossRef\]](#)
44. Shen, H.; Tzempelikos, A. Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading. *Build. Environ.* **2013**, *59*, 303–314. [\[CrossRef\]](#)
45. Dubois, M.-C.; Blomsterberg, Å. Energy saving potential and strategies for electric lighting in future north european, low energy office buildings: A literature review. *Energy Build.* **2011**, *43*, 2572–2582. [\[CrossRef\]](#)
46. Chen, C. A study on the renewal construction of office building exterior. *Procedia Eng.* **2011**, *21*, 155–162. [\[CrossRef\]](#)
47. Wong, S.L.; Wan, K.K.W.; Lam, T.N.T. Artificial neural networks for energy analysis of office buildings with daylighting. *Appl. Energy* **2010**, *87*, 551–557. [\[CrossRef\]](#)
48. Boafu, F.E.; Kim, J.-H.; Ahn, J.-G.; Kim, S.-M.; Kim, J.-T. Slim curtain wall spandrel integrated with vacuum insulation panel: A state-of-the-art review and future opportunities. *J. Build. Eng.* **2021**, *42*, 102445. [\[CrossRef\]](#)
49. Chan, Y.-C.; Tzempelikos, A. Daylighting and energy analysis of multi-sectional facades. *Energy Procedia* **2015**, *78*, 189–194. [\[CrossRef\]](#)
50. Kassem, M.; Mitchell, D. Bridging the gap between selection decisions of facade systems at the early design phase: Issues, challenges and solutions. *J. Facade Des. Eng.* **2015**, *3*, 165–183. [\[CrossRef\]](#)
51. Sanders, R.M. Curtain Walls: Not just another pretty façade. *J. Archit. Technol.* **2006**, *23*, 1–8.

52. Jelle, B.P.; Hynd, A.; Gustavsen, A.; Arasteh, D.; Goudey, H.; Hart, R. Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Sol. Energy Mater. Sol. Cells* **2012**, *96*, 1–28. [\[CrossRef\]](#)
53. Cuce, E.; Riffat, S.B. A state-of-the-art review on innovative glazing technologies. *Renew. Sustain. Energy Rev.* **2015**, *41*, 695–714. [\[CrossRef\]](#)
54. Van Den Bergh, S.; Hart, R.; Jelle, B.P.; Gustavsen, A. Window spacers and edge seals in insulating glass units: A state-of-the-art review and future perspectives. *Energy Build.* **2013**, *58*, 263–280. [\[CrossRef\]](#)
55. Rezaei, S.D.; Shannigrahi, S.; Ramakrishna, S. A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. *Sol. Energy Mater. Sol. Cells* **2017**, *159*, 26–51. [\[CrossRef\]](#)
56. Richman, R.C.; Pressnail, K.D. A more sustainable curtain wall system: Analytical modeling of the solar dynamic buffer zone (sdbz) curtain wall. *Build. Environ.* **2009**, *44*, 1–10. [\[CrossRef\]](#)
57. Arnesano, M.; Pandarese, G.; Martarelli, M.; Naspi, F.; Gurunatha, K.L.; Sol, C.; Portnoi, M.; Ramirez, F.V.; Parkin, I.P.; Papakonstantinou, I.; et al. Optimization of the thermochromic glazing design for curtain wall buildings based on experimental measurements and dynamic simulation. *Sol. Energy* **2021**, *216*, 14–25. [\[CrossRef\]](#)
58. Sayed, M.A.A.E.D.A.; Fikry, M.A. Impact of glass facades on internal environment of buildings in hot arid zone. *Alex. Eng. J.* **2019**, *58*, 1063–1075. [\[CrossRef\]](#)
59. Song, J.-H.; Lim, J.-H.; Song, S.-Y. Evaluation of alternatives for reducing thermal bridges in metal panel curtain wall systems. *Energy Build.* **2016**, *127*, 138–158. [\[CrossRef\]](#)
60. O'Brien, W.; Kapsis, K.; Athienitis, A.K. Manually-operated window shade patterns in office buildings: A critical review. *Build. Environ.* **2013**, *60*, 319–338. [\[CrossRef\]](#)
61. Ihara, T.; Gao, T.; Grynning, S.; Jelle, B.P.; Gustavsen, A. Aerogel granulate glazing facades and their application potential from an energy saving perspective. *Appl. Energy* **2015**, *142*, 179–191. [\[CrossRef\]](#)
62. Korea Meteorological Administration. Available online: <https://www.Weather.Go.Kr/weather/main.Jsp> (accessed on 8 August 2022).
63. Korean Statistical Information Service. Available online: <https://kosis.kr/index/index.Do> (accessed on 10 September 2022).
64. American Society of Heating, Refrigerating and Air Conditioning Engineers. *Ashrae Handbook*; ASHRAE: Atlanta, GA, USA, 2013; Chapter 4.
65. Gavrilov, A.A.; Rudyak, V.Y. Reynolds-averaged modeling of turbulent flows of power-law fluids. *J. Non-Newton. Fluid Mech.* **2016**, *227*, 45–55. [\[CrossRef\]](#)
66. Pasut, W.; De Carli, M. Evaluation of various cfd modelling strategies in predicting airflow and temperature in a naturally ventilated double skin façade. *Appl. Therm. Eng.* **2012**, *37*, 267–274. [\[CrossRef\]](#)
67. Pei, G.; Rim, D. Quality control of computational fluid dynamics (cfd) model of ozone reaction with human surface: Effects of mesh size and turbulence model. *Build. Environ.* **2021**, *189*, 107513. [\[CrossRef\]](#)
68. Shaw, E.W. Thermal comfort: Analysis and applications in environmental engineering, by p. O. Fanger. 244 pp. Danish technical press. Copenhagen, denmark, 1970. Danish kr. 76, 50. *R. Soc. Health J.* **1972**, *92*, 164. [\[CrossRef\]](#)
69. Chen, Z.; Xin, J.; Liu, P. Air quality and thermal comfort analysis of kitchen environment with cfd simulation and experimental calibration. *Build. Environ.* **2020**, *172*, 106691. [\[CrossRef\]](#)
70. The American Society of Mechanical Engineers, ASME. Procedure for estimation and reporting of uncertainty due to discretization in cfd applications. *J. Fluids Eng.* **2008**, *130*, 078001. [\[CrossRef\]](#)
71. Convertino, F.; Vox, G.; Schettini, E. Evaluation of the cooling effect provided by a green façade as nature-based system for buildings. *Build. Environ.* **2021**, *203*, 108099. [\[CrossRef\]](#)
72. Tong, S.; Wen, J.; Wong, N.H.; Tan, E. Impact of façade design on indoor air temperatures and cooling loads in residential buildings in the tropical climate. *Energy Build.* **2021**, *243*, 110972. [\[CrossRef\]](#)
73. *Standard 55-2017*; Thermal Environmental Conditions for Human Occupancy. ASHRAE: Atlanta, GA, USA, 2017.
74. Losi, G.; Bonzanini, A.; Aquino, A.; Poesio, P. Analysis of thermal comfort in a football stadium designed for hot and humid climates by cfd. *J. Build. Eng.* **2021**, *33*, 101599. [\[CrossRef\]](#)
75. Dixit, A.; Gade, U. A case study on human bio-heat transfer and thermal comfort within cfd. *Build. Environ.* **2015**, *94*, 122–130. [\[CrossRef\]](#)
76. Bay, E.; Martinez-Molina, A.; Dupont, W.A. Assessment of natural ventilation strategies in historical buildings in a hot and humid climate using energy and cfd simulations. *J. Build. Eng.* **2022**, *51*, 104287. [\[CrossRef\]](#)