CFD study with consideration of the surrounding buildings using a through-wall unit air conditioning system

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Abstract. In order to select the operation patterns of a through-wall unit (TWU) according to the air conditioning needs of the occupants, it is necessary to confirm the indoor thermal environment and natural ventilation effects by the operation patterns. CFD analysis was performed utilizing Building Information Modeling (BIM) and the outdoor fan characteristics of a TWU by a full-scale performance experiments. It was confirmed that the airside economizer mode using the outdoor fan on an improved TWU supplies a sufficient ventilation rate of about 4.5 ACPH to the office and it can provide a good indoor thermal environment during no wind conditions. In addition, CFD analysis using the night-time cool breeze mode with consideration of the surrounding buildings was conducted. As a whole, a good indoor environment of about 26 to 27°C could be obtained with about 3 ACPH ventilation and a cool breeze effect. It was confirmed that by conducting precise analysis on the whole building, a stable effect was obtained, regardless of the difference in building height and wind direction.

1. Introduction

Environmental considerations are becoming increasingly important in architecture. Achieving energy savings while maintaining thermal comfort is important, particularly in office buildings. An improved through-wall unit air-conditioner (hereinafter referred to as TWU) was created by adding a new mode to use room exhaust air for the compressor heat exchange and helped to develop a high efficiency perimeter air-conditioning system. A previous report [1] noted that, in the perimeter zone, air conditioning is performed by the TWU by combining various operation patterns of the TWU and the air handling units (AHU) in accordance with the air-conditioning demands. This enables selection or control corresponding to various air-conditioning needs in an office building.

In order to select the air conditioning mode, it is necessary to confirm the indoor thermal environment by an operation pattern. For this reason, simulation of ventilation volume caused by the internal and external pressure differences due to external wind is important. Therefore, in this report, computational fluid dynamics (CFD) analysis was conducted using these conditions and the results are presented herein. CFD analysis was conducted utilizing a BIM created during the design and construction stages and the TWU outdoor fan characteristics were conducted by actual experiment.

2. Utilization of BIM data
The building analyzed is located in Tokyo, Ikebukuro. This building is a high-rise office building with a typical floor area of approximately 2,800 m² and a height of approximately 100 meters. Figure 1 shows the BIM model which includes all mechanical systems. The BIM model was utilized from the design stage for making mechanical drawings. After that, the BIM model was utilized during the construction phase. The mechanical model was handed over at the construction stage and the data was further developed. In order to analyze the indoor environment using CFD, the air conditioning duct system was taken from the mechanical BIM data and the building structure data of typical floor was imported from the architectural BIM data during the construction stage. An example of modification of the BIM model that can be used for CFD is shown in Figure 2.

Since the space between the corridor and office does not connect with a bypass duct in BIM data, holes in the bypass duct and the ceiling surface were made. The TWU installed inside the perimeter as modeled in CFD was made with reference to the actual exterior wall construction drawing. As a result, although modification and model checking were necessary, CFD using BIM can reproduce the model relatively easily, and various air conditioning systems can be reflected.

### 3. Analysis conditions for CFD

In order to understand the indoor thermal environment in each air conditioning mode, an indoor model on a typical office floor was created. In the “normal AC” mode and “air-side economizer” mode, CFD analysis of the indoor environment was performed for one typical floor. In the “night-time cool breeze” mode, in which outside air is taken in at each floor, the analysis was carried out throughout the whole building in consideration of the influence of surrounding buildings and outdoor wind. The analysis list which includes outdoor conditions is shown in Table 1. In addition, Table 2 shows CFD analysis conditions. The outline of the indoor model is explained below.

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![Figure 1. BIM model at the design stage](image1)

![Figure 2. An example of modification of the BIM model](image2)
3.1. Indoor analysis model

An indoor analysis model of a typical floor is shown in Figure 3. This model includes building structure and mechanical information for indoor environmental analysis. Supply air from the AHU is supplied by a 500 mm x 200 mm square type ceiling diffuser. The supply air (SA) diffusers and return air (RA) slits are alternately arranged at an interval of 1.8 meters. A total of 32 TWU’s per floor are installed at the perimeter. The TWU geometry was referenced to the actual sash shape and coordinated. The outside air is taken in from the air supply grill on the southwestern outer wall and is connected to the ceiling surface of the corridor through five ducts. The common corridor and the office are connected by 10 bypass ducts.

### Table 1. Analysis case list

| Case | Air conditioning system | TWU Operation [Unit Number] | Wind direction, Speed[m/s] | Outdoor Temp.[℃] | Remarks |
|------|-------------------------|----------------------------|-----------------------------|------------------|---------|
| C1-Aug | Normal AC | AC+V mode: 24units AC mode: 8units | (Windless) | 35 | Solar radiation in August |
| C2-May | Air-side economizer | V mode: 32units | (Windless) | 15 | Solar radiation in May |
| C3-SSW | Night-time cool breeze | V mode: 32units | (Windless) | 18 | Solar radiation in May |
| C3-NNW | | | | 18 | |
| C3-N | | | | 18 | |

### Table 2. CFD Analysis conditions

- **CFD Software**: Software Cradle Co., Ltd. STREAM V13
- **Turbulence Model**: Standard k-epsilon model
- **Moving term difference scheme**: QUICK method / first order upwind method (indoor side)
- **Inflow surface**: Power law flow velocity / flow velocity regulation (indoor side)
- **Outflow surface**: Pressure regulation 0 pa / spontaneous outflow
- **Top / side**: Free slip boundary
- **Bottom surface**: Stress condition of power measurement
- **Building surface**: Smooth wall stress boundary (logarithmic law)
- **Calculation area**: x1450m×y1650m×z400m
- **Element split**: Approximately 40 million (Target floor is 7F, 11F, 15F)

The opening ratio of the bypass ducts and other air openings is all 50%.
3.2. Fan characteristics

Figure 4 shows the outdoor fan characteristics of the TWU obtained by full-scale performance experiments and control methods. Figure 5 shows the model shape of the TWU. When the external static pressure is between -110 Pa and 195 Pa, the TWU is operated in the "AC+V mode" in which indoor air is exhausted to the outside. In other cases, it is controlled to switch to the “AC mode” by a wind resistance pressure sensor attached to the equipment. If the exhaust air volume is less than 480 CMH/unit, it will not satisfy the required cooling/ heating capacity for perimeter processing. Therefore, the upper limit value of the external static pressure is set to 195 Pa, and at the static pressure beyond 195 Pa, the displacement amount is set to zero.

3.3. Other analysis conditions

In consideration of the operating conditions, internal heat generation was set to 55 W/person × 0.2 person/m², the lighting was set at 10 W/m², outlets were set as 30/m² during “normal AC” mode and “air-side economizer” mode.

In the “night-time cool breeze” mode, assuming overtime work during night time, the human body heat generation was 55 W/person × 0.05 person/m², the lighting was 10 W/m², and the outlets were 10 W/m².

4. Outside analysis conditions

4.1. Purpose of Analysis

For the “night-time cool breeze” mode, it is important to understand the influence of a high-rise building, with a height of about 100 m, and the outer wind conditions, with open surroundings as a building standing over a railway line. Therefore, outdoor environmental conditions were examined for the entire surrounding building area in order to carry out a more detailed analysis, close to the actual environment. 3D data modeling of future planned buildings and surroundings was created by SketchUp in 3DS format and incorporated into the CFD software.

4.2. Analysis area and element division of model

Figure 6 shows an analytical model of the planned building and surrounding buildings. Figure 7 shows a mesh diagram of the analysis model. In order to reproduce a planar external wind, the calculation area captures peripheral building data in an area of about 780 m × 910 m for a building of 63 m × 45 m, securing an analysis area of 1,450 m × 1,650 m.

4.3. External wind, temperature conditions
Wind rose were created using the standard year EA data of Tokyo, Otemachi (EA = Extended AMeDAS weather data, Japan Architectural Institute) with the wind direction for temperatures of 15°C or more outside, as shown in Figure 8. The calculation conditions were created using 3 frequent wind directions (SSW, NNW and N). Figure 9 shows the wind speed distribution. The average wind speed converted to 60 m above the ground was 3.3 m/s, and the cumulative ratio of the external wind speed of 5 m/s was 90%. The wind speed for the analysis conditions was 5 m/s at a reference height of 60 m.

Table 3. Vertical solar radiation amount in each direction and air conditioning condition

| Wind Direction | Solar radiation amount [W/m²] | TWU operation [Unit number] | Supply Temp. [°C] | Solar radiation amount [W/m²] | TWU operation [Unit number] | Supply Temp. [°C] |
|----------------|-------------------------------|----------------------------|------------------|-------------------------------|----------------------------|------------------|
| NE             | 151                           | V mode : 10 units          | 22.0             | 128                           | V mode : 10 units          | –                |
| SE             | 237                           | V mode : 5 units AC mode : 3 units | 21.0         | 193                           | V mode : 8 units          | –                |
| SW1            | 293                           | V mode : 2 units AC mode : 1 units | 19.0      | 292                           | V mode : 3 units          | –                |
| SW2            | 19.0                           | V mode : 2 units AC mode : 1 units | 19.0      | 292                           | V mode : 3 units          | –                |
| NW             | 136                           | V mode : 5 units AC mode : 3 units | 23.0      | 149                           | V mode : 8 units          | –                |
| Interior zone  | –                             | SA : 288                   | 19.0             | –                             | SA : 288                  | 15.0             |

*Converted to 60 m above ground level
"1" on the horizontal axis represents 0.5 to 1.4 m/s

Figure 6. Analytical model of planned building and surrounding buildings

Figure 7. Mesh diagram of analysis model

Figure 8. Wind rose (Temp. ≥ 15°C)

Figure 9. Wind speed distribution (Tokyo/Temp. ≥ 15°C)
4.4. Solar radiation conditions and air conditioning operation

Considering the solar load, the temperature distribution occurs over the entire floor, making it difficult to evaluate the difference in each TWU operating mode, so the solar radiation load was set to zero and the basic performance was confirmed. Because it is necessary to check the temperature distribution due to solar radiation, we assumed the solar radiation in August, during normal air-conditioning mode.

On the other hand, during airside economizer utilization, the solar radiation in the intermediate season of May, a low heat load is assumed. The design total solar radiation amount by month and orientation was used and the assumed time was 12 PM. The vertical solar radiation amount [2] in each direction and the air conditioning condition are shown in Table 3.

The air volume of the TWU’s indoor fan is 660 m³/h per unit. The indoor fan was operated as the supply air temperature to process solar radiation load in each direction because it automatically operates while changing the air supply temperature and air volume, so that the set room temperature will be reached. Moreover, in order to process the internal heat generation, the air volume of 38,340 m³/h is uniformly supplied at a temperature of 19°C from the 288 air supply diffusers on the ceiling surface of one floor.

5. Normal AC mode result

An indoor fan of the TWU operates for cooling and heating of the perimeter, and the outdoor fan of some of the TWU’s operate as “AC+V mode” and the others operate as “AC mode”. During conditions with no wind, 24 TWU’s out of 32, on one floor, were operated in the “AC+V mode” with the outdoor fan at low speed (480 m³/h/unit) operation and the remaining 8 units were in the “AC mode”. In both modes, the indoor fan was at high speed (660 m³/h/unit). In terms of control, the operation pattern of the TWU’s can be changed. The exhaust air (EA) volume of the outdoor fan of the TWU can be changed so that the CO₂ concentration in the room becomes the set value while the EA volume by occupancy changes.

Figure 10 shows the room temperature distribution plan/section at an outside temperature of 35°C, with no wind, and considering the amount of solar radiation at 12 o’clock PM in August. Figure 11 shows the airflow distribution/section. The room temperature is the result of FL (floor) +1.0 m in the occupied zone. The wind speed distribution shows the result of FL+0.1m, because the TWU’s draw indoor air from a slit at the bottom of the perimeter, so it is easy to understand the difference in air flow according to each air conditioning mode. In the following sentences, \( T_{ave} \) means the average room temperature (FL+0.0m~2.0m) in the office), \( V_{ave} \) means the average wind speed in the room (FL+0.1m). In normal air-conditioning, \( T_{ave} \) was 25.5°C. and \( V_{ave} \) was 0.11 m/s.

![Figure 10. Temperature distribution plan/section (Case C1_Temp. 35°C, No wind, FL+1.0m)](image1)

![Figure 11. Airflow distribution plan/section (Case C1_Temp. 35°C, No wind, FL+1.0m)](image2)
6. Air-side economizer mode result
During airside economizer utilization, the installed fresh air volume per floor by the AHU is increased to 28,400m$^3$/h (12m$^3$/h/m$^2$ of the office area), and the air is exhausted by outdoor fans from the TWU’s and the exhaust fans of the toilets. All TWU’s then operate in "V mode". The outdoor fans are operated at 840m$^3$/h/unit on high speed. During airside economizer use, the office on the west and eastern sides has 4.5 ACPH and the north side office has an ACPH of about 3.6.

Figure 12 shows the temperature distribution plan/section under windless conditions, and Figure 13 shows the airflow distribution plan/section. Both results are under windless conditions and the condition of solar radiation at 12 o'clock PM in May. $T_{ave}$ was 26.6°C and $V_{ave}$ was 0.12 m/s. A part of the south side perimeter into which the solar radiation penetrates is around 29.0°C, but the whole floor has reached room temperature of approximately 25.5°C to 27.5°C. Even when considering solar radiation and internal heat generation is at a maximum (51W/m$^2$), it was found that if the outside air temperature is about 15°C in the intermediate season, the thermal environment becomes close to that in the air conditioning mode. In actual operation, air conditioning operation of each TWU can also be performed by switch. It is also possible to cope with the thermal environment unevenness during airside economizer use, expanding the effective period. According to Figure 13, since the outside air supplied from the diffuser on ceiling surface is exhausted by the TWU installed in the perimeter zone, the airflow in the room flows slowly from the corridor side in the office to the perimeter zone at a wind speed of 0.3 m/s or less.

7. Night-time cool breeze mode.

7.1. Southern-south west wind condition
Figure 14 shows the wind speed distribution section, and Figure 15 and 16 show wind speed distribution at 30 m and 60 m above the ground. Figure 17 shows the wind pressure coefficient distribution in each direction. There are railway tracks on the south and west sides of the building which becomes an open space. As a result, the SSW wind does not decay, it hits the building, and the south side wall becomes windward under positive pressure.

At a height of 60 m or more, the wind speed is about 5m/s because the number of high-rise buildings is small in the surrounding area, therefore the wind pressure coefficient on the south facade is 0.5 to 1.0, and the wall pressure maximum is about 20 Pa. In particular, the central part of the south facade where the air supply grill is located tended to be higher than the others. On the other hand, the
north side wall surface was slightly negative pressure regardless of the height, the wind pressure coefficient was -0.2 to -0.4, and the wall pressure was about -5 Pa.

**Figure 17.** Wind pressure coefficient distribution in each direction (SSW wind)

7.2. Northern North-west wind condition

Figure 18 shows the wind speed distribution section, and Figure 19 and 20 show wind speed distribution at 30 m and 60 m above the ground. Figure 21 shows the wind pressure coefficient distribution in each direction. Because there are large buildings on the north side of the building and the north-northwest direction across the railway track, the wind speed declined until about 30 m in height from the north-northwest wind direction, and it became about 2.0 m/s even when the height was over 60 m.

The wind pressure coefficient was 0 to 0.4 and the wall pressure was about 10 Pa, regardless of the height on the north and west windward sides. A part of the south and east side façade facing leeward was at a negative pressure of -10 to -20 Pa at a height of 60 m or more. Whereas, during north wind conditions, the wind speed did not attenuate due to the influence of the large building on the north and the north-northwest direction across the railway track.
8. Indoor Environment Result

Table 4 shows the results of ventilation volume and ventilation air changes per hour in each wind direction on the 3 floors (7F, 11F, 15F) of the reference floor as the analysis target. During night-time cool breeze mode, a good indoor environment of about 23 to 26°C was achieved by the cooling effect of about 3 ACPH. It was confirmed that by conducting precise analysis on the whole building, a stable effect was achieved regardless of the difference in height and wind direction. Under windless conditions, the exhaust air volume of the TWU was 527 m³/h/unit for all units because the exhaust air volume decreased from the air supply louver more than the rated value, due to pressure loss through the corridor and bypass duct. The ventilation volume was about 17,000 m³/h (2.9 ACPH). The $T_{ave}$ was about 26.0 °C, the $V_{ave}$ was about 0.11 m/s.

| Floor (Height) | C3 (No wind) | C3_South-South West (SSW) | C3_North-North West (NNW) | C3_North (N) |
|----------------|---------------|---------------------------|---------------------------|--------------|
| 15F (72m)      | 19,370 m³/h (3.3ACPH) | 18,730 m³/h (3.2ACPH)   | 18,610 m³/h (3.3ACPH)   |               |
| 11F (54m)      | 19,280 m³/h (3.3ACPH)  | 18,780 m³/h (3.2ACPH)   | 18,690 m³/h (3.3ACPH)   |               |
| 7F (37m)       | 17,740 m³/h (3.0ACPH)  | 17,400 m³/h (3.0ACPH)   | 17,330 m³/h (3.0ACPH)   |               |

8.1. South-south west wind result

Figures 22 and 24 show the temperature distribution for 7F and 15F, and Figures 23 and 25 show the relationship between the exhaust air flow rate of the TWU, and the indoor/outdoor pressure difference. The $T_{ave}$ in 7F, 11F, 15F was about 23.5 ~ 26.0 °C, the $V_{ave}$ was about 0.16 m/s.

The EA volume of each TWU varied between the negative pressure side and the positive pressure side of the entire building. On one hand, more than 500 m³/h/unit, which is close to the minimum, was secured even in the TWU on the south side on the 15F. On the other hand, the TWU’s on the east, west and north sides became more than 600 m³/h/unit. The upper floors tended to increase the EA volume by each TWU because the pressure difference between indoor and outdoor became smaller on the negative pressure side. In a SSW wind, the outside air intake is on the windward side on the south side of the building, so it is concluded that the larger the wind pressure coefficient is on the higher floors, the larger the amount of outside air introduced by wind pressure is influenced.

8.2. North Northwest Wind Result

From Table 4, even during a NNW wind, where the outside air intake on the south side is on the leeward side, the ventilation volume per floor was not greatly different from that in a SSE wind. The variation of the wind pressure coefficient due to the difference in height is smaller than that in Figure 24, so the variation in the ventilation amount due to the floor height is also small. The $T_{ave}$ was about 24.5 °C and the $V_{ave}$ was about 0.16 m/s on either of the 3 floors.
9. Conclusion and Discussion
In this report, CFD analysis was carried out on an office building using a new air conditioning system with an improved through-wall air conditioner. CFD analysis, with consideration of surrounding buildings, was conducted utilizing BIM data and the outdoor fan characteristics of the TWU by actual experiments. In airside economizer mode, by exhausting the indoor air with the outdoor fan of the TWU, it was possible to ensure a sufficient ventilation rate of about 4.5 ACPH, without any wind. Even under the condition that considers the solar radiation and the internal heat generation, in the intermediate seasons, it turns out that the thermal environment becomes close to that of the the air conditioning mode. In the cool breeze ventilation mode, during night-time, a good indoor environment of about 23 to 26°C was achieved by the cooling effect of about 3 ACPH. It was confirmed that by conducting precise analysis on the whole building, a stable effect was achieved regardless of the difference in height and wind direction. Since the ventilation rate is also 2.9 ACPH under windless conditions, by using the TWU exhaust fan, the stability of natural ventilation effect, independent of wind presence and wind direction, was confirmed.

References
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Figure 22. Temperature distribution plan (15F_FL+1.0m)

Figure 23. TWU EA volume & wind pressure (15F_SSE wind)

Figure 24. Temperature distribution plan (7F_FL+1.0m)

Figure 25. TWU EA volume & wind pressure (7F_SSE wind)

*The numbers in the figure indicate the device numbers of the TWU.