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# Wind Environment Assessment around High-Rise Buildings through Wind Tunnel Test and Computational Fluid Dynamics

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**Abstract** High-rise buildings constructed adjacent to low-rise structures experience frequent damage caused by the associated strong wind. This study aimed to implement a standard evaluation of the wind environment and airflow characteristics around high-rise apartment blocks using wind tunnel tests (WTT) and computational fluid dynamics (CFD) simulations. The correlation coefficient between the CFD and wind tunnel results ranged between 0.6–0.8. Correlations below 0.8 were due to differences in the wake flow area range generated behind the target building according to wind direction angle and the effect of the surrounding buildings. In addition, a difference was observed between the average velocity ratio of the wake flow wind measured by the WTT and by the CFD analysis. The wind velocity values of the CFD analysis were therefore compensated, and, consequently, the correlations for most wind angles increased.

**Keywords** Wind tunnel test, computational fluid dynamics, wind environment, velocity ratio.

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## 1. Introduction

Building wind or wind damage refers to the environmental damage caused by strong wind occurring around large buildings. The building wind damage frequently occurs around high-rise buildings built between low-rise buildings. Strong airflow in the sky is blocked and redirected by high-rise buildings toward the ground. The strength of wind encountered in everyday life is not only associated to the magnitudes of the wind speed but also the wind frequency, as wind damage is mostly caused by sudden strong wind, which pertains to wind frequency. Therefore, wind environment assessment ought to consider those criteria that combine the magnitude and frequency of the wind speed. Penwarden (1975), Gandemer (1982), and Murakami (1986) proposed methods for predicting the wind speed and its occurrence frequency that affect humans. Davenport (1972) and Melbourne (1978) proposed a method for measuring the wind speed occurrence frequency (e.g., once a week, once a month, and once a year) and predicting the wind speed accordingly. In addition, the criterion for wind environment assessment is the wind speed at the measurement location. The wind speed varies on an average or instantaneously, depending on the assessment time, together with the variation according to the height from the ground. Therefore, when the wind environment assessment criteria of each country are compared and examined, the following parameters influencing the wind speed ought to be clarified: (1) the measurement height (the height specified for assessment), (2) wind speed type (e.g. mean wind speed, gust wind speed, and effective wind speed), (3) averaging time for mean wind speed, (4) assessment time for gust wind speed, and (5) value of the turbulent component magnification factor for effective wind speed. The measurement height can be divided into two heights. As a height of 10 m from the ground is generally used as the standard wind speed measurement height by local meteorological agencies, it has been adopted as the indicator height in some standards. Many standards, however, adopt an indicator height of 1.5-2.0 m from the ground, considering the height of humans who are affected by wind. For the averaging time, the one-hour average is used as the wind speed for assessment in Europe and the United States according to Penwarden (1975). In addition, Murakami et al. (1986) proposed the annual mean wind speed as a criterion. Davenport (1975) and Lawson (1975) proposed the Beaufort number, to allow ordinary people to conduct wind environment assessment with relative ease. For predicting wind environment around buildings in urban areas, the wind tunnel test (WTT) and computational fluid dynamics (CFD) simulations have been used globally. For the WTT, it is possible to accurately predict the wind

environment of the analysis target; however, there are limitations in predicting the overall wind environment, owing to the limited measurement locations and the time required to prepare marginal models. CFD can predict the overall wind environment of the analysis target, however possesses limitations in the analysis time and the accuracy of the predicted wind speed in urban areas because of turbulence models. In recent years, various studies have been conducted on CFD for turbulent flow environment. In this study, the wind environment around high-rise apartment buildings was comparatively assessed with respect to the WTT and CFD results.

## 2. Wind Environment assessment

### 2.1. Murakami criteria

Murakami's assessment criteria (Murakami et al., 1986) use the daily wind condition as a measure. The daily wind speed indicator was used because humans experience a daily cycle. In addition, the use of the daily wind speed indicator considerably simplifies statistical calculations, because the number of wind speed occurrences becomes the number of days. Murakami analyzed the relationship between the impression of wind or the degree of environmental damage and the wind speed over two years through the experiences of residents in low-rise houses in the vicinity of 14-story apartments. Table 1 shows the wind environment assessment criteria for the allowable frequency of the daily maximum gust wind speed based on the results. The assessment time of the wind speed indicator used for assessment was 2-3 s, and the daily maximum gust wind speed at a measurement height of 1.5 m was used. The wind speeds included for the assessment were 10, 15, and 20 m/s. For the three daily maximum gust wind speeds, 10 m/s represents the speed at which garbage is blown up or laundry is blown away; 15 m/s represents the speed at which signboards and bicycles fall over or walking is difficult. 20 m/s indicates the speed at which people feel that they can be blown away by the wind. Areas for wind environment assessment were divided into three ranks considering the residence time and the degree of influence by wind. In addition, when the mean wind speed was used for the assessment, the daily maximum gust wind speed (wind speed for assessment) was converted into the daily maximum mean wind speed by dividing it by the gust factor (G.F.). G.F. ranges from 1.6–3.0 for places with strong wind and from 2.0-3.5 for urban areas.

Wind speed measurements are discrete, and a frequency distribution can be drawn using the number of measurements within a certain measurement period. A theoretical probability distribution was applied to this frequency distribution, which was used for various analyses, such as the prediction of the strong wind occurrence frequency. The wind speed occurrence frequency was expressed by the Weibull distribution shown in Eq. (1). In addition, it was confirmed that the daily maximum mean wind speed and daily maximum gust wind speed can be sufficiently approximated by the Weibull distribution. As the mean values are addressed in the typical WTT, the occurrence frequency of the daily maximum mean wind speed was obtained.

$$P(V_g > V_{g1}) = \sum_n A(a_n) \cdot exp\left[-V_{g1}/C(a_n)\right]^{k(a_n)} \quad (1)$$

where $P(V_u > V_1)$ represents the frequency at which the wind speed is at the reference location; $V_g$ exceeds $V_{g1}$; $A(a_n)$ denotes the occurrence frequency for a given wind direction, $a$ (%); $c(a_n)$, $k(a_n)$ represents the Weibull coefficient.

The velocity ratio between the wind speed at the assessment location, $i$, on the ground obtained from the WTT ($V_i$) and the wind velocity at the sky ($V_g$) is given as:

$$R_i(a_i) = \frac{V_i(a_n)}{V_g(a_n)} \quad (2)$$

Substituting Eq. (2) into Eq. (1), the wind speed exceedance frequency at the assessment location on the ground can be

**Table 1**. Criteria for the assessment of pedestrian wind environment based on the occurrence frequency of strong wind

| Rank | Effect of strong wind | Level of assessment of strong wind and acceptable exceedance frequency | | |
|---|---|---|---|---|
| | | Daily maximum gust wind speed (m/s) | | |
| | | 10 | 15 | 20 |
| | | Daily maximum mean wind speed (m/s) | | |
| | Areas applicable | 10/G.F. | 15/G.F. | 20/G.F. |
| 1 | Areas used for purposes most susceptible to wind effects<br>Outdoor restaurant Open shopping | 10%<br>(37 days per year) | 0.9%<br>(3 days per year) | 0.008%<br>(0.3 days per year) |
| 2 | Areas used for purposes not too susceptible to wind effects<br>Residential area park | 22%<br>(80 days per year) | 3.6%<br>(13 days per year) | 0.6%<br>(2 days per year) |
| 3 | Area used for purpose least susceptible to wind effects<br>Office street | 35%<br>(128 days per year) | 7%<br>(26 days per year) | 1.5%<br>(5 days per year) |

**Table 2**. Occurrence frequency and Weibull coefficient with respect to wind direction (Ulsan meteorological observatory)

| Wind Direction | N | NNE | NE | ENE | E | ESE | SE | SSE |
|---|---|---|---|---|---|---|---|---|
| A(a) | 5.76 | 7.59 | 7.59 | 8.31 | 7.30 | 7.22 | 5.74 | 2.80 |
| c(a) | 6.48 | 6.63 | 6.51 | 6.16 | 5.78 | 5.76 | 5.51 | 6.28 |
| k(a) | 3.34 | 3.46 | 3.45 | 3.53 | 3.29 | 3.32 | 3.60 | 2.93 |
| Wind Direction | S | SSW | SW | WSW | W | WNW | NW | NNW |
| A(a) | 4.49 | 4.81 | 3.95 | 3.54 | 5.50 | 9.01 | 10.57 | 5.84 |
| c(a) | 7.01 | 7.40 | 7.30 | 7.40 | 7.88 | 8.03 | 7.36 | 6.43 |
| (a) | 3.34 | 3.29 | 3.12 | 3.07 | 3.22 | 3.25 | 3.18 | 3.16 |

The unit of A(a) is %.

obtained as follows:

$$P(V_i > V_1) = \sum_n A(a_n) \cdot exp\left[-\left(\frac{V_1/R_i(a_n)}{C(a_n)}\right)^{k(a_n)}\right] \quad (3)$$

where $P(V_i > V_1)$ represents the frequency at which the wind speed is at the assessment location on the ground; $V_i$ exceeds $V_1$; $A(a_n)$ denotes the occurrence frequency for a given wind direction.

Table 2 shows the occurrence frequency and Weibull coefficient of the daily maximum wind speed measured at the Ulsan meteorological observatory from 1979 to 2019 with respect to wind direction. Based on the daily maximum wind speed data from the observatory, the Weibull coefficient was calculated by homogenizing the wind speed according to the ground surface roughness of the target location, considering the anemometer height of the observatory, altitude of the target location, and ground surface roughness.

## 3. Wind tunnel test and CFD ANALYSIS

### 3.1. Wind Tunnel Test

The WTT was conducted in an open wind tunnel device with the measurement space of 2.0 m (width) × 1.7 m (height) × 12 m (length), located in the Jeonbuk National University. As it is located in a low-rise residential area around apartment complexes, a turbulent boundary layer airflow corresponding to the ground surface roughness, C (α = 0.15), was adopted in the wind tunnel. The reference height of the wind environment experiment was set to 20 m, which reflects the anemometer installation height of the Ulsan meteorological observatory and the altitude of the target location, was set to 6.6 cm in the model scale. The experimental wind speed used 4 m/s at the reference height. Figure 1 shows the distribution of the mean wind speed and turbulence intensity with respect to height in the wind tunnel. The solid line represents the values obtained using the theoretical formula.

### 3.2. Experimental model and measurement method

The wind environment experiment was performed at 22 locations within the complex with two apartment buildings. Wind environment experimental model was prepared at a scale of 1:300. Figure 2 shows the measurement locations.

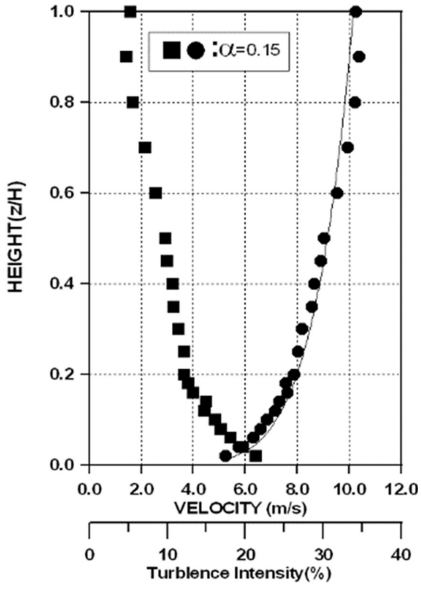



**Figure 1.** Distribution of velocity and turbulence intensity in wind tunnel.

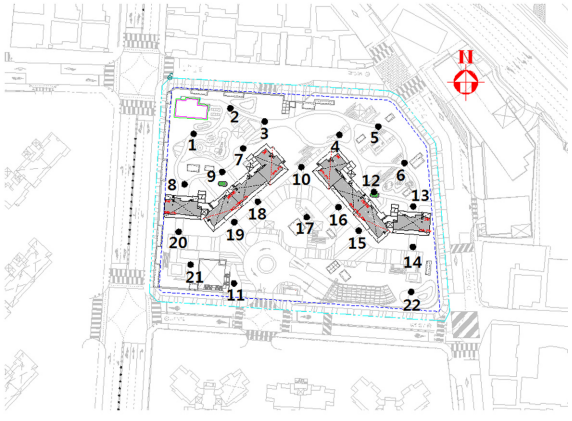



**Figure 2.** Three-dimensional (3D) modeling for entire domain.

### 3.3. Computational Fluid Dynamics

On obtaining the velocity ratio through CFD analysis, to predict the airflow around the buildings, the wind environment was assessed similarly as in the WTT through a computational model that replicated the city using

**Table 3**. Conditions adopted for computational fluid dynamics (CFD) analysis

| | | |
|---|---|---|
| Domain size | | 3.0 m × 3.0 m × 0.5 m |
| Scale | | 1/300 |
| Program | | SC Stream V13 |
| Mesh | | About 6,000,000 |
| Turbulence model | | Standard K-$\varepsilon$ Turbulence Model |
| Terrain category | | C ($\varepsilon$ = 0.15) |
| Reference Velocity | | 4 m/s |
| Reference Height | | 6.6 cm (20 m) |
| Scheme for convection terms | | Quick |
| Convergence criteria | | 1e-05 for all variables |
| Boundary condition | Inlet | Velocity inlet (Power-law) |
| | Outlet | Pressure outlet |
| | Top | Free-slip |
| | Bottom | Power-law wall shear stress condition |

CAD. The wind environment was predicted by dividing the space above the model in detailed (grids) and by numerically analyzing the equations that describe the flow. Despite the advanced computational performance of computers, it was not easy to directly solve the equations for complex flows such as building wind. The equations that describe the flow were converted into models to obtain the solutions even if the grid size increased. Reynolds averaged Navier-Stokes simulation (RANS) is used in most studies addressing building wind. Therefore, RANS modeling is used in this study. The input and analysis conditions for CFD are listed in Table 3. Figure 3 shows Three-dimensional (3D) modeling for entire domain.

## 4. Analysis results and discussion

The WTT results were expressed using the velocity ratio, and its definition is given by Eq. (4), as follows:

$$R_i = \frac{U_i}{U_r} \tag{4}$$

where $R_i$ is the velocity ratio at measurement location, $i$; $U_i$(m/s) is the mean wind speed at the measurement location, $i$; and $U_r$ is the mean wind speed (m/s) at the reference point.

The velocity ratio is an important parameter that draws the relationship between the WTT results and the actual situation. This is because the velocity ratio is assumed to be a constant irrespective of the wind speed at the reference point. In general, if the reference point is assumed to be a meteorological observatory, the result of the WTT can be replaced with the actual wind speed.

### 4.1. Wind tunnel test results

The exceedance frequency at each measurement location in the apartment complex according to the wind direction angle was obtained using Eq. (3) and Table 2. Figure 4 show the exceedance frequency at each measurement location. The Murakami assessment criteria in Table 1 were used as the wind environment assessment criteria at each measurement location. Based on the mean wind speed values measured from the WTT, the urban wind environment was assessed using the daily maximum mean wind speed of 5 m/s, which was obtained using G.F. = 2.0 for the daily maximum gust wind speed of 10 m/s. Most measurement results were lower than the charac-teristics of a typical urban wind environment. However, at the measurement location 10, where valley wind blows between the two

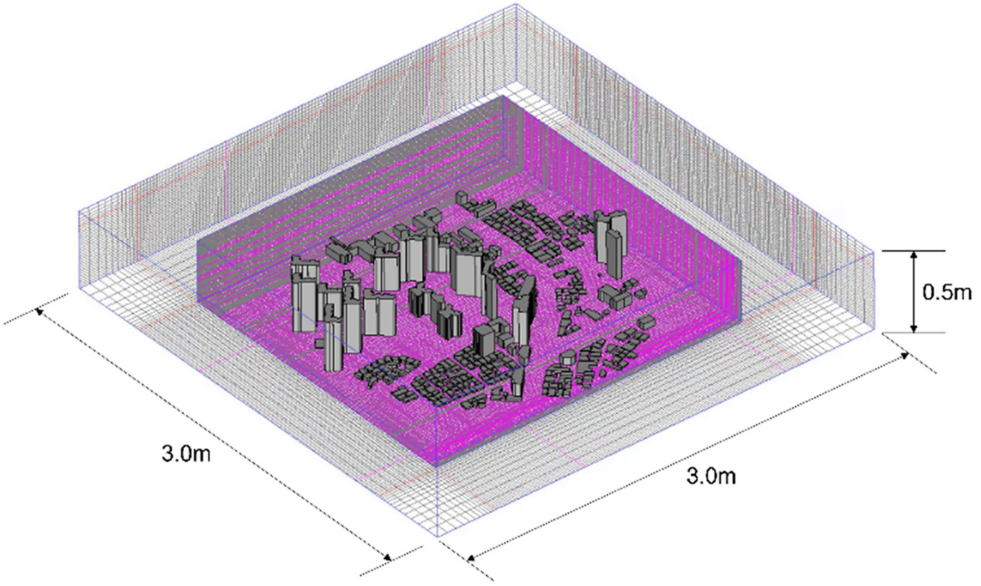



**Figure 3.** Three-dimensional (3D) modeling for entire domain.

**Table 4.** Correlation coefficient by wind direction.

| Wind direction | Correlation coefficient | Wind direction | Correlation coefficient |
|---|---|---|---|
| N | 0.703 | S | 0.733 |
| NNE | 0.723 | SSW | 0.643 |
| NE | 0.674 | SW | 0.723 |
| ENE | 0.720 | WSW | 0.768 |
| E | 0.683 | W | 0.671 |
| ESE | 0.791 | WNW | 0.716 |
| SE | 0.840 | NW | 0.686 |
| SSE | 0.752 | NNW | 0.692 |

| Wind direction | Correlation coefficient | | Wind direction | Correlation coefficient | |
|---|---|---|---|---|---|
| | No wake zone | Wake zone | | No wake zone | Wake zone |
| N | 0.659 | 0.693 | S | 0.870 | 0.433 |
| NNE | 0.738 | 0.681 | SSW | 0.907 | 0.421 |
| NE | 0.658 | 0.681 | SW | 0.732 | 0.457 |
| ENE | 0.850 | 0.438 | WSW | 0.604 | 0.629 |
| E | 0.811 | 0.748 | W | 0.723 | 0.490 |
| ESE | 0.706 | 0.673 | WNW | 0.813 | 0.521 |
| SE | 0.863 | 0.772 | NW | 0.845 | 0.545 |
| SSE | 0.695 | 0.613 | NNW | 0.816 | 0.720 |

apartment buildings, the wind speed was higher than that of a typical urban wind environment. At measurement locations 5, 14, 15, 18, and 19, the measure-ments were lower than RANK 1. At measurement locations 10, 11, 17, and 21, a distribution of values higher than RANK 2 was observed. Therefore, according to Murakami assessment criteria, the predicted frequency of the wind speed corresponded to office streets rather than residential areas. At the measurement location 17, the influence range of the valley wind between apartment buildings from the measurement location 10 could be predicted. At measure-ment locations 11 and 21, however, it appeared that the wind speed increased because of the valley wind from other apartment complexes in proximity to the target apartment complex.

### 4.2. CFD analysis results

For CFD, the Standard K–$\varepsilon$ model, which is practically and commonly used, was used for turbulence modeling. A wall function approach was adopted for wall boundary conditions. The dimensions of the analysis domain were 3.0 m (X-direction) × 3.0 m (Y-direction) × 0.5 m (Z-direction), and the number of grid cells of the analysis model was approximately 6,000,000. The dimensionless wall distance (y+) is about 12.5. the CFD analysis software was used scSTREAM V13, and the CFD conditions are shown in

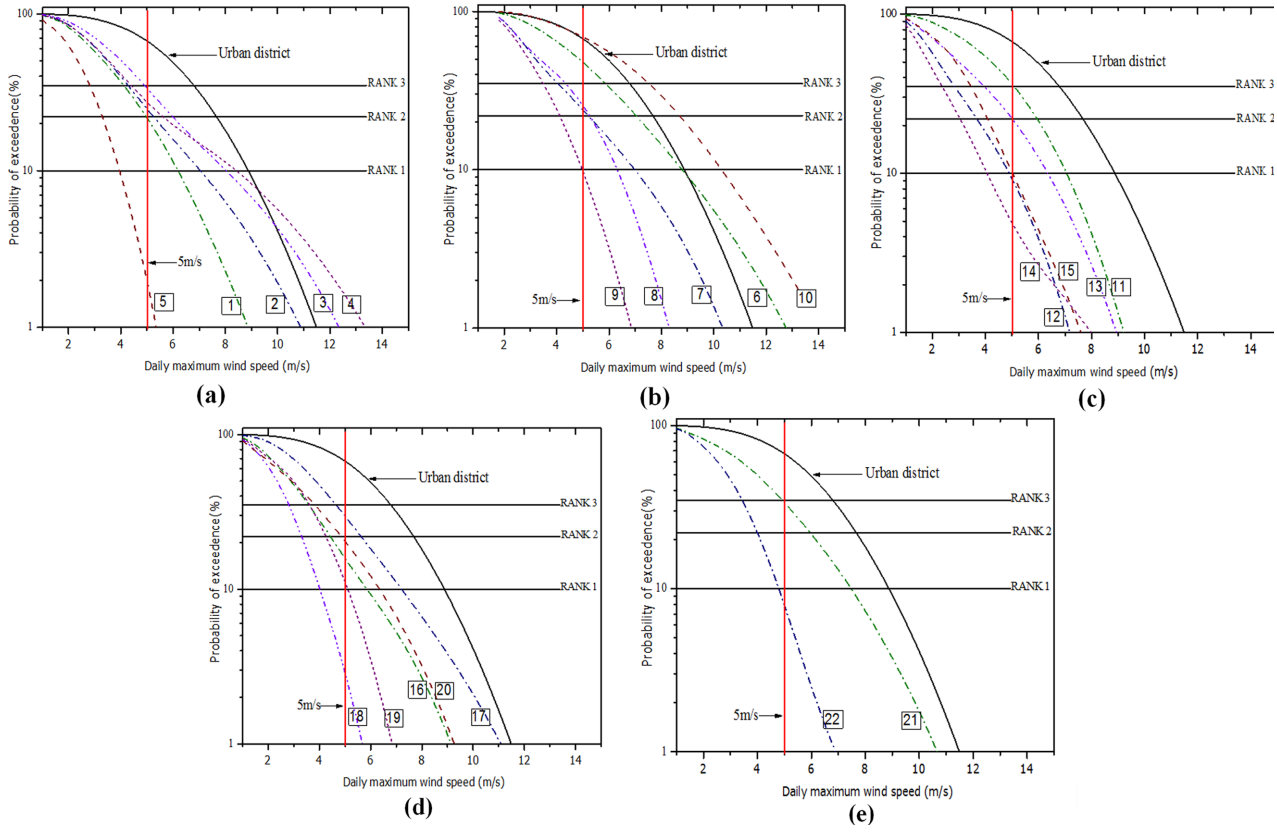



**Figure 4.** Probability of exceedance by measurement location: (a) measurement locations 1–5; (b) measurement locations 6–10; (c) measurement locations 11–15; (d) measurement locations 16–20; and (e) measurement locations 21 and 22.

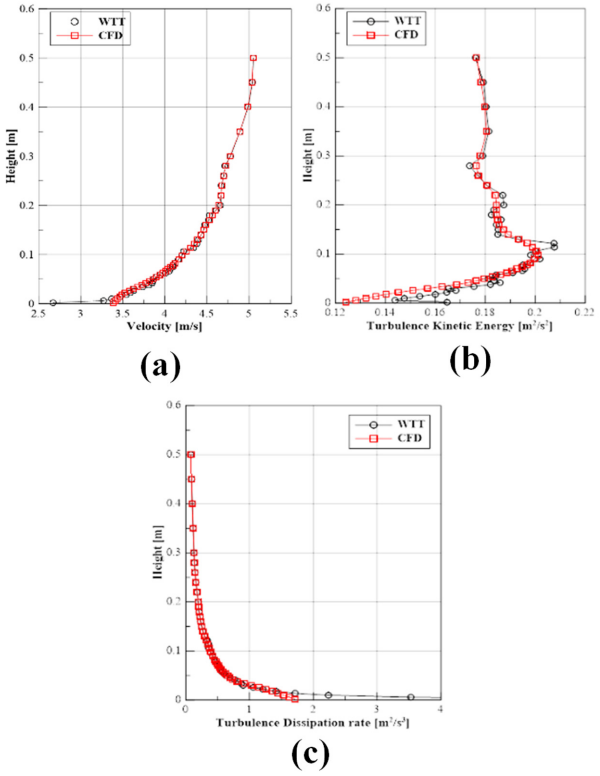



**Figure 5.** Distribution of inflow: (a) velocity, (b) turbulence energy, and (c) turbulence eddy dissipation.

Table 3. Figure 5 shows the wind speed, turbulence energy, and turbulence dissipation rate of inflow, according to the height obtained from CFD. The turbulence energy and turbulence dissipation rate of inflow were calculated using the turbulence intensity and wind speed measured through the wind tunnel experiment.

To verify CFD, the correlation coefficient was obtained by comparing the velocity ratio at each location, measured in the WTT for 16 wind directions, with the corresponding velocity ratio obtained from the CFD analysis results. The correlation coefficient is given by Eq. (5), as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{(n-1)s_x s_y} \quad (5)$$

where $\bar{x}, \bar{y}$ represent the mean values of $x$ and $y$, respectively; and $S_x$, $S_y$ are the standard deviations of x and y, respectively.

Table 4 shows the correlation coefficient between the WTT and the CFD analysis for each wind direction. Figure 6 shows the velocity ratio distribution obtained from the CFD analysis results. Figure 6(a) shows the velocity ratio distribution of the entire site of the analysis target when the wind direction was from the Southeast (SE) with a correlation coefficient of 0.840, whereas Figure 6(b) shows the distribution when the wind direction was from the South-Southwest (SSW) with a correlation coefficient

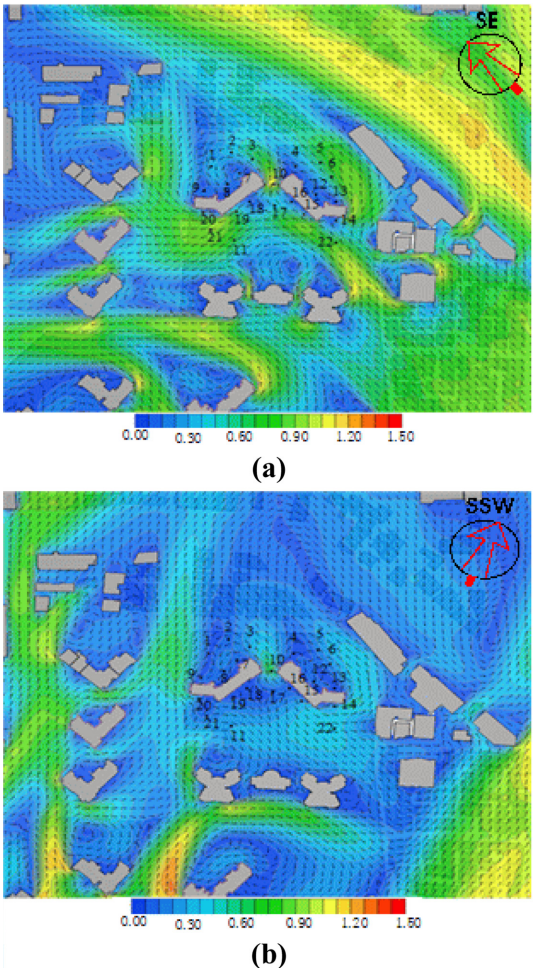



**Figure 6.** Velocity ratio distribution denoted by directional arrows, and the measurement locations numbered from 1-22. (a) Southeast; (b) South-Southwest.

of 0.643. The correlation coefficient values for each angle ranged from 0.6-0.8. The correlation coefficient values close to 0.6 were considered to be affected by the surrounding buildings and the wake zone generated behind the target building. Therefore, the correlation coefficient was analyzed separately in the wake zone and no-wake zone for each angle around the target building. Table 4 shows the correlation coefficient in the wake zone and no-wake zone according to the wind direction. Most correlation coefficient values close to 0.6 (0.421-0.748) in Table 4 were distributed in the wake zone; however, the no-wake zone showed relatively high correlation coefficient values (0.604–0.907). This confirmed that the CFD prediction results underestimated the wind speed, in comparison to the WTT in the wake zone. This could be because the calculation results may be affected by the prediction of the separated shear layer under the influence of the difference in the reproduction of building geometry.

### 4.3. Wind speed correction

The mean wind speed in the wake zone was considered

to be different between the WTT and CFD analysis, because the definition of the mean wind speed that can be obtained from the CFD analysis was different from the measurement of the anemometer used in the WTT. Therefore, the wind speed in the CFD analysis results was corrected. The wind speed measured using a thermistor anemometer is given by Eq. (6):

$$\begin{aligned}\overline{(U^2+V^2+W^2)^{1/2}} &= \overline{\{(\bar{U}+u')^2+(\bar{V}+v')^2+(\bar{W}+w')^2\}^{1/2}} \\ &= \{\bar{U}^2+\bar{V}^2+\bar{W}^2+\overline{(u'^2+v'^2+w'^2)}\}^{1/2} \\ &= (\bar{U}^2+\bar{V}^2+\bar{W}^2+2k)^{1/2}\end{aligned} \tag{6}$$

where, $U$, $V$, $W$ represent the gust wind speed (m/s) in each cartesian coordinate direction, $\overline{U},\overline{V},\overline{W}$ is the mean wind speed (m/s) in each cartesian coordinate direction, $u',v',w'$ represent the fluctuating wind speed (m/s) in each direction, and $k=\frac{\overline{u'^2+v'^2+w'^2}}{2}$ is the turbulence energy ($m^2/s^2$).

The wind speed shown in the RANS model of CFD analysis, is the scalar wind speed obtained from the average component of the wind speed in each direction and is defined as shown in Eq. (7):

$$(\overline{U}^2+\overline{V}^2+\overline{W}^2)^{1/2} \tag{7}$$

which is smaller by $2k$, for the wind speed obtained through CFD, when compared to the that measured using a thermistor anemometer. Therefore, the CFD analysis results were corrected by obtaining the average component of each component and turbulence energy ($k$). Table 5 shows the correlation coefficient for each wind direction after wind speed correction, which showed increments in most wind directions despite decrements in some wind directions as the wind speed value increased. Figure 7 shows the WTT and CFD analysis results for each measurement location according to the wind direction. It can be observed that the change in the correlation coefficient according to the wind direction was significantly affected by the surrounding buildings. For the wind directions in which airflow was blocked by the surrounding buildings, the wake zone was large and the wind speed at the measurement locations in the wake zone was evaluated to be low, resulting in low correlation coefficient values close to 0.6. In the case of the wind directions in which the introduction of airflow was easy because of the long distance between buildings or the long distance from the surrounding buildings, the wake zone was small. Consequently, relatively high correlation coefficient values were observed.

**Table 5.** Correlation coefficient values with respect to wind direction after correction

| Wind direction | Correlation coefficient | Wind direction | Correlation coefficient |
|---|---|---|---|
| N | 0.799 | S | 0.786 |
| NNE | 0.703 | SSW | 0.728 |
| NE | 0.722 | SW | 0.827 |
| ENE | 0.691 | WSW | 0.801 |
| E | 0.680 | W | 0.679 |
| ESE | 0.822 | WNW | 0.729 |
| SE | 0.824 | NW | 0.693 |
| SSE | 0.807 | NNW | 0.739 |

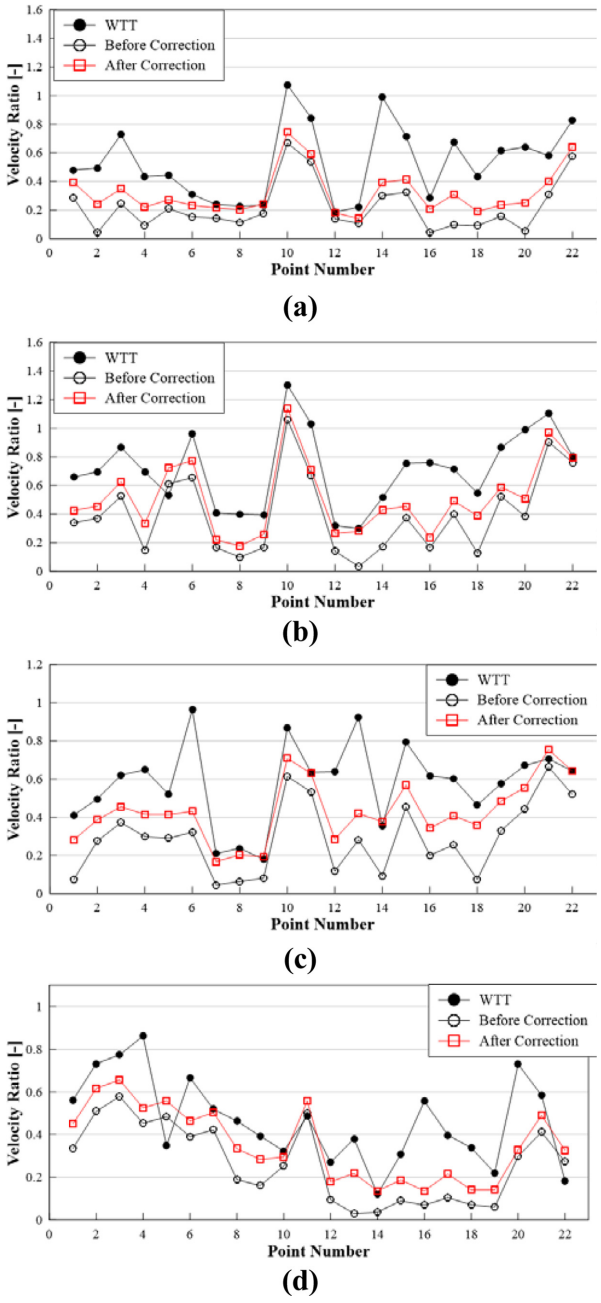



**Figure 7.** Velocity ratio with respect to wind direction: (a) Southwest; (b) Southeast; (c) East; and (d) West.

**Table 6.** Exceedance frequency of wind speed by measurement location

| POINT | Wind tunnel test results | | CFD analysis results | |
|---|---|---|---|---|
| 1 | 21.77 | RANK 2 | 19.82 | RANK 2 |
| 2 | 24.83 | RANK 3 | 21.41 | RANK 2 |
| 3 | 33.62 | RANK 3 | 27.98 | RANK 3 |
| 4 | 27.43 | RANK 3 | 22.59 | RANK 3 |
| 5 | 1.99 | RANK 1 | 0.66 | RANK 1 |
| 6 | 35.98 | N.G. | 29.04 | RANK 3 |
| 7 | 17.09 | RANK 2 | 14.42 | RANK 2 |
| 8 | 15.18 | RANK 2 | 11.10 | RANK 2 |
| 9 | 4.08 | RANK 1 | 1.76 | RANK 1 |
| 10 | 58.21 | N.G. | 44.52 | N.G. |
| 11 | 36.47 | N.G. | 27.96 | RANK 3 |
| 12 | 9.24 | RANK 1 | 3.92 | RANK 1 |
| 13 | 22.09 | RANK 3 | 21.73 | RANK 2 |
| 14 | 4.89 | RANK 1 | 2.16 | RANK 1 |
| 15 | 11.17 | RANK 2 | 10.21 | RANK 2 |
| 16 | 15.83 | RANK 2 | 13.56 | RANK 2 |
| 17 | 29.64 | RANK 3 | 24.42 | RANK 3 |
| 18 | 2.86 | RANK 1 | dlf r0.39 | RANK 1 |
| 19 | 13.09 | RANK 2 | 11.21 | RANK 2 |
| 20 | 20.39 | RANK 2 | 17.42 | RANK 2 |
| 21 | 33.73 | RANK 3 | 26.23 | RANK 3 |
| 22 | 7.93 | RANK 1 | 5.21 | RANK 1 |

### 4.4. Exceedance frequency analysis

Table 6 show the exceedance frequency of wind speed with respect to the measurement locations obtained from the WTT and CFD analysis. For the wind environment assessment criteria, the RANK areas proposed in Table 1 were compared. Overall, the exceedance probability of the CFD analysis was lower than that of the WTT. The wind environment assessment of the WTT and CFD analysis, however, showed similar RANK areas.

## 5. Conclusions

In this study, wind environment assessment was conducted for 22 measurement locations in an apartment site with two apartment buildings, through WTT and CFD analysis. The following conclusions can be drawn from the study:

1. The correlation coefficient between the CFD and WTT results ranged from 0.6-0.8. The correlation coefficient values lower than 0.8 were considered to be affected by the surrounding buildings and the difference in the wake zone generated behind the target building depending on the wind direction. The correlation coefficient obtained through separately analyzing the wake zone and no-wake zone were found to be 0.421-0.748 (relatively low) and 0.604-0.907 (relatively high), respectively.

2. The mean wind speed in the wake zone was different between the WTT and CFD analysis, because the definition of the mean wind speed in the CFD analysis was different from the measurement of the anemometer used in the WTT. Therefore, the wind speed of CFD analysis was corrected. Consequently, the correlation coefficient increased in most wind directions.

3. The WTT results showed that most measurements at the twenty-two measurement locations were lower than the characteristics of a typical urban wind environment. When the wind environment of the apartment complex was assessed based on the WTT results RANK 2 (residential area) criterion was predominantly observed. However, the measurement locations 10, 11, 17, and 21 exhibited the characteristics of RANK 3 (Office street). At the locations where valley wind blows between the two apartments buildings and the locations affected by the valley wind from the surrounding buildings, high exceedance probability values were observed as the wind speed increased. For these locations, wind environment measures are required.

4. The exceedance probability of the wind speed at each measurement location was obtained from the WTT and CFD analysis. Overall, the exceedance probability of CFD analysis was lower than that of the WTT. The wind environment assessment of the WTT and CFD analysis, however, showed similar RANK categories.

## Acknowledgments

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