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Wind-induced turbulent ventilation for a simplified building using large-eddy simulation

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SUMMARY

Turbulence-driven ventilation plays an essential role in differentiating nominal and effective ventilation rates, especially when an opening is located on a wall parallel to the dominant flow direction. To establish a method for appropriately evaluating the contribution of turbulence to effective ventilation, this study conducted a large-eddy simulation on the airflows around a cross-ventilation model with two opposing openings on the side walls. The simulation results were carefully validated against a wind-tunnel experimental dataset obtained by particle image velocimetry, which provides spatial distributions of the velocity components on both indoor and opening planes. The mechanism of turbulence-induced ventilation is mainly discussed using the unsteady three-dimensional flow fields at the ventilation opening. Mean and turbulent ventilation rates were directly determined using the velocity time series to quantify the impact of turbulent flow exchange via the opening. Based on this analysis, this study proposes a prediction method for turbulent ventilation rates.

Keywords: *Wind-induced ventilation, Large-eddy simulation, Wind-tunnel experiment*

1. INTRODUCTION

Wind-induced ventilation is a common passive way to introduce fresh air into indoor spaces. In general, ventilation through windows of buildings is classified into cross ventilation via two openings on the walls normal to the dominant wind direction, and side ventilation through an opening or openings on the side walls aligned with the flow (e.g., Adachi et al. 2020, Hirose et al. 2021). Wind-induced ventilation has been extensively studied in previous research by computational fluid dynamics and experimental approaches, and accordingly, it is well known that mean ventilation rates can be estimated using a steady-state model such as the orifice equation once the opening discharge coefficients are obtained (The Society of Heating, Air-Conditioning & Sanitary Engineers of Japan, 2017). However, owing to the unsteady outdoor turbulent flow around buildings and openings, ventilation is commonly affected by such turbulent airflows, causing accurate estimation of ventilation rates challenging using numerical simulations or experiments, especially for side-ventilation scenarios. This study aims to establish a method for appropriately evaluating ventilation performance in a side-ventilation case of a simplified building model. A large-eddy simulation (LES) was performed for airflows around and within the model. The same building model employed for a wind-tunnel experiment previously were used to validate the simulation results. Using the unsteady three-dimensional flow field at the ventilation opening obtained from the numerical fluid dynamics analysis, this study clarifies the mechanisms of turbulent ventilation phenomena.

2. METHODOLOGY

An LES of airflows around a side-ventilated building was conducted using OpenFOAM. The model is a cubical simplified block with a square opening at the center of each side wall. The model height is $H = 0.32$m and the opening size is $L = 0.1$m, giving 10% opening porosity. The simulation domain is $6.12 \times 2.2 \times 1.8$ m^3 in the streamwise, spanwise, and vertical directions, identical to a referencing wind-tunnel experiment (Wang et al. 2025), and the corresponding coordinates and velocity components are denoted as x, y, z and u, v, w. The experiment acquired the time-series data of the velocity components in indoor and opening plains using particle image velocimetry (PIV). Approximately 9.8 million hexahedral orthogonal cells were used to discretize the domain, with a local refinement around the ventilation model. The standard Smagorinsky model with the Smagorinsky constant $C_s = 0.12$ were employed as a turbulence model. The second-order backward and linear scheme were employed for the temporal and spatial derivative terms, respectively. The inlet turbulent airflow was separately calculated by reproducing the referencing wind-tunnel experiment with explicitly resolved barrier, spires, and roughness elements, and given to the simulation domain with the ventilation model. For the solid walls of the wind tunnel and building were treated as non-slip walls with the Spalding's wall function. A zero-pressure condition was applied at the outlet face.

Three ventilation rates are defined: Q_{net}, Q_{gross}, and Q_{inst}. Q_{net} is a nominal net ventilation rate defined by the average wind speed in the opening and opening area. Since Q_{net} in the present building model is theoretically zero due to the symmetry shape of the building and satisfying the continuity equation, Q_{gross} considers the reverse flow contribution by taking absolute values of the time averaged wind speed within the opening. In addition, the instantaneous ventilation rate Q_{inst} is defined to consider the contribution of the instantaneous reverse flow to the ventilation rates as follows.

$$Q_{inst} = \frac{1}{T}\int \sum_i |u_i| \Delta A_i dt \tag{1}$$

Since Q_{inst} can consider the accumulated exchange of air via the opening, it is more appropriate to evaluate the ventilation when turbulence effects dominate the ventilation rate. In the present building and opening condition, Q_{net}, or the opening-averaged wind speed, is ideally zero, Q_{gross} is slightly larger than zero because of the reverse flow, while Q_{inst} is non-zero due to the turbulent exchange of air, implying that we need to accurately estimate Q_{inst}. We propose a estimation model for Q_{inst}, denoted as Q_{est}, as follows.

$$Q_{est} = \frac{1}{N}\sum_n \sum_i |u_{nest}| \Delta A_i \tag{2}$$

$$u_{nest}(x, y, z, n) = \overline{u_n}(x, y, z) + Z(n)\sigma_{u_n}(x, y, z) \tag{3}$$

Here, $u_{n,i}$ denotes the wind velocity normal to the opening face, and ΔA_i denotes the area within the opening at computational grid i. T denotes the total sampling duration used for evaluating the ventilation rate, N is the number of samples within this period, and Z represents the standardized random variable following Gaussian distribution. $\overline{\phi}$ and $|\phi|$ denote the time-averaged value and absolute value of the variable ϕ, respectively.

3. RESULTS

3.1. Indoor flow distribution

Figure 1 shows the mean velocity components, $\overline{u}$ and $\overline{v}$, variances, σ_u^2 and σ_v^2, and Reynolds-shear stress $\overline{u'v'}$ obtained by LES and PIV in the horizontal cross-section at height $z/H = 0.5$. The areas enclosed by the red lines indicate regions that could not be measured due to experimental limitation. Figure 1 clearly demonstrates that the LES generates a symmetric flow field in terms of the mean flow patterns and turbulent statistics, indicating that the simulation time was sufficient. In addition, comparison between the LES and PIV results confirms that the simulation accurately produces these statistics similar to the PIV. However, two caveats should be noted: one is smaller values within the areas marked by the red dashed lines, and the other is that the predicted values of the turbulences seemingly be larger in the LES. Both of these are due to the unmeasured areas near the openings in the experiments. Due to page limitations, the results of the validation metrics (e.g., hit rate and FAC2) are presented and discussed in the presentation.

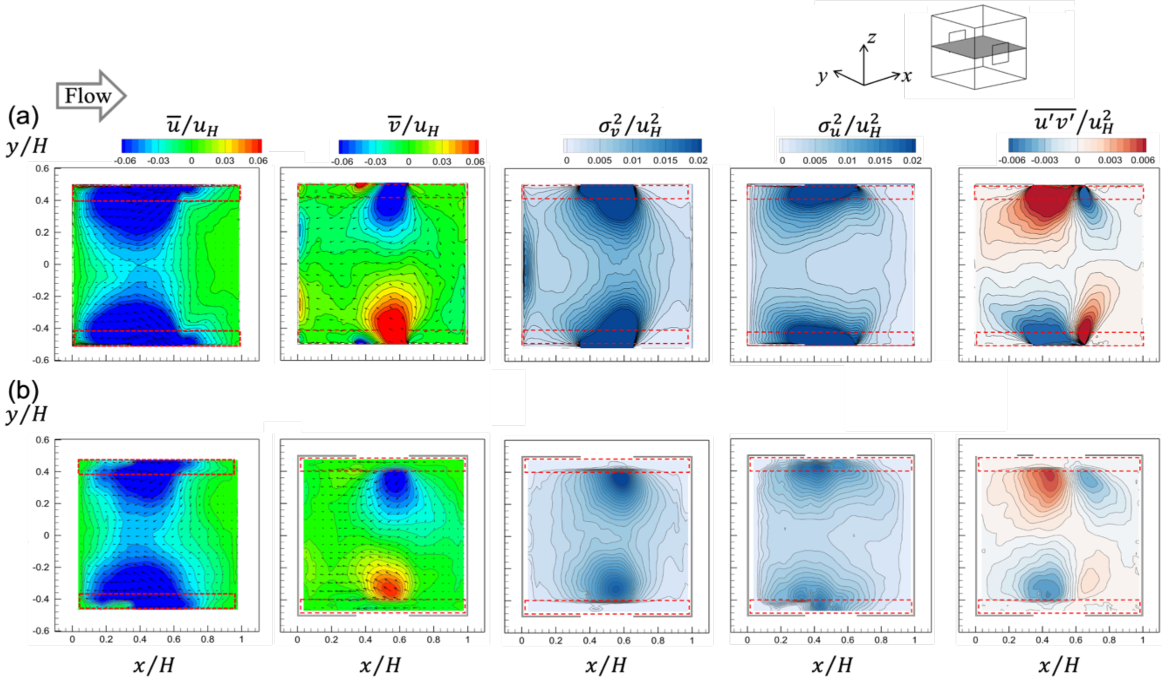

Figure 1: Spatial distribution of mean velocity components $\overline{u}$ and $\overline{v}$, velocity fluctuations σ_u^2 and σ_v^2, and Reynolds shear stress $\overline{u'v'}$ obtained by (a) LES and (b) PIV in the horizontal cross-section at height $z/H = 0.5$

3.2. Ventilation rate

Figure 2 shows a comparison of the three types of the ventilation rates obtained by the WTE and LES. For the various ventilation rates, the LES results agree well with those of the WTE results, confirming that ventilation performance can be evaluated based on the LES data. Q_{net} is nearly zero as expected, while Q_{gross} is around 0.05 because the inflow and outflow concurrently occur in the time averaged velocity fields. Furthermore, Q_{inst} is dramatically larger than Q_{gross}, indicating both inflow and outflow instantly occur and contribute to the accumulated air exchange.

In addition to the evaluation, our prediction model shows that Q_{est} can also approximate the Q_{inst} with good accuracy. Since the model needs the spatial distribution of the mean and standard deviation of the opening-normal wind speed, Q_{inst} based on these statistics at one, three, and nine points in the opening was calculated. The ratios between Q_{inst} and that based on the nine points and three points are 98% and 90%, respectively, demonstrating Q_{inst} can be estimated using limited numbers of data within the opening. By reducing the measurement points to one point at the center of the opening, the ratio decalins to 78%. Therefore, it is demonstrated that the instantaneous ventilation rate can be reliably estimated from appropriately selected representative points.

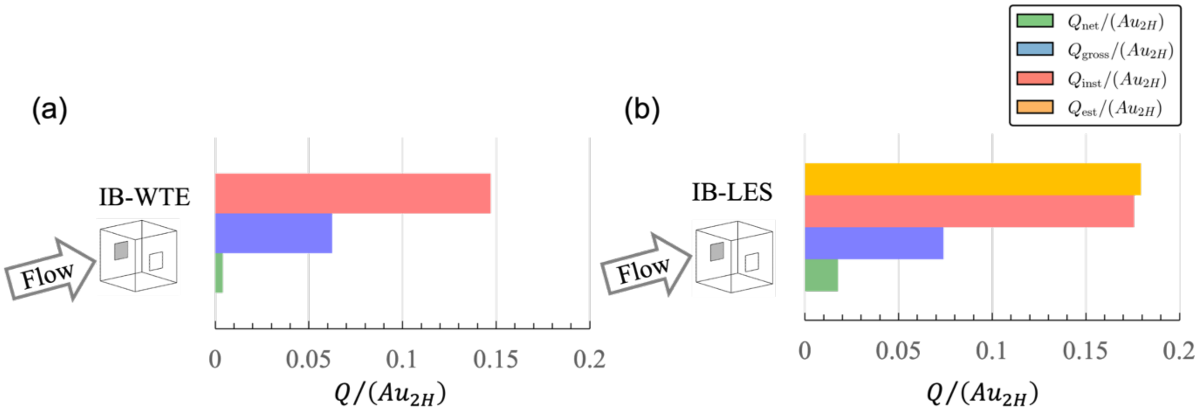

Figure 2: Net, gross, and instantaneous ventilation rates (Q_{net}, Q_{gross}, Q_{inst}) obtained from (a) WTE and (b) LES. Q_{est} in LES data indicates the estimated ventilation rate using mean and standard deviation of the opening-normal velocity component.

4. CONCLUSIONS

This study employed LES on cross ventilation buildings to validate results against WTE and accurately evaluate ventilation rates. The LES results generally reproduced the WTE results in terms of both spatial distributions of statistics and various ventilation rates. These results clearly demonstrate that ventilation performance of the side-ventilation scenario can be quantified by the LES. Based on the well-validated datasets by the LES, future work focuses on clarifying the fundamental mechanism how the turbulent air exchange occurs and contributes to the total ventilation rates to propose a simple and practical prediction model of ventilation rates.

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