CWE-8
June 7-11, 2026
London, ON, Canada

Comparative numerical simulation of wind-driven natural ventilation of low-rise buildings with varying window arrangements

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SUMMARY

This study investigates the influence of multi-planar corner windows on Natural Ventilation Systems (NVS) in low-rise buildings, compared to single-planar windows. Numerical simulations were conducted using Computational Fluid Dynamics (CFD) to evaluate airflow velocity and temperature distributions. Two generic rectangular building models with varying window configurations were analyzed using a steady-state Reynolds-Averaged Navier–Stokes (RANS) approach with k–ε turbulence model. Building Information Modeling (BIM) geometry models at a conceptual level of development (LOD 100) were created and transferred to the CFD environment to support flow pattern analysis and velocity distribution assessment. The ventilation performances of the two window configurations were quantitatively compared. The results indicate that, under the conditions examined, multi-planar corner windows do not provide a significant improvement in natural ventilation performance. Nevertheless, the findings establish a basis for future investigations into the impact of window design on NVS, contributing to a deeper understanding of how building form influences ventilation effectiveness.

Keywords: *Natural ventilation system, Computational fluid dynamics, Cross-ventilation, Corner window, Air velocity, Temperature distribution.*

1. INTRODUCTION

The United Nations (2016) officially set the Sustainable Development Goals (SDG), including climate action and clean energy. According to Abergel et al. (2018), as cited in Röck et al. (2020), buildings consume 36% of the world's energy and account for 39% of energy-related CO_2 emissions, contributing to global warming. The energy-intensive operations of mechanical ventilation systems account for 7 – 25 % of the total energy consumed by the building (Giama, 2019). Studies suggest that the use of passive design measures, such as NVS, contributes to reduced energy consumption by buildings (Ben-David & Waring, 2016), accounting for 18 – 33% (Gil-Baez et al., 2017)

There is a substantial amount of research on the NVS of several window arrangements on single planar window arrangements, with the focus on parameters such as size, position, height, and orientation. However, the studies fail to provide comparative evidence on multi-plane windows such as corner windows. This leads to limited numerical and experimental evidence for practitioners to apply evidence-based design decisions involving multi-planar corner windows for optimal NVS.

This paper aims to compare the impact of a multi-planar corner window with a standard planar window arrangement by measuring the indoor air flow and thermal comfort of a generic rectangular low-rise building with a 90° inflow angle to the windward face.

2. METHODOLOGY

Air velocity and temperature distributions within the indoor space were evaluated to compare the natural ventilation performance of the two window opening configurations. Air velocity was selected as a primary indicator of natural ventilation performance, as it directly informs key ventilation metrics such as airflow distribution, ventilation rate, and air exchange rate (Choi & Song, 2020; Omrani et al., 2017). Indoor air temperature was also analyzed due to its direct relationship with thermal comfort and its relevance in assessing ventilation effectiveness (Omrani et al., 2017).

Two separate numerical simulation cases were considered: (i) a building equipped with multi-planar corner windows, and (ii) a building with conventional single-planar window openings. The building geometries were developed in Rhino 7 and exported to STAR-CCM+ for computational analysis. CFD simulations were performed using a steady-state Reynolds-Averaged Navier–Stokes (RANS) approach with the standard k–ε turbulence model. All simulations were executed on SHARCNET high-performance computing resources, enabling efficient solution convergence and post-processing. The resulting airflow and temperature fields were analyzed to quantify and compare the ventilation performance of the two window configurations.

Table 1: Simulation cases

Simulation cases	Window type	Wind direction/ angle of attack
Case 1	Multi-planar corner window	90°
Case 2	Single planar window	90°

2.1. CFD models and boundary conditions

Neither additional parameter nor geometries are intentionally considered to avoid any undesirable interactions between them and the wind flow that could affect the result. The computational domain is shown in Figure 1.

Table 2: Geometric model and computational domain modeling dimension and

	Modeling dimensions	**Value**
Models [1 & 2]	Model width (W) [x-axis]	4 m
	Model length (L) [y-axis]	7 m
	Model height (H) [Z-axis]	3 m

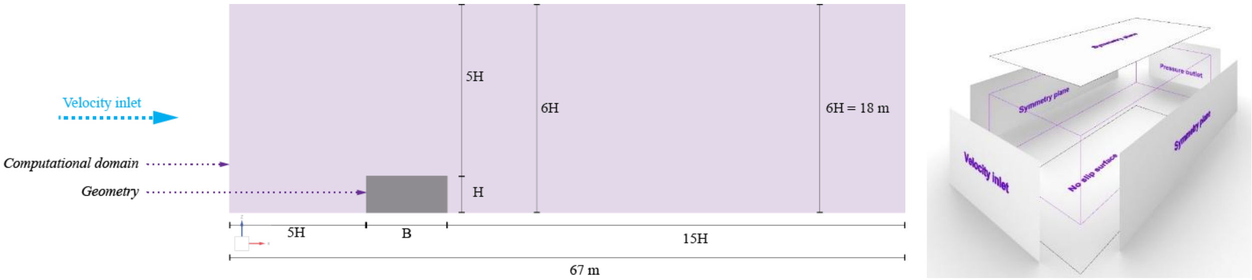

Figure 1: Left side view (top) and top view (bottom) of the geometry and computational domain, Boundary surfaces of the geometry and computational domain (right)

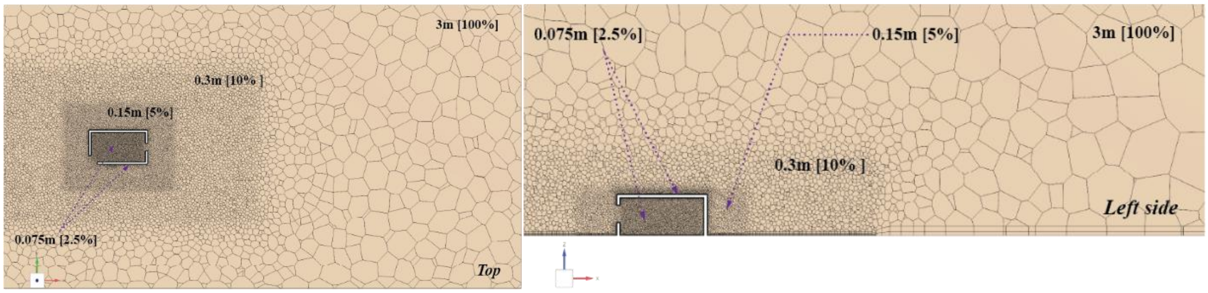

Figure 2: Top view of the discretized mesh of model 1 (left), Side view of the discretized mesh of model 1 (right)

A RANS method was employed, using a realizable K-ε turbulence model, to accurately simulate the airflow through the building, entering through the inlet and exiting through the pressure outlet. Despite its flaws of uncertainty of precision (Evola & Popov, 2006) and its dependence on the regime and validation requirement (Nimarshana et al., 2022), the *K-ε* turbulence model is an ideal method to simulate indoor ventilation due to its balance between accuracy and computational efficacy (Zhao, 2025), such as measuring wind flow around structures and the mean flow of wind (Shirzadi et al., 2017). The ABL wind profile is applied as the inflow velocity profile, with turbulent kinetic energy and dissipation rate described in Equations 1-3, based on the study by Vandewiel et al. (2025).

$$U_{(z)} = \frac{u_*}{\kappa} \cdot ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

$$k_{(z)} = \frac{u_*^2}{\sqrt{c_\mu}} \tag{2}$$

$$\varepsilon_{(z)} = \frac{u_*^3}{\kappa(z+z_0)} \tag{3}$$

Where u_* is the friction velocity (0.46 m/s), κ is the Von Karman constant (0.42), z is the height of the building (3.2 m), z_0 is the aerodynamic roughness length (0.3m for suburban Vancouver, BC, with low-density single houses with gardens, street trees, and some shops (Grimmond & Oke, 1999), and C_μ is an empirical constant (0.09).

3. RESULTS AND DISCUSSION

3.1. Air velocity

Relatively lower internal air velocity is recorded for the multi-planar corner window in case 1 compared to the result in case 2 featuring the single plane window at a 90° angle of attack. In Case 1, which is the corner window, the two edges of the opening induced a more turbulent and unpredictable flow separation (Figure 3). This separation at the first window corner significantly affected the velocity and volume of air entering the interior, thereby severely limiting the potential for higher ventilation performance. The placement, orientation, and proximity of the corner window's edges contributed to an alteration of the air velocity compared to the single planar window in case 2. As a result, a lower air velocity is measured, suggesting a lower ventilation performance. This finding aligns with the findings from Wang et al. (2017) and Yin et al. (2023), suggesting that the window geometry details and components affect the natural ventilation.

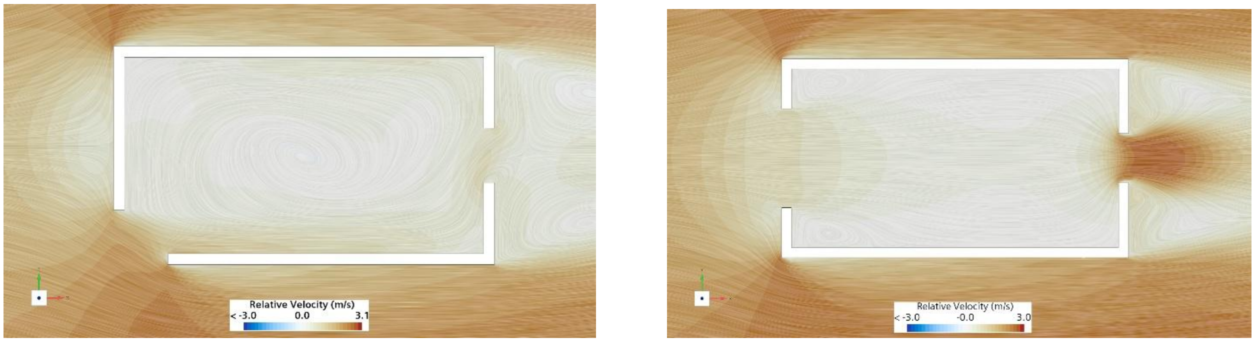

Figure 3: Air velocity in and around model 1(left) and model 2 (right) at 1.5m height along Z-axis

In addition, it is important to consider the angle of attack, which is 90°, giving the single planar window an advantage to facilitate faster air flow. This can be explained by the geometry of the corner window changed the angle of attack/ opening orientation to 45° (Figure 4), prohibiting increased air velocity and flow volume into the interior, converging with several studies reporting the effect of inflow orientation on ventilation performance (Aldawoud, 2017; Díaz-Calderón et al., 2023; Elshafei et al., 2017; Montazeri & Montazeri, 2018).

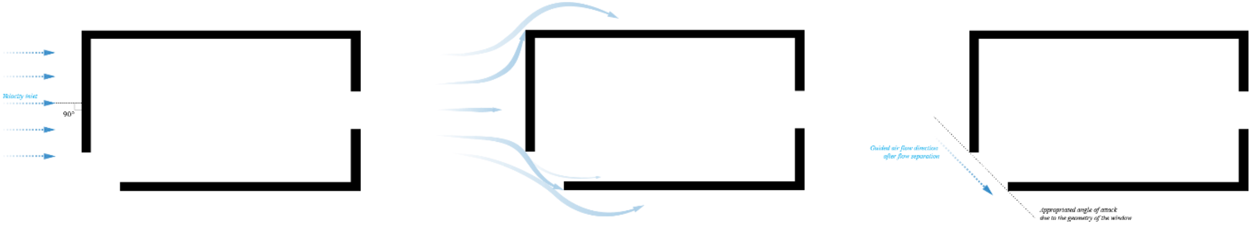

Figure 4: Angle of attack of wind (left), Flow separation caused by edges (middle), and appropriated angle of attack because of the interaction between the opening geometry and wind flow for the corner window.

3.2. Temperature distribution

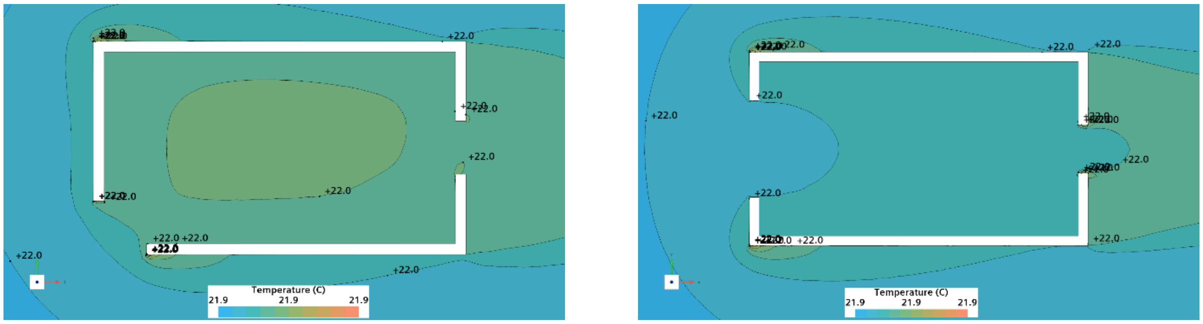

Figure 5: Temperature distribution in and around model 1(left) and model 2 (right) at 1.5m height along Z-axis

In this section, a temperature distribution simulation was carried out. There is a significantly low reduction in temperature in case 1, while a small drop in indoor temperature is noticed in case 2. Once again, the single planar window has a better performance in terms of indoor temperature. The discussions regarding orientation, window geometry detail, and opening style have a direct impact on the air flow, affecting the temperature distribution. Hence, manipulating those factors could provide a different result.

4. CONCLUSION

It can be inferred that a multi-planar corner window arrangement does not always improve wind-driven ventilation performance. The effectiveness of this configuration appears to be influenced by multiple aerodynamic factors, including window orientation, opening style, and the size and location of outflow openings. These parameters interact in complex ways, affecting the overall ventilation performance.

In general, to acquire thorough and reliable evidence with the aim of utilizing the corner window arrangement, multiple simulations with varying values of parameters and set up conditions must be conducted, helping practitioners make evidence-based design decisions for improved performance of NVS. Future work should focus on investigating the interplay of these variables and validating the simulations using experimental analysis.

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