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Determination of single-sided ventilation rates in multistory buildings: Evaluation of methods

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ABSTRACT

This study aims to evaluate the performance of different methods in determining single-sided ventilation rates in multistory buildings. The study is motivated by the fact that the methods established from very simple physical models, such as a single-room building, have been applied directly to multistory buildings. On-site measurement in a multistory building was conducted to verify the applicability of existing empirical models. A computational fluid dynamics (CFD) simulation was performed to (a) examine the integration method and the tracer gas decay method and (b) investigate the ventilation characteristics of a multistory building and how these differ from the ventilation characteristics of a single-room building. The empirical models are not applicable to multistory buildings as they cannot account for the difference in ventilation rate between different rooms in the same building. This study finds that the CFD method is particularly suitable for the determination of ventilation rates in multistory buildings despite the fact that the methods reproduced by CFD simulation are compromised by the accuracy of the velocity and turbulence fields generated by the selected numerical model. Finally, a parametric study shows that an increase in the incident k profile leads to a significant decrease in ventilation rate to the leeward rooms.

1. Introduction

Compared to cross ventilation, single-sided ventilation is more common in practice, especially in densely populated urban areas like Hong Kong where many rooms are characterized by a single window and a closed door. In addition, the majority of buildings in cities are multistory rather than single story. The accurate prediction of single-sided ventilation rates in multistory buildings is thus of great importance to ventilation design for this type of urban building.

Predicting single-sided ventilation rates is difficult as the airflow can enter into and exhaust from a room from any part of an opening in an unsteady and fluctuating manner. Among the existing prediction methods, the empirical correlations (see Table 1) can provide rapid estimations. Warren [1] proposed a pair of simple equations to calculate the wind-driven (Q_w) and the buoyancy-driven (Q_b) single-sided natural ventilation rate, respectively; the larger of these two single-sided ventilation rates is taken as the total ventilation rate due to the combined effect of wind and buoyancy. This model has been widely used (e.g. [2–4]) and has even become a baseline for natural ventilation design [5]. The semi-empirical model developed by Phaff and De Gids [6] considers the contributions of wind and buoyancy effects together. However, its accuracy is affected by window characteristics as the discharge coefficient of window (C_d) is not included in the model. A common limitation of these two models is that they both ignore wind direction [7], and this inspired Larsen and Heiselberg [8] to make a new correlation despite the fact that they found that ventilation rate has an unclear relationship with wind direction. Recently, Caciolo et al. [9] compared the three models above with their full-scale experiments and observed that the equations of Warren [1] provide the best overall predictions, although all of the models underperform on the leeward side. They [10] eventually proposed a new equation especially for leeward rooms; however, this equation neglects scenarios where ventilation is purely wind induced. In order to predict the fluctuating ventilation rate, Wang and Chen [11] used spectrum analysis to derive the contributions of pulsating flow [12,13] and eddy penetration [14]. Nevertheless, in addition to omitting wind direction, their model [11] assumes a uniform velocity distribution along the horizontal direction of a window. In general, these empirical models are established on the basis of a single-room building or a specific room of a building (see Table 1); thus, an evaluation of their applicability to multistory buildings is necessary.

Experimental measurement is another way to determine single-sided ventilation rates. Measuring the air velocity at an opening [9,15–17] is one method that can be used. In practice, the constant changes in airflow profiles at an opening mean that a large

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Nomenclature

A	area (m^2)
A_r	Archimedes number
A_{eff}	effective area (m^2)
C	tracer gas concentration (ppm)
C'	equal to $C_d\sqrt{C_p}/2$
C_1, C_2, C_3	empirical constants
C_d	discharge coefficient
C_p	pressure coefficient
C_{t_0}	tracer gas concentration at the time of t_0 (ppm)
C_{t_i}	tracer gas concentration at the time of t_i (ppm)
C_μ	empirical constant
D_1, D_2, D_3	empirical constants
f	frequency (Hz)
g	gravitational acceleration (m/s^2)
H	height (m)
H_O	opening height (m)
H_b	building height (m)
I_u	turbulence intensity in X direction (%)
k	turbulence kinetic energy (m^2/s^2)
K_s	geometrical roughness height (m)
l	opening width (m)
L	length (m)
M_1, M_2	integration constants for inlet turbulence profiles
$\widehat{n}$	frequency of power spectrum (Hz)
$\bar{Q}$	ventilation rate due to wind gust (m^3/s)
Q_b	ventilation rate due to buoyancy effect (m^3/s)
Q_T	total ventilation rate (m^3/s)
Q_w	ventilation rate due to wind effect (m^3/s)
R_ε	strain-dependent term
S	power spectrum
S_φ	source term of an equation
ΔT	temperature difference (K)
T_{av}	mean temperature (K)
$\bar{U}$	mean speed (m/s)
u^*	friction velocity (m/s)
$U_{j,k}$	mean normal velocity on the grid (Δy_j, Δz_k) (m/s)
U_{ref}	reference speed (m/s)
u, v, w	velocity components in the X, Y, Z directions (m/s)
u', v', w'	fluctuating velocities in the X, Y, Z directions (m/s)
V	room volume (m^3)
W	width (m)
y^+	dimensionless distance
Δy_j	grid size in y direction (m)
z	Z position (m)
z_0	aerodynamic roughness height (m)
z_n	Z position of the neutral plane (m)
z_p	centroid height of the first grids
z_{ref}	Z position of reference (m)
Δz_k	grid size in z direction (m)
σ_q	fluctuating ventilation rate (m^3/s)
σ_{qe}	fluctuating ventilation rate due to eddy penetration (m^3/s)
σ_{qp}	fluctuating ventilation rate due to pulsating flow (m^3/s)
ε	turbulence dissipation rate (m^2/s^3)
θ	wind angle
κ	Von Karman's constant, 0.4187
Γ_φ	effective diffusion coefficient

number of simultaneous high-fidelity velocity measurements are required, which makes this kind of experiment difficult and expensive to conduct. Pressure coefficient measurements on a sealed building model have also been used to estimate ventilation rate [18–21]. However, this method has many limitations, and numerous assumptions, which have been summarized in [14,22,23], are required. The use of tracer gas techniques [24] should be the most common and reliable experimental method [9,16,25,26]. However, it is difficult to use this method simultaneously in many rooms in a multistory building. In addition, wind tunnel experiments are limited by their resolution in the indoor airflow of scaled-down models [27], and full-scale measurements are restricted by model availability, especially in the design stage.

More and more researchers are using computational fluid dynamics (CFD) to study single-sided ventilation [10,28–34] as a CFD simulation can provide detailed information about airflow to an acceptable level of accuracy and calculate the ventilation rate for different configurations in an efficient manner. However, these researchers have mostly focused on model validation and parametric analysis using very simple physical models. It is necessary, especially from the viewpoint of ventilation design, to extend their studies to multistory buildings. Recently, Caciolo et al. [10,34] compared the large-eddy simulation (LES) and the Reynolds Averaged Navier Stokes (RANS) turbulence models against full-scale measurements and found that the RANS models provide acceptable predictions at a computational cost that is at least one order of magnitude lower than that of the LES. Therefore, the RANS models should be the more realistic options when using current computational hardware to study multistory buildings. In addition, previous studies have ignored the difference in envelope airflow pattern between rooms in a multistory building and a single-room building. This difference, which could lead to completely different ventilation characteristics in these two types of buildings, can easily be revealed using the CFD method.

This study intends to evaluate the prediction methods used to calculate single-sided ventilation rates in multistory buildings. First, on-site measurements of the ventilation rate in a multistory building are conducted to verify the applicability of existing empirical models used for multistory buildings. Then, using CFD simulation, the integration method and the tracer gas decay method are compared against experimental data. Finally, the validated CFD model is employed to examine the envelope airflow patterns and ventilation characteristics of a multistory building and the difference compared to a single-room building. The effect of approaching turbulence profile on the ventilation rate of rooms in the multistory building is also examined.

2. On-site verification of empirical models

2.1. Description of on-site measurement

The on-site measurement of single-sided ventilation rates was conducted in a multistory residential building in Hong Kong in early May 2013. The measured room ($6.54(L) \times 3.15(W) \times 2.94(H)\,m^3$) was located on the 12th floor of a 27-story building. Two opening configurations were considered: one floor-extended larger opening ($1.15(W) \times 2.3(H)\,m^2$) and one window-like smaller opening ($0.8(W) \times 1.44(H)\,m^2$) with a windowsill height of 0.86 m. CO_2 was used as a tracer gas to determine the ventilation rate. With the opening closed, CO_2 was released into the room until the indoor CO_2 concentration was elevated to the level of 3000–5000 ppm and mixed uniformly, and then the window was opened slowly to allow the concentration to decay freely. During this process, four sets of Telaire 7001 CO_2 monitors (Telaire, Goleta, CA, USA), which were placed at different locations in the room, were employed to record the concentration decay with time. The well-known tracer gas concentration decay method [24,35] was then employed to derive the hourly air change rate (ACH) in the room, which was the average