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Assessment of single-sided natural ventilation driven by buoyancy forces through variable window configurations

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ABSTRACT

Natural ventilation has great potential to create desirable indoor air quality and reduce energy consumption in buildings. Accurately modeling the windows of buildings is important to quantify airflow in single-sided natural ventilation. However, a simplification of real windows into rectangular openings has been widely applied in published literature, which seriously affects predictions of airflow through real windows. This investigation numerically evaluates the performances of real windows in the case of buoyancy-driven, single-sided ventilation. Several typical windows used in buildings are analyzed. The Reynolds-averaged Navier-Stokes (RANS) model and k-ω turbulence model are combined to solve airflow characteristics inside and outside the building. The results reveal that the computational fluid dynamics (CFD) model is sensitive to computational domain sizes and boundary conditions, while the sensitivities for different window configurations are different. The ventilation rates and thermal profiles inside the building varied for each window type, although the open window areas are almost identical. According to the comparison of CFD and analytical methods, it was found that the specification of constant discharge coefficients is no longer suitable to estimate the ventilation rates through real windows, and further investigations are needed to find better estimates of the coefficients for a particular window configuration.

1. Introduction

The United States Energy Information Administration (EIA) reported that about 40% of national energy consumption had been contributed to residential and commercial buildings [1]. Heating and cooling are the primary sources of building energy use. Although heating and cooling sectors consume a large amount of energy used in buildings, the higher degree of thermal comfort and better air quality in the indoor environment is still a challenge. In order to achieve the desirable thermal comfort and indoor air quality, supplying more fresh air becomes an effective measure [2]. A study by Fisk [3] revealed that the incidences of sick building syndrome could be reduced by greater use of fresh air, saving 10–30 billion dollars in the United States. Natural ventilation, as a passive cooling strategy in buildings, can potentially reduce energy costs while maintaining enough fresh air and ventilation rates [4,5]. Airflow patterns in buildings due to natural ventilation are generally classified into two types: cross ventilation and single-sided ventilation. However, building shapes, fire codes, security issues and privacy concerns prevent efficiently utilizing cross-ventilation in buildings [6]. Therefore, single-sided natural ventilation is still attractive for more common space requirements even if it is less efficient than the other strategy.

Single-sided natural ventilation is generally driven by three forces, namely, buoyancy forces, wind forces and their combination [7]. For the buoyancy-driven flow, the air passing through an opening is caused by the temperature difference between the indoor and outdoor environment. Due to temperature differences, the air pressure inside and outside is not identical and thus drives the airflow. Compared to buoyancy-driven flow, the physical process of wind-driven flow is complex [8]. Although the wind directly creates a pressure gradient and induces airflow across an opening, wind is unpredictable and therefore unsteady. Rapid fluctuations of air speed and random changes of air direction make turbulent characteristics of the incoming wind difficult to quantify. Indoor airflow also becomes drastically unsteady and turbulent owing to the fluctuating momentum source [9]. In most cases, the single force driving airflow in single-sided natural ventilation is not practical. The buoyancy force and wind force may act simultaneously, thus the combined force determines airflow through an opening.

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Nomenclature

A	Physical open area (m^2)
ACH	Air change rate per hour (1/h)
Ar	Archimedes number
C_d	Discharge coefficient (−)
D_ω	Cross-diffusion term in the ω equation ($\mathrm{kg/m^3{\cdot}s^2}$)
g	Gravitational acceleration ($\mathrm{m/s^2}$)
G_k	Generation of turbulence kinetic energy ($\mathrm{kg/m{\cdot}s^3}$)
G_ω	Generation of specific dissipation rate ($\mathrm{kg/m^3{\cdot}s^2}$)
GCI	Grid convergence index (−)
h	Height of window (m)
H	Height of building (m)
i	Serial number of open area (−)
k	Turbulence kinetic energy ($\mathrm{m^2/s^2}$)
K	Conductivity (W/m·K)
L	Length of building (m)
M	Mass flow rate (kg/h)
N	Number of grid cells (−)
Q	Volume flow rate ($\mathrm{m^3/s}$)
r	Average size of grid cells (m)
T	Air temperature (°C)
u	Air velocity (m/s)
w	Width of window (m)
W	Width of building (m)
$x/y/z$	Space coordinate (m)
Y_k	Dissipation of turbulence kinetic energy ($\mathrm{kg/m{\cdot}s^3}$)
Y_ω	Dissipation of specific dissipation rate ($\mathrm{kg/m^3{\cdot}s^2}$)

Greek symbols

β	Thermal expansion coefficient (1/K)
δ	Physical open gap (m)
ΔP	Pressure difference (Pa)
ΔT	Temperature difference (K)
θ	Open angle of window (°)
μ	Absolute viscosity (kg/m·s)
μ_t	Turbulent viscosity (kg/m·s)
ξ	Grid quality (−)
ρ	Air density ($\mathrm{kg/m^3}$)
σ_ω	Turbulent Prandtl number (−)
φ	representative variable for GCI
ω	Specific dissipation rate (1/s)

Subscripts

ANA	Analytical
CFD	Computational fluid dynamics
eff	Effective
norm	Normalized
ref	Reference
RANS	Reynolds -averaged Navier-Stokes
s	Surrounding wall
∞	Ambient environment
*	Dimensionless

Since the two forces may produce the same or opposing pressure differences, the ventilation can be reinforced or weakened by the combined force [10].

Single-sided natural ventilation has been extensively studied and reported for decades. Jiang and Chen [11] used full-scale experiments and CFD methods to study single-sided buoyancy-driven natural ventilation with a simple opening. Ventilation rates and detailed airflow characteristics inside and outside a room were obtained. Favarolo and Manz [12] combined analytical and CFD methods to investigate a similar flow. The airflow patterns and their effects on the discharge coefficient included in the analytical model were discussed. To make the research more practical, Park and Battaglia [13] applied CFD to examine the impacts of various environmental conditions, heat loads and furniture placement on indoor thermal conditions for buoyancy-driven flows. Compared to buoyancy-driven flows, the research on wind-driven ventilation has received more attention recently. Dascalaki et al. [14] carried out full-scale experiments on wind-driven single-sided ventilation and measured the velocity profiles and mean ventilation rates. To obtain the characteristics of turbulence in wind-driven flow, Jiang et al. [15] combined wind tunnel tests and large-eddy simulation (LES) to validate and predict velocity characteristics around and within buildings. In view of the pulsating flow and eddy penetration of single-sided, wind-driven natural ventilation with a single opening, an empirical model was developed by Wang and Chen [16] that could predict both the mean and fluctuating ventilation rate. Chu et al. [17] investigated wind-driven ventilation for buildings with two openings on a single wall, and a semi-empirical formula was proposed to predict ventilation rates based on wind tunnel experiments. Meanwhile, several studies on wind-driven ventilation were also performing based on RANS equations [18–20] using CFD. Research on single-sided natural ventilation driven by a combination of wind and buoyancy has been investigated using experimental, analytical and CFD methods [8,21,22]. However, the airflow resulting from the interaction between buoyancy and wind forces is far from being fully understood [23]. More efforts are needed to explore the criteria for determining the interaction of buoyancy and wind forces [6].

Due to the fact that single-sided natural ventilation not only depends on driving forces but also on the configurations of the openings, airflow characteristics may vary greatly under comparable conditions. Most CFD building models represent one or more rectangular openings to simulate doors or windows, which can deviate from real building scenarios. To evaluate the influence of window configurations, real window models were applied to investigate natural ventilation. Heiselberg et al. [24] took two types of single-hung windows and measured the ventilation rates across them. The impacts of open area and temperature difference on discharge coefficients that are used to calculate ventilation rates by analytical models were discussed. Gao and Lee [25] studied the air change effectiveness in a residential building with three types of windows and evaluated the effects of window configurations on natural ventilation. Wang et al. [26] performed an experimental and numerical study to consider the effects of single-hung windows in wind-driven natural ventilation, and corresponding models for predicting their ventilation rates were developed. Grabe [27] experimentally studied ventilation rates through typical windows in the case of buoyancy-driven flow and proposed several relationships of mass flow rate versus opening area based on experimental data. Unfortunately, analyses on the thermal flow profiles inside and outside the building with respect to different configurations of windows were not studied.

The geometrical model applied in the study represents one room in a building. For example, it is common that residential buildings and student dormitories are composed of many rooms (such as the room used in the study). In those buildings, the windows generally become the only vent when the doors are closed and heating, ventilation and air conditioning (HVAC) system is not operating. Also, for many natural ventilation strategies, there are no HVAC systems thus windows are an important feature of the room. For example, in many regions of China, student dormitories do not have HVAC systems. Available research reveals that most attention has focused on the determination of airflow patterns and ventilation rates in single-sided ventilation, especially for the case of wind-driven flow and combined buoyancy- and wind-driven flow. Due to complex turbulent characteristics of the incoming wind and