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# Wind-induced single-sided natural ventilation in buildings near a long street canyon: CFD evaluation of street configuration and envelope design

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ABSTRACT

Wind-induced single-sided natural ventilation in buildings was widely investigated based on isolated buildings. However, owing to the presence of surrounding buildings, the wind flow pattern around a building in an urban area becomes very different from that around an isolated building. Considering an urban context, this study investigates the wind-induced single-sided natural ventilation in buildings near a long street canyon under a perpendicular wind direction using CFD method. Four aspect ratios (AR) of the street canyon, from 1.0, 2.0, 4.0 to 6.0, are investigated to examine the influence of street configuration, while eight envelope features are compared to explore the possibility of envelope design in improving natural ventilation performance of urban buildings. Ventilation rate of rooms in buildings is particularly analyzed. AR influences ventilation rate and its distribution among rooms along height of buildings. The percentage decrease of ventilation rate of buildings reaches 67% when AR of a street canyon is increased from 1.0 to 6.0. Envelope design provides a possibility to enhance the adaptability of buildings to dense urban environments. A good envelope design, such as a horizontal feature at the middle of an opening, can break effectively the along-facade flow and thus create a large pressure difference to drive ventilation. The findings of this study are intended to increase the understanding of natural ventilation performance in urban buildings and thus provide information for urban planning and building design.

## 1. Introduction

Natural ventilation is widely existed in urban buildings intentionally or unintentionally. It is intentionally designed to create a healthy and thermally comfortable indoor environment by utilizing optimally the driving force of wind and buoyancy effects, when the outdoor microclimate environment is desirable. In many buildings including particularly residential buildings, window(s) are not necessarily opened for obtaining natural ventilation, but natural ventilation is certainly formed in such situations. Regardless of intentions, the wide existence of natural ventilation in urban buildings is worthy of a special attention, considering that the indoor environmental quality in these naturally ventilated buildings is strongly influenced by their nearby urban microclimate (Ai and Mak, 2015).

Compared to cross natural ventilation, single-sided natural ventilation is much more common in buildings, especially in densely populated urban areas where many rooms are characterized by a single window and a closed door. While buoyancy effect is an important driving force of natural ventilation in buildings where there are large differences in both indoor/outdoor air temperature and vertical distance of intake and exhaust openings, wind effect is normally the dominated driving force for natural ventilation in most buildings like residential buildings. Wind-driven single-sided natural ventilation is a complex process that is influenced by the turbulent nature of the approaching wind and the bi-directional airflow interaction at the opening (Haghighat et al., 1991, 2000; Linden, 1999; Ai and Mak, 2014a). Single-sided natural ventilation can be predicted by empirical models (Warren, 1977; Phaff and De Gids, 1982; Larsen and Heiselberg, 2008; Wang and Chen, 2012), experimental measurements (Caciolo et al., 2011; Dascalaki et al., 1996; Karava et al., 2011), and computational fluid dynamics (CFD) models (Jiang and Chen, 2001; Caciolo et al., 2012; Ai et al., 2013, 2016; van Hooff and Blocken, 2010). Compared with the first two approaches, CFD simulation has some advantages for the study of single-sided natural ventilation that involves coupled urban wind flow and indoor air flow (van Hooff and Blocken, 2010; Blocken and Gualtieri, 2012; Ai and Mak, 2014a). These previous studies are very useful in revealing basic flow behaviours, examining parameters and validating CFD models, which, however, are mostly limited to isolated buildings, such as a single-room building (e.g.,

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Jiang and Chen, 2001; Straw, 2000; Ai and Mak, 2014a) and a multiple-room building (e.g., Ai et al., 2013; Ai and Mak, 2016).

Given that few buildings in urban areas can be regarded as isolated buildings, the urban microclimate would directly influence the natural ventilation in buildings. Studies in urban physics and wind engineering indicate that wind speed in a street canyon flanked by buildings is decreased significantly compared to that above the canyon (Oke, 1987; HKPD, 2005; Georgakis and Santamouris, 2006). Depending on aspect ratio (AR, ratio of the mean building height to the street width) (Oke, 1987; Li et al., 2006; Ai and Mak, 2015), flow pattern in a street canyon can be categorized into three regimes: isolated roughness flow (AP < 0.3–0.4), wake interference flow (0.3–0.4 < AR < 0.65–0.7) and skimming flow (AR > 0.65–0.7). The study of atmospheric processes in skimming-flow street canyons were paid particular attentions, as they are considered to be with the worst flow and dispersion conditions when compared to those in lower AR streets. Review of on-site measurements (Georgakis and Santamouris, 2006; Andreou and Axarli, 2012; Nakamura and Oke, 1988; Santamouris et al., 1999; Manning et al., 2000; Buller, 1976; Niachou et al., 2008; Kitous et al., 2012) of wind speeds inside and outside (mostly above) street canyons by Ai and Mak (2015) suggests that, depending on AR, the ratio of wind speed inside a canyon to that outside the canyon ranges mostly between 10% and 30%. The review (Ai and Mak, 2015) also shows that wind direction in vicinity of a building near a street canyon is dominated by the along canyon flow combined with upward and downward movements, while the normal-to-facade flows are very weak. The decreased wind speeds and substantially changed flow patterns inside street canyons would influence (mostly lower) wind-induced pressure difference for natural ventilation in buildings, which thus highlight the importance of taking into account urban context in natural ventilation studies.

On-site measurement of natural ventilation rate (Georgakis and Santamouris, 2006; Gilkeson et al., 2013; Li et al., 2014; Santamouris et al., 2008) is a useful method to reveal the real-life ventilation performance of naturally ventilated buildings in urban areas. However, since the natural ventilation rate is influence by many factors, such as wind speed and direction, opening configuration, surrounding characteristics and floor location in a building, these measured results vary significantly between different cases and over time, which are thus cannot provide a general view on the influence of surrounding buildings on natural ventilation performance. A few studies examined the natural ventilation performance in buildings when considering the influence of surrounding buildings, which show that the wind speed near building facades could be lowered by up to 86.8% (Gao and Lee, 2012) and the natural ventilation performance in urban buildings could drop by up to 96% (van Hooff and Blocken, 2010; Georgakis and Santamouris, 2006) when compared to isolated buildings. These findings are, however, case dependent and again may not be applicable to a different situation.

In general, current understanding of natural ventilation in urban buildings is far from sufficient, and there is still a strong need to provide a systematical investigation using a general urban geometry. From both street configuration and envelope design perspectives, the objective of this study is to investigate the wind-induced single-sided natural ventilation in urban buildings. A long street canyon flanked by two buildings is considered, while four AR values are investigated, including 1.0, 2.0, 4.0 and 6.0, which all correspond to the aforementioned skimming flow regime (Oke, 1987; Ai and Mak, 2015). Based on the four AR values, eight envelope features are examined to explore the possibility of improving the natural ventilation performance of urban buildings through envelope design. Each of the two buildings contains 11 floors and 23 rooms on each floor. As the street canyon is considered to be ideally infinitely long, only the rooms located on the vertical centres are created for investigation. Ventilation performance of rooms is particularly evaluated using air change rate per hour (ACH). CFD simulations are conducted and steady-state results are obtained by solving the Reynolds-Averaged Navier-Stokes (RANS) equations using the Renormalization group (RNG) $k-\varepsilon$ turbulence model. The rationality and limitation of such steady-state simulations are discussed in Section 5. CFD model is validated first to ensure its reliability (Section 2). Section 3 describes in detail the investigated street canyons, buildings and envelope features as well as computational settings. Section 4 presents results and analyses, Section 5 discussions and Section 6 conclusions.

## 2. CFD simulations: model validation

Model validation against experimental data is a basic requirement to ensure the reliability of any CFD simulations. Natural ventilation in buildings near a street canyon investigated in this study involves two elementary flow problems: (a) single-sided natural ventilation that includes a coupled indoor and outdoor flow field, and (b) street canyon flow that includes the interaction between the flows inside and above the street canyon. It is necessary to validate the two elementary flow problems. However, an experiment involving both the two flow problems is rarely found in previous literature. In this study, the two flow problems were validated separately using different experiments. First, for single-sided natural ventilation in buildings, a wind tunnel experiment by Jiang et al. (2003) and a field experiment by Dascalaki et al. (1996) were employed to conduct validations. Detailed validation processes and comparisons between the simulated results and the experimental data can be found in our previous papers (Ai et al., 2013; Ai and Mak, 2014a, b). In general, both the predicted flow field (Jiang et al., 2003; Ai et al., 2013; Ai and Mak, 2014a) and ACH value (Dascalaki et al., 1996; Ai and Mak, 2014a) show an acceptable agreement with the measured data. These comparisons justified the use of our CFD model in the prediction of single-sided naturel ventilation in buildings. Second, for street canyon flow, a water tunnel experiment by Li et al. (2008a) was used. The detailed description of this validation is presented in the following Sections 2.1–2.3.

### 2.1. Validation of street canyon flow

Li et al. (2008a) conducted a water tunnel ($L_T \times W_T \times H_T$: 10 m × 0.3 m × 0.5 m) experiment to measure the flow field inside a street canyon. Two types of street canyons of AR ($H_B/W_S$) equal to 1.0 and 2.0 were investigated, which were formed by eight and ten identical building models ($L_B \times W_B \times H_B$: 0.3 m × 0.1 m × 0.1 m), respectively. The water flow approaches the street canyons in a perpendicular direction (Fig. 1 (b)). The height of the buildings was fixed at $H_B = 0.1$ m, while the width of the street canyons $W_S$ was varied to form the two AR values. The depth of water in the two sets of experiments was fixed at 0.4 m. The Reynolds number based on the reference water speed ($U_{ref}$) in freestream at $z = 0.3$ m and the building height was 12,000, implying that $U_{ref}$ was equal to 1.8 m/s. No roughness elements on the tunnel ground were considered. Velocity components in the streamwise and vertical directions along three vertical lines and two horizontal lines on the vertical centerplane ($y = 0$) of the target street canyon (see Fig. 1 (a)) were measured using a two-colour laser Doppler anemometer (LDA).

The building model and street canyon model used in CFD simulations are the same with those in the experiments (see Fig. 1 (a) and (b)). Computational domain and its dimensions (see Fig. 1 (b)) are selected based on the existing best practice guidelines for CFD simulation of urban aerodynamics (Franke et al., 2007; Tominaga et al., 2008), except that the height and lateral length of the domain follow those in the experiments. The whole computational domain is constructed using structured hexahedral cells (see Fig. 1 (c)). After a grid sensitivity test, two grids, with 3,168,000 and 2,880,000 cells in total, are eventually used for the cases of AR = 1.0 and 2.0, respectively. The height of the first cells near the ground and walls is 1.665 mm, yielding the $y^+$ values at these first cells ranging between 0 and 15, with an average value equal to 5.3. Large $y^+$ values appear only at the top corners of the windward facades.

Same with the experiments, a uniform wind speed at 1.8 m/s is defined at the inlet of the computational domain. After a sensitivity