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Natural ventilation assessment in typical open and semi-open urban environments under various wind directions

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ABSTRACT

Semi-open street roofs protect pedestrians from intense sunshine and rains. Their effects on natural ventilation of urban canopy layers (UCL) are less understood. This paper investigates two idealized urban models consisting of 4(2 × 2) or 16(4 × 4) buildings under a neutral atmospheric condition with parallel (0°) or non-parallel (15°, 30°, 45°) approaching wind. The aspect ratio (building height (H)/street width (W)) is 1 and building width is $B = 3H$. Computational fluid dynamic (CFD) simulations were first validated by experimental data, confirming that standard $k–\varepsilon$ model predicted airflow velocity better than RNG $k–\varepsilon$ model, realizable $k–\varepsilon$ model and Reynolds stress model. Three ventilation indices were numerically analyzed for ventilation assessment, including flow rates across street roofs and openings to show the mechanisms of air exchange, age of air to display how long external air reaches a place after entering UCL, and purging flow rate to quantify the net UCL ventilation capacity induced by mean flows and turbulence.

Five semi-open roof types are studied: Walls being hung above street roofs (coverage ratio $\lambda_a = 100\%$) at $z = 1.5H$, $1.2H$, $1.1H$ ('Hung1.5H', 'Hung1.2H', 'Hung1.1H' types); Walls partly covering street roofs ($\lambda_a = 80\%$) at $z = H$ ('Partly-covered' type); Walls fully covering street roofs ($\lambda_a = 100\%$) at $z = H$ ('Fully-covered' type). They basically obtain worse UCL ventilation than open street roof type due to the decreased roof ventilation. 'Hung1.1H', 'Hung1.2H', 'Hung1.5H' types are better designs than 'Fully-covered' and 'Partly-covered' types. Greater urban size contains larger UCL volume and requires longer time to ventilate. The methodologies and ventilation indices are confirmed effective to quantify UCL ventilation.

1. Introduction

Wind from rural areas provides cleaner rural air into urban canopy layers (UCL) to help pollutant and heat dilution. Good UCL ventilation has been known as one of the possible mitigation solutions to improve urban air environments [1–11], meanwhile ameliorate indoor air quality through building ventilation systems.

Complemented by wind tunnel/field experiments, computational fluid dynamics (CFD) simulations have been widely used to predict turbulent airflow, mass transports and energy budgets within, close to and above different UCLs [2,4–11,17–26,28–37], ranging from street canyons, street intersections, cavities and courtyards, up to structured building arrays and realistic urban areas. Good reviews on this topic can be found in the literature [12–15]. For two-dimensional (2D) street canyons [1,15–19], street aspect ratio (building height/street width, H/W) is the first key parameter to affect the flow regimes and pollutant dispersion. For three-dimensional (3D) urban canopy layers, total street length or urban size [8,11,30], building packing density and frontal area density [8,10,20–23], ambient wind directions [23,24,32,37], building layouts and height variations [8,21–23,25–26] etc, are significant parameters and have been widely investigated.

In addition to the widely studied urban models with open street roofs, semi-open street roof is one of popular urban design elements existing in the realistic urban areas to protect pedestrians from strong sunshine and reduce the inconveniences in rainy or snowy days. Such semi-open street roofs have been reported and investigated by experiments and CFD simulations in the literature [5–7], including a large naturally ventilated semi-open market building [5], a semi-open shopping mall being located in Lisbon,

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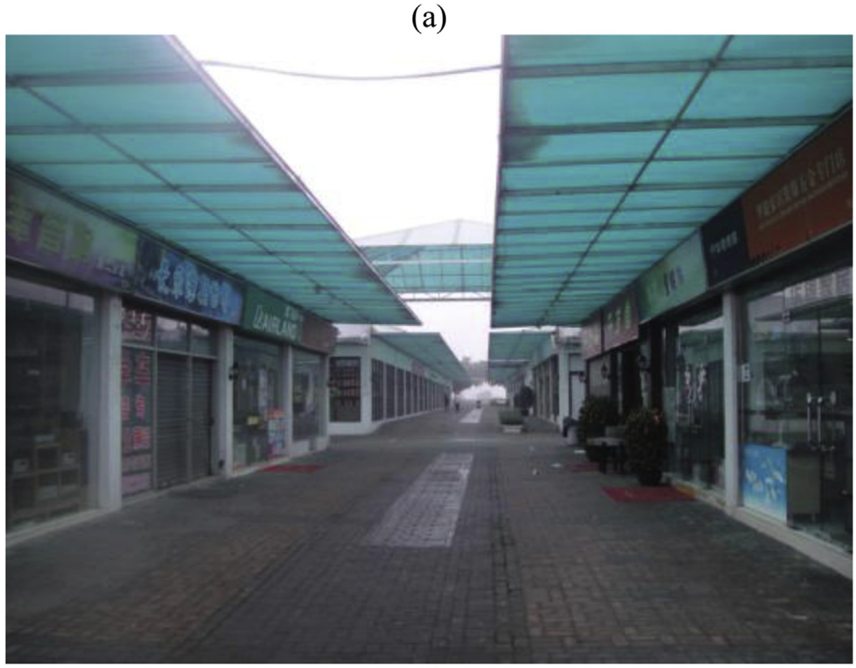
Portugal [6], enclosed-arcade (or semi-open) markets of Korea with eleven arcade-type designs (or semi-open street roof) [7]. Although the requirements of design are different according to various climate conditions, sufficient natural UCL ventilation has been considered as an important environment design factor for more healthy semi-open outdoor environments [5–7]. Fig. 1 shows two other kinds of semi-open street roof designs in the suburb of Guangzhou China, which are located in a subtropical region annually characterized by intense solar radiation and precipitation. Fig. 1a shows walls being hung above street roofs of a food court, and Fig. 1b displays walls partially covering street roofs of a retail center. Each shop or restaurant has its own enclosed space with air conditioners inside for cooling in summer (April to September) and with doors connected to the semi-open streets. These semi-open outdoor environments are naturally ventilated to reduce energy consumption. Such semi-open street roof designs are used to provide convenience for pedestrians, but they possibly deteriorate UCL ventilation performance. This paper aims to quantitatively evaluate these effects. Although thermal buoyancy force induced by temperature difference and atmospheric stability also influence urban airflows and UCL ventilation [19,28,29], this paper takes the first step to consider a neutral atmospheric condition assuming that the ambient wind velocity is sufficiently large and thermal effects are negligible.

In building ventilation, as reviewed by Chen [27], indoor ventilation indices have been widely used to evaluate how external

(a)



(b)

Fig. 1. Two urban configurations of semi-open street roof design: (a) Walls being hung above street roofs of food court, (b) Walls being partly covered at street roof height ($z = H$) of retail center.