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Effects of envelope features on pollutant exposure in 2D street canyons

ABSTRACT Most of the related research on pollutant dispersion has mainly focused on flat-facade buildings. However, envelope features can significantly affect the near-wall flow, which in turn affects the natural ventilation and consequent pollutant dispersion in urban canyons. We conducted an outdoor experiment to investigate the influence of different envelope features (balconies, overhangs, and wing walls) on pollutant exposure in wide and narrow street canyons (H/W = 1, 2). Wing walls effectively increase pollutant dispersion in wide and narrow street canyons, which results in an increase in the personal intake fraction (P_IF). The highest growth rate of the P_IF, reached 291 % and 400 %. However, balconies can decrease the P_IF on the second, third and fourth floors of both the east and west buildings. Additionally, envelope features notably increase the daily pollutant exposure index (*Ed*) and the order of the impact is wing walls > balconies > overhangs. In wide and narrow street canyons, the presence of wing walls yielded a significant increase in the *Ed* values compare with flat-facade canyons on all floors of both the east and west buildings, with the highest growth rate of *Ed* reaching 280 %. Meanwhile, the presence of balconies caused a significant increase in the *Ed* values on the first floor of both the east and west buildings in the narrow street canyons, but a decrease in the *Ed* values on the other floors of both buildings. This study provides valuable insights into the impact of envelope features on pollutant exposure in street canyons.

1. Introduction

The ongoing decline in urban air quality poses a significant challenge to the sustainable development of cities. Traffic exhaust-related pollutants have emerged as the primary source of atmospheric pollution [1,2]. These pollutants can infiltrate indoor spaces or buildings near streets through entrances, windows, ventilation systems, and even small gaps [3]. Residents in densely populated urban areas are exposed to high concentrations of airborne pollutants originating from vehicular emissions, leading to detrimental effects on their physical and mental well-being over prolonged periods [4]. Hence, understanding the natural ventilation conditions in urban areas is of paramount importance. Such a study could contribute to mitigating pollutant dispersion and fostering the development of sustainable and health-conscious urban building environments. Pollutant dispersion in urban environments is influenced by various factors [5–10]. With the increasing emphasis on green buildings, envelope features such as balconies, overhangs, and wing walls have become common features in green building design. These envelope features offer advantages such as shading, noise reduction, and enhanced ventilation. However, compared to flat-facade buildings, these envelope features can disrupt the wind pressure distribution around buildings, causing the formation of localized eddies and increased turbulent kinetic energy near exterior windows. This phenomenon can intensify pollutant dispersion and alter the pathways through which pollutants travel between households [11,12]. As a result, the envelope features of buildings play a significant role in urban natural ventilation, the thermal environment, pollutant dispersion, and indoor and outdoor air quality levels. Several studies have shown that different envelope features have varying impacts on ventilation performance. For example, Ai and Mak et al. investigated the influence of balconies on building ventilation performance and observed that balconies could alter airflow patterns inside and around buildings [11,13–15]. In their subsequent research, they examined the impact of eight envelope features on the natural ventilation performance of buildings. They found that horizontal envelope features can enhance indoor natural ventilation. The presence of balconies can lead to multiple separation and recirculation areas near building façades [16,17]. The ventilation performance of balcony canyons is lower than that of flat-façade canyons [18]. Additionally, the presence of overhangs significantly enhances ventilation performance in the windward direction of street canyons [19]. Hanging envelope features, such as wing walls, can increase average indoor wind speeds, resulting in higher hourly air exchange rates and improved natural ventilation performance under different wind directions and speeds [20, 21]. Murea and Zheng et al. investigated the effects of balconies on pollutant dispersion in street canyons and determined that the presence of balconies can strongly affect the wind flow field and pollutant dispersion in street canyons. Generally, balconies can reduce induced turbulence and prevent airflow from penetrating deep into the bottom of a canyon [10,22]. These studies collectively demonstrate that envelope features significantly influence natural ventilation performance and pollutant dispersion in buildings. However, these studies have focused primarily on wind momentum considerations. These factors do not account for the buoyancy effect on natural ventilation performance; in turn, they affect pollutant dispersion in street canyons. With increasing urban building density, the wind speed in the urban environment decreases, and buoyancy increasingly becomes an important boundary condition that cannot be ignored. Solar radiation influences envelope features, causing a significant temperature difference between the building facade and the indoor environment. Under the combined influence of wind momentum and buoyancy, this temperature difference can enhance or weaken natural ventilation in street canyons [21,23]. Additionally, urban ventilation and solar radiation affect the turbulence characteristics and pollutant dispersion patterns associated with envelope features. Therefore, it is essential to study the turbulent flow characteristics and pollutant dispersion mechanisms of various envelope features in urban street canyons under the combined influence of both wind momentum and buoyancy. In previous studies on natural ventilation and pollutant dispersion in urban street canyons based on wind momentum, numerical simulations and wind tunnel experiments have been utilized [24,25]. However, under the combined influence of wind momentum and buoyancy, the flow should be verified to satisfy the independence requirement of both the Reynolds number (*Re*) and Richardson number (*Ri*) in wind tunnel experiments but a substantial temperature difference is usually needed (≈100 ◦C). Consequently, outdoor scaled experiments should be performed to investigate natural ventilation and pollutant dispersion in street canyons under the combined influence of wind momentum and buoyancy. Kanda et al. demonstrated that outdoor scaled experiments could be performed to explore the impact of different building parameters on urban layouts while considering the same meteorological conditions and meeting thermodynamic similarity requirements [26]. Nakamura and Oke et al. conducted outdoor scaled experiments to observe wind and heat characteristics under different stable conditions in east–west street canyons [27]. Moreover, Chen et al. studied the effects of the street aspect ratio and urban thermal storage on the temporal characteristics of the urban thermal environment in the SOMUCH [28,29]. Since envelope features create shaded areas on building façades, they can cause temperature differences and influence urban ventilation, which in turn affects urban pollutant dispersion. However, in their experiments, they did not focus on the impact of envelope features on pollutant dispersion in two-dimensional (2D) street canyons under real urban climate conditions. In this context, this paper aims to investigate the following questions. (1) How do different envelope features (flat-facades, balconies, overhangs, and wing walls) in 2D street canyons (*H/W* = 1,2) affect the wind flow characteristics and pollutant dispersion under the combined influence of wind momentum and buoyancy? (2) Quantitative metrics, such as the pollutant intake fraction (*IF*), personal pollutant intake fraction (*P_IF*), and daily pollutant exposure index (*Ed*), were employed to evaluate the risk of pollutant exposure in street canyons. As evaluated by the above quantitative metrics, which kinds of envelope features significantly contribute to the risk of pollutant exposure. (3) Additionally, we also compare the effects of the same envelope features on the risk of pollutant exposure on different floors to determine which floor, experiences the high risk of pollutant exposure. The rest of this article is structured as follows: Part 2 introduces the experimental setup and data analysis methods. The results and discussions are presented in Part 3. Finally, Part 4 summarizes the conclusions.

2. Methodology

2.1. Experimental setup

To investigate the impact of different envelope features (flat-facades, balconies, overhangs, and wing walls) on pollutant dispersion in wide (*H/W* = 1) and narrow (*H/W* = 2) street canyons, a comprehensive series of outdoor scaled experiments were conducted from November 2020 to January 2021. The SOMUCH is located in a suburb of Guangzhou, Guangdong Province, China (23◦1′ N, 113◦25′ E). The experimental models were scaled down to a ratio of 1:10 relative to real-world dimensions, with individual building models measuring 0.5 m in length, 0.5 m in width, and 1.2 m in height, equivalent to actual building sizes of 5 m × 5 m × 12 m. To replicate a high-density urban environment, a significant number of building models were arranged according to predefined rules, forming urban street canyons (Fig. 1a). These models were manufactured of concrete and hollow structures, all of which had identical dimensions: 0.5 m in length, 0.5 m in width, 1.2 m in height, and 0.015 m in thickness. By aligning these building models side by side, street canyons were created, with each canyon contained 24 concrete building models on both sides, resulting in a total canyon length (*L*) of 12 m. The experiments involved street canyons with a fixed building model height (*H* = 1.2 m) and varied street canyon widths, allowing for the examination of street canyons with aspect ratios of 1 and 2 in the north–south direction. Notably, all the street canyon models in the experiment exhibited length-to-width ratios (*L*/*W*) exceeding 7, which suggests that the research obtained from the experimental results primarily applies to long street canyons [30–32]. The buildings in the street canyon exhibited different envelope features, including flat-facades, balconies, overhangs, and wing walls (Fig. 1b). CO2 was adopted as the tracer gas in this outdoor scaled experiment [33–35]. CO2 was transported by an emission device, which included four flowmeters, a plastic ball (diameter of 30 mm) and three silicone plastic tubes (diameter of 8 mm). The emission device was positioned in the middle of the street canyon at a height of 0.15 m. The concentration of the source gas was 105 ppm, and the flow rate was adjusted to 1.2 L/min.

2.2. Instrument arrangement

The instrumentation used in the experiment included thermocouples, CO2 sensors, ultrasonic anemometers, and weather stations, each serving different monitoring purposes and positioned at various locations in the street canyon. A detailed overview of the instrumentation is provided in Table 1. An ultrasonic anemometer placed at the center of the street canyon at a height of 0.15 m above the ground, was used to continuously measure the wind speed and direction at the pedestrian level. Thermocouples were utilized to monitor various parameters, including the surface temperatures of both the east and west buildings, the air temperature within the street canyon, and the ground temperature. CO2 sensors were utilized to monitor the CO2 concentrations in both the east and west buildings. The thermocouples and CO2 sensors were centrally placed along the centerline of the windows on each floor at heights of 1.05, 0.75, 0.45, and 0.15 m from top to bottom. The positioning of the thermocouples for surface temperature measurements and the CO2 sensors for determining CO2 concentrations is shown in Fig. 2. To avoid interference with anemometer operation, the thermocouple responsible for monitoring the air temperature in the street canyon was attached to the metal rod of the ultrasonic anemometer at the same height of 0.15 m. Furthermore, a thermocouple was placed on the ground at the center of the street canyon to measure the ground temperature (Fig. 2). Regarding background environmental data collection during the experiment, a 10-m wind pole and two meteorological stations were installed at different locations in the field. The 10- m wind pole housed anemometers at heights of 2.4, 5, and 10 m above the ground, while the monitoring points at the meteorological stations were 2.4 m above ground level (Fig. 1a). Anemometer on the 10-m wind pole and ground-based meteorological stations were used to monitor the background wind speed, wind direction, temperature, relative humidity, and solar radiation intensity throughout the entire experimental duration.

2.3. Similarity criteria In studying the dispersion of gaseous pollutants in street canyons, the concentration ratio (*CR*) has been widely employed as a metric. *CR* represents the ratio of the pollutant concentration at a given designated location to the pollutant concentration at the source, facilitating the evaluation of the gas pollutant distribution in the street canyon. This conventional approach provides an objective assessment of pollutant dilution and aggregation under natural ventilation conditions.

However, the *CR* solely focuses on the dispersion characteristics of gas pollutants but does not consider the behavioral aspects of the target population, such as the respiration rate and allocation of time for indoor and outdoor activities. Consequently, the pollutant *CR* may not accurately capture the impact of gas pollutants on the exposed population. Therefore, the scope of this study goes beyond *CR* analysis to encompass the age structure, respiration rate, and time allocation for indoor and outdoor activities of the target population. This is accomplished by introducing the personal pollutant intake fraction (*P_IF*) and daily pollutant exposure index (*Ed*) to quantify the risk of pollutant exposure for the target population more precisely while also examining the transport and dispersion characteristics of gaseous pollutants under natural ventilation conditions. *2.3.1. Pollutant intake fraction (IF)* The intake fraction (*IF*) represents the ratio of the total amount of gaseous pollutants inhaled by the target population to the total amount of pollutants emitted. An *IF* value of 1 ppm indicates that the target population has ingested 1 mg of gaseous pollutants under total pollutant emissions of 1 kg. In other words, the former is 1 × 106 times higher than the latter. The *IF* has been extensively utilized in studies examining urban microclimates to assess the risk of exposure to traffic pollutants across different age groups [24,36]. For instance, Habilomatis and Chaloulakou employed the *IF* to evaluate the risk of pedestrian exposure to ultrafine particles emitted by vehicular traffic in the street canyons [37]. The *IF* can be mathematically expressed as follows: $IF = \Sigma N\ i\ \Sigma M\ j\ PiBi,j\Delta ti,jCj/q$ (2-1) where *N* denotes the target population encompassing a total of *N* age groups, *i* is the *i*-th group, and *Pi* is the number of individuals within the target population in the *i*-th group affected by pollutants. Moreover, *j* and *M* denote the microclimate conditions under which the target individuals in the *i*-th age group under the *j*-th microclimate condition [24,38]. Δt*i*, *j* is the time spent indoors (the dwell time) by individuals in the *i*-th age group under the *j*-th microclimate condition. *Cj* denotes the pollutant concentration at the pedestrian level in the street canyon, and *q* denotes the total amount of pollutant emissions. *2.3.2. Personal pollutant intake fraction (P_IF)* To ensure the independence of the population density, the personal pollutant intake fraction (*P_IF*) is introduced by considering the population structure depicted in Table 2 in relation to the *IF*. The *P_IF* represents the per-capita intake of pollutants and can be mathematically expressed as follows [24]: $P□\ IF = IF/\Sigma N\ i\ Pi$ (2-2) In this study, the target population was divided into three age groups (*N* = 3) based on census data. These age groups include children (*i* = 1), adults (*i* = 2), and elderly individuals (*i* = 3). Four microenvironmental conditions (M = 4) were considered, including indoor environments near street-level windows, other indoor environments, outdoor environments near vehicles, and outdoor environments away from vehicles (Fig. 3). The respiration rates of individuals in each age group are listed in Table 3. Additionally, activity patterns during different periods and population proportions of each age group in Shenzhen were determined by referring to relevant literature [38–41]. *2.3.3. Daily pollutant exposure index (Ed)* The daily pollutant exposure index (*Ed*) differs from the personal pollutant intake fraction (*P_IF*), as it represents the overall exposure of the target population to a given pollutant over the course of a day [42, 43]. *Ed* can be defined as follows: $Ed = \Sigma M\ j\ Ed,j = \Sigma M\ j\ \Sigma N\ i\ Ci,jti,j$ (2–3) where *Ci,j* is the pollutant concentration and t*i,j* is the time spent on different activities. Similar to the definition of the *P_IF*, *i* and *N* denote the age groups of the target population, while *j* and *M* denote the microenvironmental conditions to which the target population is exposed. *2.3.4. Reliability analysis of the experiments* The scaled model can represent the full-scale model; however, this evaluation requires that the geometric and dynamic characteristics of the scaled model accurately replicate those of real cities (i.e., similar airflow, radiation, and thermal inertia) [44–46]. The similarities of radiation and thermal inertia in scaled models were discussed in previous studies [26,44,47,48]. Therefore, our scaled models were constructed from concrete materials to match the thermal properties of real urban cities. The thermal conductivity *μ* (*μ* = 1761 Jm□ 2s□ 1/2K□ 1) of the concrete materials used in our experiments falls within the thermal conductivity range of typical urban materials (*μ* = 1200–2100 Jm□ 2s□ 1/2K□ 1). Given that this experiment involves a scaled model with a scale of 1:10, it is essential to evaluate the validity of the experimental findings in relation to the actual urban environment. To assess this consistency, the Reynolds number (*Re*) was employed as a validation metric, following existing research [49]. The Reynolds number can be defined as follows: $Rescaled = UrefHb\ vk$ (3-3) where *Uref* is the free flow velocity, *Hb* is the street canyon height, and *vk* is the kinematic viscosity of air, which has a value of 14.8 × 10□ 6 m2/s. According to a related study by Synder, the air flow state in an outdoor scaled experiment can be considered similar to the actual state as long as the Reynolds number in the experiment satisfies the Reynolds number independence requirement, which entails a value exceeding 11000 [44]). Moreover, in a series of studies conducted by Guanwen Chen and Dongyang Wang et al., utilizing the outdoor scaled experimental field of the SOMUCH, it was demonstrated that the Reynolds number (*Rescaled*) in the experimental process equals 41096 or 164384, thereby meeting the Reynolds number independence requirement [28]. The experimental Reynolds numbers used in this study are shown in Figs. 4 and 5. It is evident that except for a few *Rescaled* values less than street canyons with different aspect ratios, the remaining experimental results satisfy the Reynolds number independence requirement. Based on this observation, the corresponding data that did not meet the aforementioned independence requirement were excluded from the subsequent analysis of the experimental results. Consequently, it could be concluded that the wind environment of real high-density urban street canyons was effectively simulated in the outdoor scaled experiments described in this study.

3. Results and discussion

3.1. Analysis of the background environment

In this study, street canyons were classified into four categories based on their envelope features: flat-facade canyons, balcony canyons, overhang canyons, and wing wall canyons. The pollutant concentrations in each of these canyon types were individually assessed to determine the outdoor pollutant concentrations. Specifically, experiments were conducted involving balcony street canyon ($H/W = 2$) and wing wall street canyon ($H/W = 2$) during the evening of the first day. The experimental periods for these canyons were as follows: 19:56 to 21:11 and 21:51 to 22:38. Additionally, experiments involving wide street canyons ($H/W = 1$) were performed on the second day, while experiments involving flat-facade street canyon ($H/W = 2$) and overhang street canyon ($H/W = 2$) were conducted on the second morning. The experimental periods for these canyons were as follows: 10:06 to 10:45, 11:17 to 12:05, 14:56 to 15:46, 18:06 to 18:51, 19:06 to 19:55, and 20:49 to 21:20. Based on previous research [33–35], we compared background data collected during the experimental period and analyzed the temperature differences between the east and west buildings and between two wind velocity components in street canyons to avoid the effects of these inconsistencies, which have been confirmed effective by the literature [33–35]. *3.1.1. Analysis of the background wind direction and wind speed statistics* Throughout the experiment, the wind speed and direction in the background environment were continuously monitored by a weather station positioned at a height of 2.4 m ($2H$). Monitoring was conducted at 5-min intervals, and the recorded results are shown in Figs. 6 and 7. In the wide canyons ($H/W = 1$), the prevailing wind directions observed during the experiment for pollutant exposure in the flat-facade, balcony, overhang, and wing wall canyons were 22.5◦ SSE, SE, due W, and due S, respectively. The wind speeds most frequently associated with these dominant wind directions ranged from 0.4 to 0.8 m/s, 0.3–0.6 m/s, 1.2–1.4 m/s, and 0.2–0.8 m/s, respectively. In the narrow canyons ($H/W = 2$), the dominant wind direction in the background environment during the experiment in the flat-facade street canyon was due to the south. The wind speed range corresponding to this dominant wind direction ranged from 1.8 to 2.1 m/s. During the pollutant concentration experiment in the balcony street canyons, the prevailing wind direction in the background environment was southwest, and the wind speeds mostly ranged from 0.2 to 0.3 m/s, 0.4–0.5 m/s and 0.6–0.7 m/s. Subsequently, the dominant wind directions observed in the overhang and wing wall street canyon experiments were north and southwest, respectively. The wind speeds corresponding to these dominant directions ranged from 2 to 2.2 m/s and 0.8–1.0 m/s, respectively. *3.1.2. Analysis of the background temperature and solar radiation intensity* During the experiment, thermocouples were used to monitor the wall temperatures of the east and west buildings of the street canyons and the wall temperatures of the building with different envelope features. Additionally, two weather stations (Weather Stations 4 and 8) were installed at different locations within the experimental field to record the air temperature and solar radiation data for the entire field. The obtained weather station monitoring results indicated that during the evening of the first day during the above experimental periods, the temperature in the balcony street canyon (H/W = 2) and wing wall street canyon (H/W = 2), showed a consistent decline, ranging from 20.6 to 21.3 ◦C and 19.8–20.5 ◦C, respectively (Fig. 8a). On the morning of the second day, in the street canyon (H/W = 2) pollutant dispersion experiment, the air temperature remained relatively stable within the range of 20.8–21.1 ◦C. Similarly, the solar radiation intensity remained stable during the same period, except for a significant increase at 10:45 a.m., reaching approximately 21 W/m2 for the remainder of the day. In the flat facade street canyon (H/W = 2) experiment, the temperature by a rapid decrease. Concurrently, the solar radiation intensity briefly increased from 11:17 to 11:26 a.m., followed by a subsequent decrease (Fig. 8b). In the street canyon (H/W = 1) experiment conducted from 14:56–15:46 on the second day, both the temperature and solar radiation intensity reached their maximum values of the entire day, ranging from 23 to 23.8 ◦C and 22.4–25.1W/m2, respectively. During the subsequent experimental phases in the flat-facade, balcony and wing wall street canyons, solar radiation was absent, leading to a gradual decline in temperature. The temperature changes observed during these three experimental phases ranged from 21.4 to 21.8 ◦C, 20.7–21.3 ◦C and 20.1–20.3 ◦C, respectively (Fig. 8c and d).

3.2. Analysis of the wall temperature difference between the east and west buildings of the street canyon

Fig. 9 shows the temperature differences between the east and west walls of the building with different envelope features in the wide street canyons (H/W = 1). The flat-facade street canyon experiment showed that the temperature of the east wall consistently remained higher than that of the west wall. The absolute temperature difference increased with increasing height from the ground, and after 18:39,ΔTeast-west (temperature difference between the east and west walls) tended to remain unchanged on the first and second floors. In contrast, ΔTeast-west in the balcony street canyon was relatively stable, but the relative magnitude of the difference on each floor varied over time. In addition, *ΔTeast-west* was consistently higher on the fourth floor than on the third floor before 15:12 in the overhang street canyon, but the opposite trend was observed thereafter. However, *ΔTeast-west* remained higher on the third and fourth floors than on the first and second floors by approximately 0.7 ◦C and 1.1 ◦C, respectively, decreasing with increasing time. Finally, throughout the wing wall street canyon experiment, the west wall consistently faced the upwind direction, resulting in a higher west wall temperature than the east wall temperature. *ΔTeast-west* also increased with increasing temperature measurement point height, except that the absolute temperature difference on the first floor exceeded that on the second floor after 21:06. Fig. 10 shows the temperature differences between the east and west walls of the building with different envelope features in the narrow street canyon (H/W = 2). The flat-facade canyon experiment revealed that on the first floor of the building, the west wall temperature was higher than the east wall temperature. The absolute temperature difference remained stable at 0.5 ◦C or less. However, on the second, third and fourth floors, the east wall temperature was higher than the west wall temperature. *ΔTeast-west* was the largest on the second floor, followed by the fourth floor. In the balcony street canyon, the east wall temperature was lower than the west wall temperature at the first, second and third floors, but the absolute temperature difference was small and remained at approximately 0.2 ◦C. However, the east wall temperature on the fourth floor was significantly higher than the west wall temperature. In the overhang street canyon, the temperature of the east wall on the fourth floor was always lower than that of the west wall, and the absolute temperature difference gradually increased over time. Simultaneously, *ΔTeast-west* on the remaining floors fluctuated more obviously, but the absolute temperature difference always remained within 0.2 ◦C. Before 10:21, the east wall temperature on the third floor was always temperature overtook the east wall temperature. *ΔTeast-west* on the second floor fluctuated between positive and negative values. In addition, the east wall temperature on the first floor was always higher than the west wall temperature except for a few moments. Finally, in the wing wall street canyon, the east wall temperature was always lower than the west wall temperature, both on the lower and higher floors. *ΔTeast-west* was the largest on the fourth floor, followed by the first and third floors. The temperature difference between the two walls on the fourth floor was the smallest.

3.3. Analysis of the wind environment in the street canyons

To further analyze the wind environment in the street canyon, the wind velocity components in the street canyon were examined. As mentioned in the preceding section, the street canyon wind velocity in this study was continuously measured using an ultrasonic anemometer positioned at the center of the street canyon. The ultrasonic anemometer was situated at a height of 0.15 m above the ground. To facilitate a concise description of the wind environment in the street canyon, the wind velocity during the experimental period was divided into two wind velocity components: u (parallel to the street canyon direction) and v (perpendicular to the street canyon direction). Fig. 11 shows the wind velocity components along the u and v directions at the pedestrian height in each street canyon during the pollutant dispersion experimental periods in the wide street canyon ($H/W = 1$) for the different envelope features. Specifically, the average measured wind velocity components along the u direction in the flat-facade, balcony, overhang and wing wall street canyons were 0.104, 0.057, 0.018 and 0.064 m/s, respectively. This indicates that during the experimental period, the prevailing wind direction along the u direction at the pedestrian height was south to north in all street canyons. Of the u-direction wind velocity components in the different street canyons, the highest u-direction wind velocity component was recorded in the flat-facade street canyon, followed by the wing wall street canyon. The u-direction wind velocity component in the balcony street canyon was slightly lower than that in the wing wall street canyon, while the u-direction wind velocity component in the overhang street canyon was significantly lower than that in the other street canyons. Regarding the v-direction wind velocity component, average values of □ 0.032 and □ 0.046 m/s were observed in the flat-facade and balcony street canyons, respectively. These values indicate that the prevailing wind direction along the v direction at the pedestrian height in the corresponding street canyons was west to east, with a higher wind velocity in the balcony street canyon. Conversely, during the experimental period, the prevailing wind direction along the v direction in the overhang and wing wall street canyons was from east to west, with average wind speeds of 0.038 and 0.011 m/s, respectively.

Fig. 12 shows the wind velocity components along the u and v directions at the pedestrian height in each street canyon during the pollutant dispersion experimental periods in the narrow street canyon (H/W = 2) for the different envelope features. The average measured wind velocity components along the u direction in the flat-facade, balcony, overhang and wing wall street canyons were measured at □ 0.057, 0.053, □ 0.145 and 0.066 m/s, respectively. The u-direction wind velocity components significantly fluctuated in the flat-facade, overhang and wing wall street canyons. Regarding the v direction wind velocity component, average values of □ 0.136, 0.004, 0.106 and 0.028 m/s were observed in the flat-facade, balcony, overhang and the wing wall street canyons, respectively. In the flat-facade street canyon, the v directions wind velocity components fluctuated significantly. However, the v-direction wind velocity components in the balcony street canyon exhibited relatively stable behavior, with a low and nearly constant value throughout the experimental period. Furthermore, in the overhang and wing wall street canyons, the v direction wind velocity components demonstrated lower variability throughout the experimental period.

3.4. Analysis of pollutant dispersion and exposure risk in street canyons

In this study, the pollutant concentrations in wide (H/W = 1) and narrow (H/W = 2) street canyons with different envelope features were measured. The measured data were utilized to quantitatively assess the impacts of envelope features on the exposure risk of residents to pollutants in wide (H/W = 1) and narrow (H/W = 2) street canyons. To account for the presence of background CO2 in the atmosphere, the initial CO2 concentrations were measured on each floor of the buildings (Tables 4 and 5). Subsequently, CO2 was released from a pollutant source located at the center of the street canyon, and the CO2 concentration on each floor was measured in real time over a specific duration (Figs. 14 and

15). The pollutant concentrations on each floor during the experiment were then averaged, and the corresponding initial concentrations were subtracted from the obtained average pollutant concentrations to obtain the final concentrations (Figs. 13 and 16). 3.4.1. Pollutant dispersion in the wide street canyons (H/W = 1) Fig. 14 shows the pollutant concentrations on each floor in the wide street canyons (H/W=1) for the different envelope features. In the flat-facade street canyon, the average pollutant concentration on the first floor was notably higher than that on the other floors. Additionally, the average pollutant concentration gradually decreased with increasing height, and this pattern remained consistent across the different envelope features. Moreover, the average pollutant concentration on each floor of the west building consistently exceeded that on the corresponding floors of the east building. In the balcony street canyon, the average pollutant concentrations on the second, third and fourth floors of the east building, as well as on all floors of the west building, were lower than those in the flat-facade street canyon. However, there was a significant increase in the average pollutant concentrations on the first floor of the east building due to the presence of a balcony. Nonetheless, the average pollutant concentrations on all floors of the west building were lower than those on the corresponding floors of the east building. Similarly, in the overhang and wing wall street canyons, the average pollutant concentrations on each floor of the west building exceeded those on the corresponding floors of the east building. However, in the overhang street canyon, the average pollutant concentrations were lower than those in the flat-facade street canyon for both the east and west buildings. In contrast, the presence of wing walls resulted in higher average pollutant concentrations on all floors of the east and west buildings than those in the flat-facade street canyon. 3.4.2. Pollutant dispersion in the narrow street canyons (H/W = 2) Fig. 15 shows the pollutant concentrations on each floor in the narrow street canyons (H/W = 2) for the different envelope features. Compared to that in the wide street canyons (H/W = 1), pollutant dispersion in the narrow street canyons showed significant variation. Nevertheless, the general trend of decreasing average pollutant concentrations on all floors of the east and west buildings remained consistent. In the flat-facade street canyon, the average pollutant concentrations on all floors of the west building were generally lower than those on the corresponding floors of the east building, except for the first floor. However, in the balcony street canyon, there was a notable increase in the average pollutant concentration on the first floor of both the east and west buildings. Conversely, the average pollutant concentrations on all other floors were lower than those in the flat-facade street canyon. Moreover, the average concentrations on all floors of the east buildings were higher than those on the corresponding floors of the west building. In the overhang street canyon, the presence of overhangs also resulted in an increase in the average pollutant concentration on the first floor of the east and west buildings. However, the average concentrations on the second, third, and fourth floors of the east building were significantly lower than those on the same floors of the east building in the flat-facade street canyon. Conversely, except for the fourth floor, the average concentration on the second and third floors of the west building decreased relative to the flat-facade street canyon. Finally, in the wing wall street canyon, the presence of wing walls caused an increase in the average pollutant concentrations on all floors of both the east and west buildings. Simultaneously, the average concentrations on the second, third, and fourth floors of the west building were higher than those on the corresponding floors of the east building, except for the first floor.

3.5. Risk assessment of pollutant exposure

3.5.1. Analysis of the personal intake fraction (P_IF) Fig. 17 shows that the personal intake fraction (P_IF) for residents on each floor of the buildings with different envelope features in the wide street canyons (H/W=1). In the balcony street canyon, the presence of balconies contributed to an increase in the P_IF on the first floor of the east building, with a growth rate of 109 %. However, the P_IF decreased on the second, third and fourth floors of the east building, as well as on all floors of the west building. In the overhang street canyon, the presence of overhangs led to a reduction in the P_IF on all floors of both the east and west buildings. The highest decline rate, namely, 44 %, was observed on the second floor of the east building, while the lowest decline rate of 1 % was observed on the first floor of *the east building. In each floor of the buildings with different envelope features in the narrow street canyons (H/W=2). In the balcony street canyon, there was a significant reduction in the P_IF on the second, third, and fourth floors of both the east and west buildings. However, the P_IF on the first floors of both the east and west buildings markedly increased, at growth rates of 244 % and 45 %, respectively. In contrast, the presence of overhangs caused an increase in the P_IF on the first floor of the east building, while the P_IF on the other floors of the east building decreased. Conversely, regarding the west building, the P_IF on the first, second and third floors of the west building increased, whereas the P_IF on the fourth floor decreased. Additionally, the presence of wing walls significantly increased the P_IF on each floor of the east and west buildings. Notably, the impact was particularly pronounced on the third floor of the west building, with a substantial P_IF growth rate of 400 % (see Fig. 19). 3.5.2. Analysis of the daily pollutant exposure index (Ed) Fig. 20 shows that the daily exposure index (Ed) for the residents increased with decreasing height from the ground on each floor of both the east and west buildings in the wide (H/W = 1) and narrow (H/W = 2) flat-facade street canyons. Moreover, this pattern did not change with increasing street canyon aspect ratio, regardless of the envelope features present. However, the aspect ratio and envelope features could impact the specific value of Ed on each floor of the buildings. (1) The street canyon aspect ratio was increased from 1 to 2. In the flat-facade street canyon, the Ed values on the second, third, and fourth floors of the east building significantly increased, with growth rates of 27.9 %, 35.6 %, and 95.9 %, respectively. Conversely, the Ed values for the second, third, and fourth floors of the west building decreased by 9.15 %, 33.7 %, and 26.1 %, respectively, except for an 11.7 % increase on the first floor. For the balcony canyons, increasing the aspect ratio resulted in higher Ed values, which increased by 62.5 % and 5.2 % for the first and second floors, respectively, of the east building. The Ed values of the third and fourth floors decreased by 21.3 % and 46.4 %, respectively. On the west building, all floors experienced an increase in Ed as the aspect ratio increased. The highest increase in the Ed value reached 89.5 %. For the overhang street canyons, an increase in the aspect ratio leads to higher Ed values for the first and fourth floors of the east buildings, which increase by 241.9 % and 39.9 %, respectively. The values for the second and third floors of the west building increased by 36.1 % and 18.1 %, respectively. Additionally, for the wing wall street canyons, the increase in aspect ratio led to a reduction in the Ed values for all floors of the east and west buildings. The highest decline rate of the Ed values was observed on the fourth floor of the east building, reaching 44.5 % (Fig. 20). Overall, for the atmospheric flow above a street canyon, it is more difficult for airflow to penetrate deeply into a narrow street canyon. Moreover, envelope features prevent airflow from penetrating deep into narrow street canyons. As a result, the ventilation performance of street canyons decreases as the aspect ratio increases [28,33]. This, in turn, leads to a higher Ed value in narrow canyons than in wide street canyons [9], except for wing wall street canyons. Moreover, the construction of narrow street canyons produces more shaded areas, resulting in a smaller temperature difference between the east and west walls. This decreased the ventilation performance and increased the Ed value. (2) When the envelope features were changed. In the wide street canyons (H/W = 1), the presence of a balcony caused a 108.8 % increase in the Ed values on the first floor of the east building. In the overhang street canyon, the Ed values on all floors of both the east and west buildings decreased. The highest decline rate of the Ed values was observed on the fourth floor of the east building, reaching 33.8 %. However, the presence of wing walls caused a significant increase in the Ed values on all floors of both the east and west buildings, which was especially notable on the first floors of the east and west buildings, which reached 235.1 % and 280.4 %, respectively. In the narrow street canyon (H/W = 2), the presence of balconies caused the Ed values increase 243.6 % and 44.8 % on the first floor of both the east and west buildings, respectively. The presence of overhangs also caused a 241.5 % increase in the Ed value on the first floor of the east building, while the Ed values on the second, third, and fourth floors of the east building decreased by 53.5 %, 55.5 %, and 52.7 %, respectively. However, the Ed values on the first, second, and third floors of the west building increased by 58.9 %, 18 %, and 27.8 %, respectively. Finally, the presence of wing walls yielded a significant increase in the Ed values on all floors of both the east and west buildings. The highest growth rate of the Ed values was observed on the first floor of the east* *building, reaching 276.7 %. Overall, the presence of a horizontal envelope feature breaks the downward or upward flows, resulting in a large pressure difference between the upper and lower parts and enhancing the ventilation performance [10,50,51]. In contrast, the presence of wing walls obstructed pollutant transport inside the street canyon. The continuous wing wall cannot effectively break the flow along the façade or utilize the momentum of the impinging flow to create a significant pressure difference between different areas of an opening, thereby enhancing natural ventilation [20]. Therefore, the growth rate of the Ed value was greater in the wing wall street canyon than in the balcony and overhang street canyon. The presence of the balcony slowed wall heat dissipation, which in turn increased the wall temperature and obstructed pollutant transport. The growth rates of the Ed value in the balcony street canyon were greater than those in the overhang street canyon.*

4. Conclusion

In this paper, the results of outdoor scaled experiments are presented. The aim of these experiments was to evaluate the impact of different envelope features on pollutant exposure in 2D street canyons with various aspect ratios (H/W = 1, 2). Under the combined influence of wind momentum and buoyancy, the focus of this study was to analyze the impact of different aspect ratios and envelope features on the personal intake fraction (P_IF) and daily pollutant exposure index (Ed) in street canyons. The main conclusions of the study are as follows. (1) Balconies exert a beneficial impact on mitigating pollutant exposure on the second, third, and fourth floors of the east and west buildings in both wide and narrow street canyons. However, the presence of balconies leads to an increase in the P_IF on the first floors of both east and west buildings in the narrow street canyon. The highest growth rates of the P_IF, namely, 244 % and 45 %, are observed relative to those of the flat-facade street canyon. (2) The presence of wing walls in both the wide and narrow street canyons results in elevated P_IF values on all floors of both the east and west buildings. The increase in the P_IF can be substantial, with the highest growth rates reaching 291 % in wide street canyons and 400 % in narrow street canyons relative to flat-facade street canyons. (3) The presence of balconies caused the Ed values to increase 243.6 % and 44.8 % on the first floor of both the east and west buildings, respectively. Conversely, the presence of overhangs can effectively reduce the Ed values on all floors of both the east and west buildings in wide street canyons. However, the presence of wing walls can increase the Ed values on all floors of the east and west buildings in both the wide and narrow street canyons. The highest increase in the Ed values was observed on the first floor of the east building, reaching 276.7 %. (4) The envelope feature is primarily used for energy conservation. However, climate change increases the risk of pollutant exposure in high-density urban street canyons, especially in narrow street canyons. Therefore, building designers should give more consideration to envelope features that have openings, as they can improve natural ventilation and reduce pollutant exposure. (5) This study presents effective methodologies for evaluating the impact of different building features on pollutant dispersion and exposure. The conclusions of this study can lead to the use of practical criteria for architects to construct healthy, sustainable urban environments.

Limitations and future work

In this paper, an outdoor scaled experiment was conducted to assess the risk of pollutant exposure in 2D street canyons (H/W = 1, 2) with different envelope features (flat-facades, balconies, overhangs, and wing walls) under the combined influence of wind momentum and buoyancy. This study focused primarily on the impact of envelope features on pollutant exposure in 2D symmetrical street canyons. However, many factors affect pollutant dispersion in urban street canyons. Future experiments should be conducted considering various factors (i.e., step-up/step-down canyons, building layout and roof types) [6,52,53]. Since a consistent experimental period can avoid the effect of background data, future studies could include conducting an outdoor scaled experiment with a consistent experimental period and comparing the results. Moreover, to reproduce a flow field similar to that of a real city, scaled models should satisfy the dynamic independence requirements of both the Reynolds number (Re) and

Richardson number (Ri) [54]. Two types of airflow patterns, in which wind momentum dominated and the combined influence of wind momentum and buoyancy dominated, could appear in the SOMUCH. The buoyancy effect dominated urban flow seldom occurs, and obtaining the buoyancy effect dominated urban flow while satisfying the independence requirement of the Reynolds number is difficult. However, SOMUCH outdoor scaled experiments have difficulty completely reproducing the real-urban microclimate of full-scale street canyons and have no satisfied all similarity requirements. This study can provide high-quality experimental data for numerical simulations under realistic meteorological conditions. Therefore, future work can include a combination of numerical simulation and outdoor scaled experiment to investigate the full-scale urban airflow and pollutant exposure.

CRediT authorship contribution statement Dongjin Cui: *Methodology, Conceptualization.* ***Guozhu Liang:*** *Writing – original draft, Investigation.* ***Jian Hang:*** *Conceptualization.* ***Xingdi Li:*** *Investigation.* ***Cheuk Ming Mak:*** *Project administration.* ***Declaration of competing interest*** *The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dongjin Cui reports financial support was provided by National Natural Science Foundation of China. Jian Hang reports financial support was provided by National Natural Science Foundation of China. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.* ***Data availability*** *Data will be made available on request.*

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References

[1] C. Lu, L.Q. Cao, D. Norback, Y.G. Li, J. Chen, Q.H. Deng, Combined effects of traffic air pollution and home environmental factors on preterm birth in China, Ecotox Environ Safe 184 (2019). [2] M. Hachem, N. Saleh, A.C. Paunescu, I. Momas, L. Bensefa-Colas, Exposure to traffic air pollutants in taxicabs and acute adverse respiratory effects: a systematic review, Sci. Total Environ. 693 (2019). [3] W.J. Ji, B. Zhao, Estimating Mortality Derived from indoor exposure to particles of outdoor Origin, PLoS One 10 (4) (2015). [4] E.Z. Tian, Y.L. Gao, J.H. Mo, Experimental studies on electrostatic-force strengthened particulate matter filtration for built environments: Progress and perspectives, Build. Environ. 228 (2023). [5] C.H. Jeong, S. Salehi, J. Wu, M.L. North, J.S. Kim, C.W. Chow, G.J. Evans, Indoor measurements of air pollutants in residential houses in urban and suburban areas: indoor versus ambient concentrations, Sci. Total Environ. 693 (2019). [6] J. Hang, Y.G. Li, M. Sandberg, R. Buccolieri, S. Di Sabatino, The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas, Build. Environ. 56 (2012) 346–360. [7] M.F. Yassin, Numerical modeling on air quality in an urban environment with changes of the aspect ratio and wind direction, Environ Sci Pollut R 20 (6) (2013) 3975–3988. [8] S. Vranckx, P. Vos, B. Maiheu, S. Janssen, Impact of trees on pollutant dispersion in street canyons: a numerical study of the annual average effects in Antwerp, Belgium, Sci. Total Environ. 532 (2015) 474–483. [9] D.J. Cui, X.D. Li, Y.X. Du, C.M. Mak, K. Kwok, Effects of envelope features on wind flow and pollutant exposure in street canyons, Build. Environ. 176 (2020). [10] X. Zheng, H. Montazeri, B. Blocken, Impact of building facade geometrical details on pollutant dispersion in street canyons, Build. Environ. 212 (2022). [11] C.M. Mak, J.L. Niu, C.T. Lee, K.F. Chan, A numerical simulation of wing walls using computational fluid dynamics, Energ Buildings 39 (9) (2007) 995–1002. [12] J.L. Niu, Some significant environmental issues in high-rise residential building design in urban areas, Energ Buildings 36 (12) (2004) 1259–1263. [13] C.M. Mak, C. Cheng, J.L. Niu, The Application of computational fluid dynamics to the assessment of green features in buildings: Part 1: wing walls, Architect. Sci. Rev. 48 (2) (2005) 121–134. [14] Z.T. Ai, C.M. Mak, J.L. Niu, Z.R. Li, Q. Zhou, The effect of balconies on ventilation performance of low-rise buildings, Indoor Built Environ. 20 (6) (2011) 649–660. [15] D.J. Cui, C.M. Mak, J.L. Niu, Effect of balconies and upper-lower vents on ventilation and indoor air quality in a wind-

induced, naturally ventilated building, Build Serv Eng Res T 35 (4) (2014) 393–407. [16] X. Zheng, H. Montazeri, B. Blocken, CFD simulations of wind flow and mean surface pressure for buildings with balconies: Comparison of RANS and LES (vol 173, 106747, 2020), Build. Environ. 182 (2020). [17] H. Montazeri, B. Blocken, CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis, Build. Environ. 60 (2013) 137–149. [18] K.S. Jon, C.H. Sin, Y. Luo, P.Y. Cui, Y.D. Huang, J. Tokgo, Impacts of wind direction on the ventilation and pollutant dispersion of 3D street canyon with balconies, Build. Environ. 230 (2023). [19] J. Park, J.I. Choi, G.H. Rhee, Enhanced single-sided ventilation with overhang in buildings, Energies 9 (3) (2016). [20] Z.T. Ai, C.M. Mak, Wind-induced single-sided natural ventilation in buildings near a long street canyon: CFD evaluation of street configuration and envelope design, J. Wind Eng. Ind. Aerod. 172 (2018) 96–106. [21] X.M. Xie, C.H. Liu, D.Y.C. Leung, Impact of building facades and ground heating on wind flow and pollutant transport in street canyons, Atmos. Environ. 41 (39) (2007) 9030–9049. [22] F. Murena, B. Mele, Effect of balconies on air quality in deep street canyons, Atmos. Pollut. Res. 7 (6) (2016) 1004–1012. [23] A. Dallman, S. Magnusson, R. Britter, L. Norford, D. Entekhabi, H.J.S. Fernando, Conditions for thermal circulation in urban street canyons, Build. Environ. 80 (2014) 184–191. [24] D.J. Cui, X.D. Li, J.L. Liu, L. Yuan, C.M. Mak, Y. Fan, K. Kwok, Effects of building layouts and envelope features on wind flow and pollutant exposure in height-asymmetric street canyons, Build. Environ. 205 (2021). [25] Y.X. Du, B. Blocken, S. Pirker, A novel approach to simulate pollutant dispersion in the built environment: transport-based recurrence CFD, Build. Environ. 170 (2020). [26] M. Kanda, T. Kawai, K. Nakagawa, A simple theoretical radiation scheme for regular building arrays, Bound-Lay Meteorol 114 (1) (2005) 71–90. [27] Y. Nakamura, T.R. Oke, Wind, temperature and Stability conditions in an east west Oriented urban canyon, Atmos. Environ. 22 (12) (1988) 2691–2700. [28] G.W. Chen, D.Y. Wang, Q. Wang, Y.G. Li, X.M. Wang, J. Hang, P. Gao, C.Y. Ou, K. Wang, Scaled outdoor experimental studies of urban thermal environment in street canyon models with various aspect ratios and thermal storage, Sci. Total Environ. 726 (2020). [29] J. Hang, G.W. Chen, Experimental study of urban microclimate on scaled street canyons with various aspect ratios, Urban Clim. 46 (2022). [30] C. Gromke, B. Ruck, Pollutant concentrations in street canyons of different aspect ratio with Avenues of trees for various wind directions, Bound-Lay Meteorol 144 (1) (2012) 41–64. [31] P. Ghobadi, N. Nasrollahi, Assessment of pollutant dispersion in deep street canyons under different source positions: numerical simulation, Urban Clim. 40 (2021). [32] G.W. Chen, C.K.C. Lam, K. Wang, B.G. Wang, J. Hang, Q. Wang, X.M. Wang, Effects of urban geometry on thermal environment in 2D street canyons: a scaled experimental study, Build. Environ. 198 (2021). [33] Y. Bai, Y. Dong, W. Wang, D. Pan, Y. Xu, Y. Zhong, B. Chen, G. Chen, G. Wu, L. Wu, X. Wang, J. Hang, Air pollutant dispersion in street canyons based on an outdoor scale model and machine learning, Urban Clim. 47 (2023) 101381. [34] Y.W. Dai, C.M. Mak, Y. Zhang, D.J. Cui, J. Hang, Investigation of interunit dispersion in 2D street canyons: a scaled outdoor experiment, Build. Environ. 171 (2020). [35] Y.W. Dai, C.M. Mak, J. Hang, F.Y. Zhang, H. Ling, Scaled outdoor experimental analysis of ventilation and interunit dispersion with wind and buoyancy effects in street canyons, Energ Buildings 255 (2022). [36] S.L. Greco, A.M. Wilson, J.D. Spengler, J.I. Levy, Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States, Atmos. Environ. 41 (5) (2007) 1011–1025. [37] G. Habilomatis, A. Chaloulakou, A CFD modeling study in an urban street canyon for ultrafine particles and population exposure: the intake fraction approach, Sci. Total Environ. 530 (2015) 227–232. [38] C.K. Chau, E.Y. Tu, D.W.T. Chan, C.J. Burnett, Estimating the total exposure to air pollutants for different population age groups in Hong Kong, Environ. Int. 27 (8) (2002) 617–630. [39] K. Zhang, G.W. Chen, Y. Zhang, S.H. Liu, X.M. Wang, B.M. Wang, J. Hang, Integrated impacts of turbulent mixing and NOx-O3 photochemistry on reactive pollutant dispersion and intake fraction in shallow and deep street canyons, Sci. Total Environ. 712 (2020). [40] J.R. Liu, S.H. Cui, G.W. Chen, Y. Zhang, X.M. Wang, Q. Wang, P. Gao, J. Hang, The influence of solar natural heating and NOx-O3 photochemistry on flow and reactive pollutant exposure in 2D street canyons, Sci. Total Environ. 759 (2021). [41] Z.W. Luo, Y.G. Li, W.W. Nazaroff, Intake fraction of nonreactive motor vehicle exhaust in Hong Kong, Atmos. Environ. 44 (15) (2010) 1913–1918. [42] J. Hang, Z.W. Luo, X.M. Wang, L.J. He, B.M. Wang, W. Zhu, *The influence of street layouts and viaduct settings on daily carbon monoxide exposure and intake fraction in idealized urban canyons, Environ Pollut 220 (2017) 72–86. [43] Z.J. Du, J.H. Mo, Y.P. Zhang, Risk assessment of population inhalation exposure to volatile organic compounds and carbonyls in urban China, Environ. Int. 73 (2014) 33–45. [44] M. Kanda, Progress in the scale modeling of urban climate: review, Theor. Appl. Climatol. 84 (1–3) (2006) 23–33. [45] T.R. Oke, G. Mills, A. Christen, J.A. Voogt, Urban Climates, Cambridge University Press, 2017. [46] K. Wang, Y. Li, Y. Li, B. Lin, Stone forest as a small-scale field model for the study of urban climate, Int. J. Climatol. 38 (9) (2018) 3723–3731. [47] D. Pearlmutter, P. Berliner, E. Shaviv, Evaluation of urban surface energy fluxes using an open-air scale model, J Appl Meteorol Clim 44 (4) (2005) 532–545. [48] D. Pearlmutter, P. Berliner, E. Shaviv, Urban climatology in arid regions: current research in the Negev desert, Int. J. Climatol.: A Journal of the Royal Meteorological Society 27 (14) (2007) 1875–1885. [49] J. Allegrini, V. Dorer, J. Carmeliet, Wind tunnel measurements of buoyant flows in street canyons, Build. Environ. 59 (2013) 315–326.*