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# From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement

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ABSTRACT

Many buildings in urban areas are more or less naturally ventilated. A good understanding of the current status and issues of indoor environmental quality (IEQ) in naturally ventilated urban buildings and the association with urban microclimate is fundamental for improving their IEQ. This paper reviews past studies on (a) the microclimate in urban street canyons, (b) the potential influence of such microclimate on IEQ of nearby naturally ventilated buildings, and (c) the real-life IEQ status in these buildings. The review focuses mainly on studies conducted by on-site measurements. The microclimate in urban street canyons is characterized by low wind speed, high surface temperature difference, high pollutant concentration, and high noise level. Insufficient ventilation rates and excessive penetration of outdoor pollutants are two key risks involved in naturally ventilated urban buildings. Existing knowledge suggests that reasonable urban planning and careful building envelope design are the primary methods to ensure acceptable IEQ and maximize the utilization of natural ventilation. However, quantitative studies of both microclimate in street canyons and IEQ in buildings are still highly insufficient in many aspects, which make cross comparison and influencing factors analysis currently impossible. Based on the limitations of previous studies and the current issues of naturally ventilated urban buildings, suggestions are made for future studies to better understand and improve IEQ in naturally ventilated urban buildings.


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## 1. Introduction

Many buildings in a wide spectrum of geographical regions are more or less naturally ventilated, primarily because of the well-known advantages of natural ventilation in energy saving and health effect. Driven by wind and buoyancy forces [1–3], natural ventilation has a great potential to offset energy consumption by mechanical ventilation systems [4–8]. Compared to air conditioned buildings, naturally ventilated buildings are closely associated with reduced prevalence of sick building syndrome symptoms, cross-contamination risk of airborne infectious diseases, and short-term sick leave [9–15]. However, some buildings are naturally ventilated, essentially because their windows or doors have to be open to connect indoor with outdoor. Shops on the ground floors need open doors for business. Ordinary residential and school buildings must open windows or ventilation grilles, at least intermittently, to dilute indoor stale air, because ordinary domestic air conditioners provide no fresh air [16]. It was reported that continuous operation of such air-conditioners with closed windows and doors will rapidly elevate the indoor $CO_2$ concentration [17,18] and result in a deteriorated indoor air quality [8,19]. Regardless of intentions, the wide existence of natural ventilation in urban buildings highlights the need to pay special attention to their indoor environmental quality (IEQ).

IEQ in naturally ventilated buildings strongly relies on local outdoor microclimate, including particularly wind speed, air temperature, pollutant concentration and noise level [11,20–22]. Fig. 1 presents schematically the association between IEQ in naturally ventilated buildings and the microclimate in their nearby street canyon through the breath process at building envelopes. Wind speed in urban areas, especially in high-density cities, is seriously decreased [23]. Climatic data shows that wind speed at 20 m above the ground level in urban area of Hong Kong (specifically in Tseung Kwan O) has decreased from 2.5 m/s to 1.5 m/s over a 10-year period from 1994 to 2004 [24]. Low wind speeds in street canyons result in less pressure differences around buildings to drive indoor natural ventilation. It was reported that air temperature inside a street canyon is lower by 3–5 °C than the corresponding air temperature above the canyon [25] and is higher by nearly 2 °C than that in a suburban location [25,26]. In addition, traffic-related air pollution and noise are two serious environmental issues in urban street canyons. Owing to increased traffic emissions and adverse dispersion conditions including low wind speeds [27,28], pollutants can stagnate and accumulate to reach very high levels in street canyons [29–33]. Moreover, road-side noise levels measured in street canyons frequently exceed the legislated limit of 70 dBA [34–36]. Together with low wind speeds and high air temperature, such high pollutant concentrations and high noise levels could significantly deteriorate IEQ in naturally ventilated urban buildings and even hinder its use [21].

A good understanding of urban microclimate and the associated IEQ status in naturally ventilated urban buildings is fundamental for improving their IEQ. This paper provides an overview of past studies on the microclimate in urban street canyons and the associated IEQ in naturally ventilated urban buildings. To do so, it investigated relevant publications in related journals, including particularly *Building and Environment* and *Atmospheric Environment*. Major books regarding natural ventilation and urban environment were also investigated. Among these numerous publications, this paper further focused on studies conducted by on-site measurements, whereas studies by model experiments, numerical simulations, empirical and analytical models were paid little attention. On-site measurements were focused, essentially because they provide the first-hand data to reveal the real-life street canyon microclimate and IEQ in buildings, which are thus the best choice to answer the research questions defined in this paper (see next paragraph). Model experiments, such as atmospheric boundary layer wind tunnel experiments, use reduced-scale models to investigate the basic structure of flow and pollutant dispersion around building(s) and provide benchmark data for numerical validations, which, however, are constrained by similarity criteria [37]. Numerical simulations, such as computational fluid dynamics (CFD) simulations, are very powerful and widely used to investigate flow related processes in the built environment, which can provide whole-field data and do not have similarity problems [38,39]. However, both model experiments and numerical simulations use simplified physical models and cannot take the influence of all environmental parameters into account. Empirical models provide a rapid but crude estimation normally for engineering applications, while analytical models increase the understanding of physical mechanisms but are limited to very simple flow problems.

Reviews in this paper is intended to answer three questions: (a) what are the urban microclimate conditions around buildings and their possible influences on IEQ in naturally ventilated buildings; (b) what are the actual indoor environmental conditions in naturally ventilated buildings in urban areas; and (c) what are the limitations of current studies and the possible areas for future

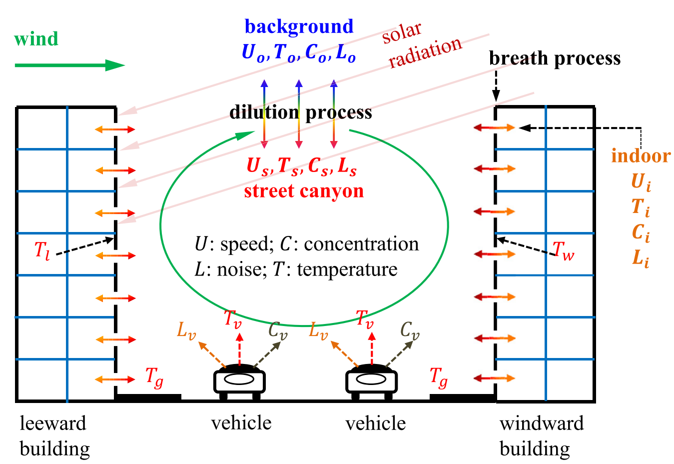


**Fig. 1.** Schematic view of the association between the IEQ in naturally ventilated buildings and the microclimate in their nearby street canyon; the subscripts *o*, *s*, *i*, *v*, *w*, *l*, and *g* of the *U*, *T*, *C*, *L* indicate outside the canyon (background), street canyon, indoor, vehicle, windward facade, leeward facade, and ground, respectively.

studies on improving IEQ in naturally ventilated urban buildings. Followed by this introduction, Section 2 reviews microclimate in urban street canyons. Section 3 reviews the IEQ in naturally ventilated urban buildings including particularly the influence of urban microclimate. Section 4 discusses existing studies and makes recommendations for future studies. Section 5 concludes this review work.

## 2. Microclimate in urban street canyons

This section provides an overview of the microclimate in urban street canyons, including airflow, temperature, pollutants and noise. Understanding urban microclimate is the basic prerequisite of understanding and thus improving IEQ in naturally ventilated urban buildings.

Air quality in skimming-flow deep canyons [23] was mostly investigated, as they represent the worst condition for pollutants dilution [91].

### 2.1. Airflow

Compared to rural areas, wind speed in urban areas is seriously decreased as a result of increased roughness caused by various constructions and complex streets [23–25]. Decrease of wind speed in street canyons poses an important limitation to apply natural ventilation in dense urban areas [40].

Flow pattern in an urban area depends on the building disposition, particularly the aspect ratio AR (ratio of the mean building height H to the street width W) [23]. When the buildings are widely spaced (AR < 0.3–0.4), their flow fields do not interact and thus are almost the same with those around isolated buildings. At closer spacing (AR up to 0.65–0.7), the wake of an upstream building is interfered by the flow field of its downstream building. At even greater spacing (AR > 0.65–0.7), the ambient flow skims over the building tops; such a flow regime is called skimming flow. The study of wind environment in skimming-flow street canyons were paid special attentions, as they are generally considered to be with a worse wind condition compared to those in lower AR streets. Flow patterns inside a street canyon are very distinctive in response to different ambient wind conditions above the canyon [11,23,25,41–45], which are particularly associated with the along and the across canyon velocity components above the canyon. Under a parallel ambient flow, if the wind speed above the canyon is high, a strong relationship between the outside and the inside flows can be found. Wind inside the canyon flows along the canyon axis with possible uplifts along the building walls, due to the friction of building walls and ground surface. Under a perpendicular ambient flow, if the wind speed above the canyon is high, the canyon flow can be seen as a secondary circulatory flow driven by the imposed flow above the canyon. Under an oblique ambient flow, which occurs in most time, helical vortexes could be developed along street canyons. For all ambient wind directions, if the wind speed above the canyon is low, the coupling between the upper flow and the canyon flow is lost, where thermal flows and mechanical disturbances play a significant role in shaping the wind flow patterns inside the canyon.

The threshold ambient wind speed depends on the canyon AR. According to [46], who worked with a street canyon with AR equal to 1.4, the threshold value to establish the coupling and to form circulatory vortexes inside the canyon is between 1.5 m/s and 2.0 m/s. Similar values are reported by Refs. [41,42,47,48]. They worked with canyons having aspect ratios ranging from 1 to 1.52. However, as shown by Ref. [49], for canyons with a higher AR (that is 2.5 in their study), the coupling is established under a much higher ambient wind speed ranging approximately between 4 m/s and 5 m/s (corresponding to the across canyon wind speed equal to 2–3 m/s). It was also stated that the correlation between the wind speed inside and above the canyon is unclear when the ambient wind speed was below this range [49]. The value 4 m/s was defined as the threshold wind speed in their later studies [50,51] of predicting wind speeds inside street canyons. Comparison of these results may imply that the threshold wind speed increases with the increase of AR value. This should be explained by that a faster wind is required to penetrate into a deeper street canyon. However, the influence of other factors, such as meteorological condition and buoyancy force, on this threshold cannot be revealed from these studies [41,42,46–51].

Some studies measured simultaneously wind speeds inside and outside (mostly above) a canyon, which are summarized in Table 1. Note that there could be several measurement locations along

**Table 1**
Comparison of measured wind speeds inside and above canyons; climate classification is made according to Köppen–Geiger Climate Classification System [52]; $U_o$ is ambient wind speed, $U_{o-m}$ mean ambient wind speed, $U_{o-p\%}$ p% of ambient wind speeds, and similar naming method for wind speed inside canyon $U_i$, L/H ratio of street length L to building height H.

| City/climate | Measurement period | AR | L/H | Ambient wind speed (m/s) | Ambient wind direction | Wind speed inside canyon (m/s) | Reference |
|---|---|---|---|---|---|---|---|
| Stafford/Maritime temperate (Cfb) | Mar.–Dec. 1997 | 0.59 | – | $U_{o-m} = 6.25U_{i-m}$ | – | Total: $U_{i-m} = 0.16U_{o-m}$ | [53] |
| Kyoto/Warm temperate (Cfa) | – | 1 | – | $U_{o-m} = 1.49U_{i-m}$ | – | Total: $U_{i-m} = 0.67U_{o-m}$ | [41] |
| Watford/Maritime temperate (Cfb) | – | – | – | $U_{o-m} = 1.59U_{i-m}$ | – | Total: $U_{i-m} = 0.63U_{o-m}$ | [54] |
| Athens/Dry-summer (Csa) | Jul. 19–23, 2002 | 1.7 | 2.25 | $U_{o-m} = 3.4$<br>$U_{o-25\%} < 2.1$<br>$U_{o-95\%} < 6.6$ | Perpendicular: 21%<br>Parallel: 13%<br>Oblique: 66% | Horizontal: $U_{i-50\%} < 0.6$, $U_{i-95\%} < 1.5$<br>Vertical: $U_{i-m} = 0.34 - 0.46$ | [55] |
| Goteborg/Maritime temperate (Cfb) | Jun. 2003–Aug. 2004 | 2.1 | 3.3 | $U_{o-m} = 1.8 - 2.5$ | – | Total: $U_{i-m} \leq 0.5$ | [45] |
| Athens/Dry-summer (Csa) | Jul. 7–15, 1997 | 2.5 | 7.1 | $U_{o-93\%} < 5.0$<br>$U_{o-50\%} < 2.0$ | Perpendicular: 7%<br>Parallel: 12%<br>Oblique: 81% | Total: $U_{i-45\%} < 0.3$, $U_{i-96\%} < 1.0$<br>Horizontal: $U_{i-m} = 0.35$<br>Vertical: $U_{i-m} = 0.26$ | [49] |
| Ghardaia/Arid (BWh) | Feb. 19–24, Sep. 6–13, 2005; Aug. 6–15, 2006 | 2.7–2.9 | 9.4–11.6 | $U_{o-m} = 1.0 - 3.0$ | – | Total: $U_{i-m} = 0.5 - 1.5$ | [56] |
| Athens/Dry-summer (Csa) | Sep. 2001 | 3.3 | 1.7 | $U_{o-(89\%-94\%)} < 4.0$ | Perpendicular:28%<br>Parallel: 16%<br>Oblique: 56% | Total: $U_{i-m} = 1.0 - 2.0$ | [25] |
| Tinos/Dry-summer (Csa) | Summer and winter | 0.7–0.9<br>2.0–4.0 | – | $U_o = 9.0 - 16.0$ | – | $U_{i-m} = 1.0 - 6.5$<br>$U_i < 2.0$, $U_{i-m} \approx 1.0$ | [26] |

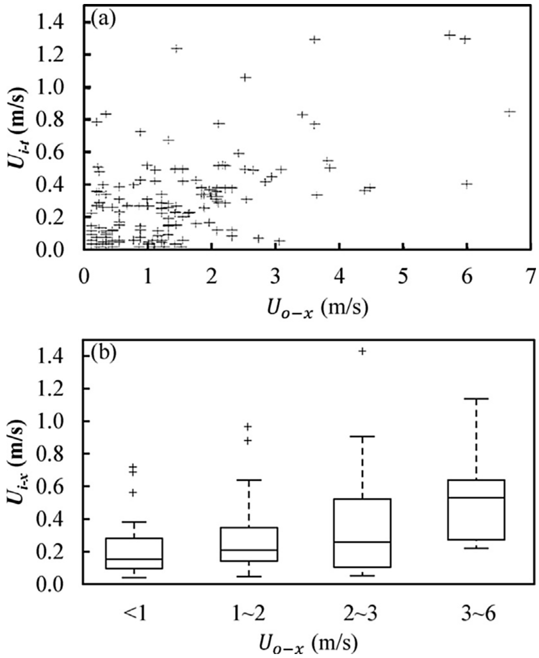


**Fig. 2.** Relationship between wind speeds inside and above a canyon with AR equal to 2.5 [49]: (a) variation of the total wind speed inside the canyon ($U_{i-t}$) as a function of the along canyon wind speed above the canyon ($U_{o-x}$), and (b) box plot of the along canyon wind speed inside the canyon ($U_{i-x}$) against various classes of the parallel to the canyon wind speeds above the canyon.

vertical and/or horizontal directions inside a canyon and their statistical values are presented. Comparison of these wind speeds inside and outside street canyons leads to four remarks.

First, regardless of other influencing factors, a significant decrease of wind speed inside a street canyon is evident in comparison with wind speed outside the canyon. Fig. 2 presents the statistical relationship between wind speeds inside and above a street canyon with an AR equal to 2.5. The ratio of wind speed inside a canyon to that outside the canyon is mostly in the order of 10–30%, whereas relatively large ratios (over 0.6) are reported by Refs. [41,54]. Variation in this ratio should be attributed to many influencing factors, such as topography, gross building coverage ratio [57], canyon AR [25,40,44], locations of measurement, and ambient wind speed and direction above the canyon. In addition, if the coupling of wind flow between canyon interior and its above atmosphere is not established, this wind ratio should be of little significance. Even if the coupling is achieved, the relationship between the wind ratio and other influencing factors is still unknown.

Second, wind direction inside street canyons is complex, which is dominated by the along canyon flow combined with upward and downward movements [49,55]. Fig. 3 presents the hourly averaged wind flow patterns on an across canyon vertical plane, where the upward and downward flows are strong and the normal-to-facade flows are very weak. In addition, it was reported that mean wind speeds in the canyon centerplane generally increase with height [25]. These first two remarks indicate the importance of considering urban effects in natural ventilation studies.

Third, wind speed inside a canyon does not necessarily decrease with the increase of canyon AR. Apart from AR, there are other important factors governing the flow field inside a canyon. For examples, it was found that thermal effects [41], end effects, or finite length canyon effects [48], canyon length ratio (L/H) [43], and traffic induced turbulent effects [43] play important roles in shaping the flow characteristics inside a canyon.

Fourth, measurements are almost independent from each other in terms of meteorological condition, measurement location,

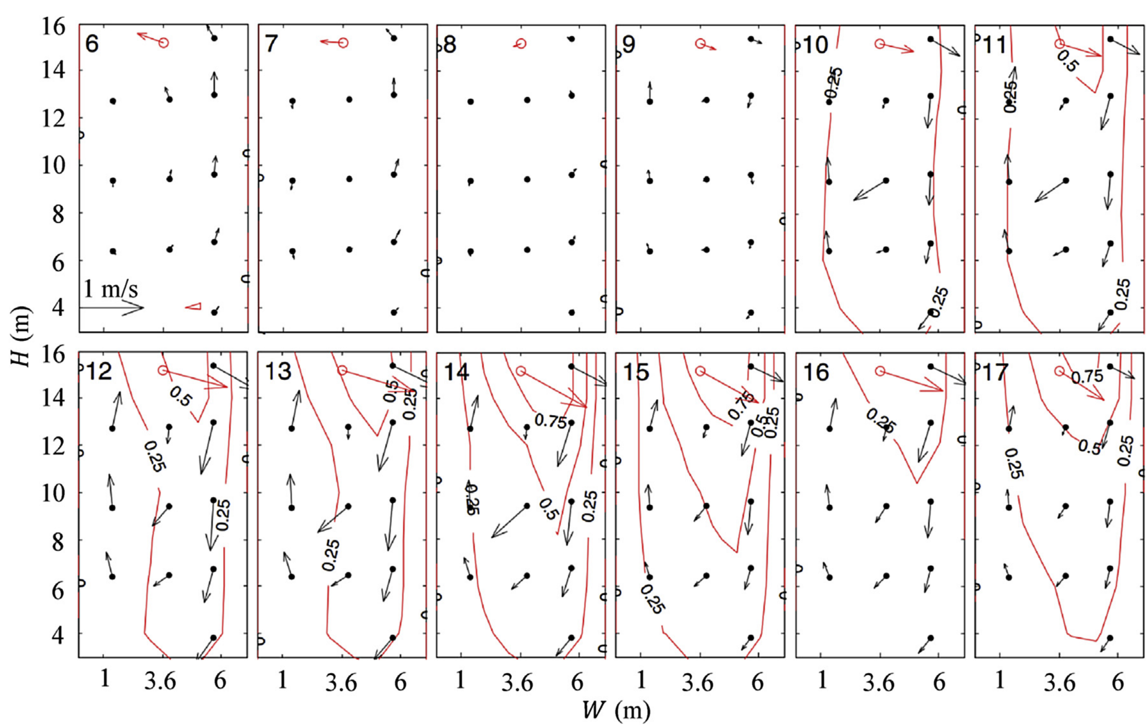


**Fig. 3.** Hourly averaged wind flow patterns inside a canyon with AR equal to 2.1 from 6:00 a.m. to 17:00 p.m. on a specific day, with the mean ambient wind speed of 1.8 m/s, ranging from 0.2 m/s to 4.7 m/s [45]. The numbers in the upper left indicate the start hour in a day. Black vectors are observed fields in the across canyon plane (a reference vector is shown in the 6 h plot). The contours show the interpolated along canyon wind speed within the canyon. The vector emanating from the circle at top center is the reference wind on the along canyon plane, where the right direction represents the east.

measurement duration and data presentation, which makes cross comparison between different measurements impossible. Particularly, the influence of climate characteristics cannot be revealed from short-term measurements, as the meteorological condition during measurements and the measurement period in a year have major influences on the measured results. Therefore, long-term measurements, such as one year or at least one season, are useful to reveal the general wind conditions for a specific urban configuration in a specific climatic region.

### 2.2. Temperature

Air temperature inside a street canyon strongly determine the cooling potential of natural ventilation of its nearby buildings [25], while temperature difference between canyon surfaces is an important driving force of flow movements in a canyon particularly when the ambient wind flow is slow.

Surface temperatures of a canyon are closely associated with local climate, urban morphology, thermal properties of building and street materials, canyon orientation, canyon AR, and sky view factor. Fig. 4 presents a schematic view of the thermal environment inside a street canyon, where the maximum temperatures and temperature differences reported in two previous studies [49,58] are also included. In general, due to different solar incidence angle, horizontal ground surfaces have much higher temperatures than vertical wall surfaces [58–62]. With a same solar incidence angle, a surface with a lower albedo can reach a much higher surface temperature than that with a higher albedo [58]. The change of solar incidence angle with time could lead to a significant change in surface temperatures inside a canyon, with daily amplitudes up to 35 °C, while the maximum temperature between two opposite building walls with and without direct solar radiation was observed to be up to 19 °C [49]. In addition, a canyon with a higher AR value has a more restricted sky view factor and thus can produce a stronger shading effect to solar radiation [26,60,63,64] than a canyon with a lower AR value. This supports considering high AR urban configurations in low latitude geographical regions, where minimization of solar radiation is a desirable criterion in urban design [60,64]. Compared to the results measured in a canyon with AR equal to 2.5 [49], relatively lower surface temperatures and temperature differences were reported in a deeper canyon with AR equal to 3.3 [25], where the maximum surface temperature during the daytime varies between 35 °C and 41 °C and the maximum daily simultaneous temperature difference between the two opposite facades, as a function of the canyon's height, was between 9 °C and 18 °C.

Air temperature inside a street canyon is much lower (up to 13 °C) than the temperature on canyon surfaces of direct solar radiation [49]. However, in contrast to surface temperature, canyon configurations and surface materials do not cause an obvious influence in air temperature [26], provided that the AR value is not extremely high (e.g., higher than 7–10 in Ref. [65]). Slightly lower air temperatures (by 1–3 °C) were observed in narrower street canyons with AR ranging from 2 to 4 than those in wider street canyons with AR ranging from 0.7 to 0.9 during the daytimes, while such temperature differences were 3–4 °C during the nighttimes [26]. It is thus believed that the average air temperature is determined dominantly by large-scale regional factors rather than street-scale factors [59,66,67]. Vertically, no pronounced temperature stratification as a function of canyon's height was observed, which should be attributed to the strong mixing and advective phenomena inside the canyon [49]. However, due to shading effect, the air temperature inside a deep canyon with the AR equal to 3.3 during the daytime was observed to be 3–5 °C lower than the corresponding air temperature above the canyon [25]. In addition, the heat island effect, namely the air temperature difference between a monitoring location inside the canyon and a background station, was mostly close to 2 °C [25,26]. However, the air temperature difference between the monitoring location above the canyon and the background one was between 4 °C and 11 °C [68,69].

The above review provides a basic understanding of thermal environment in street canyons, although cross comparison of different measurements and influencing factors analysis are difficult. From above review, two remarks can be made. First, under low latitude geographical regions, deep street canyons with high ARs are an important design criterion in urban development in order to reduce solar radiation into the canyons. However, as reviewed in the previous Section 2.1, deep canyons normally correspond to stagnant wind speeds, which lead to negative effects on removing pollutants. In this context, exploring optimal AR values are still needed when taking into account solar gain, city ventilation and pollutant removal. Second, anthropogenic heat and use of low albedo (and high absorbing) street materials are important reasons causing higher temperatures inside street canyons [49]. Akbari et al. [70] reported that changing the surface albedo from 0.25 to 0.4 in a typical mid-latitude warm climate can lower afternoon air temperatures on summer days by 4 °C. Owing to the heat rejection by air-conditioners, the recessed spaces outside high-rise residential buildings in Hong Kong have a maximum temperature elevation of 11 °C [71].

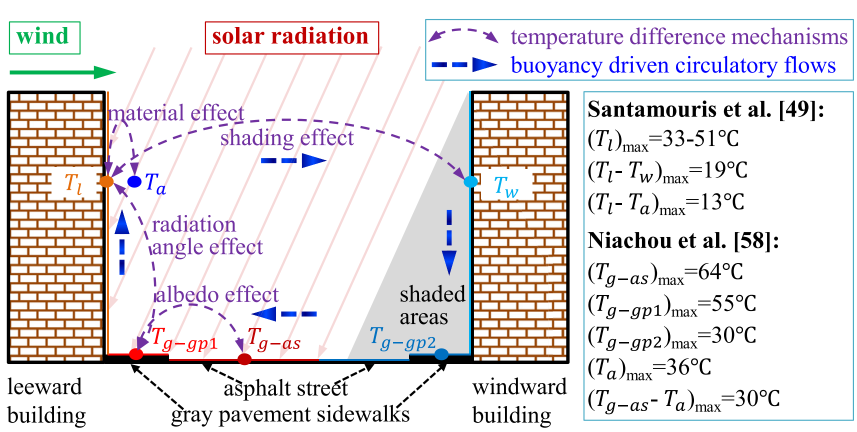


**Fig. 4.** A general view of thermal environment inside a street canyon, where the major causes of temperature differences, and the maximum temperatures and temperature differences reported in two references [49,58] are provided; symbols $T_a$, $T_{g-gp1}$, $T_{g-gp2}$, and $T_{g-as}$ indicate temperature of air, temperature of sunlit ground with gray pavement, temperature of shaded ground with gray pavement, and temperature of sunlit ground with asphalt street, respectively.

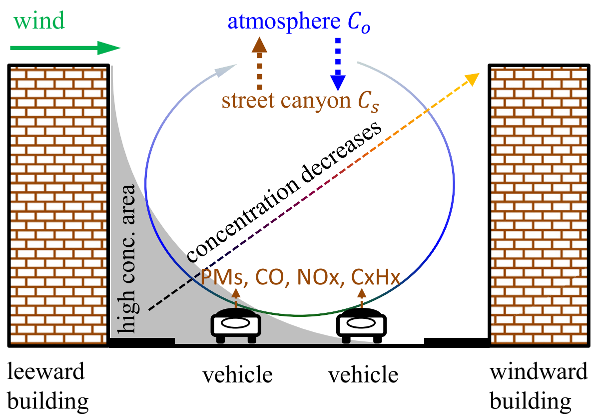


**Fig. 5.** Major influencing factors of pollutants level and their distribution inside a street canyon: traffic intensity, mass exchange rate between street canyon and its upper atmosphere, and wind flow pattern.

### 2.3. *Traffic pollutants*

Traffic exhausts have long been recognized as one of the major anthropogenic sources of air pollution in urban areas [72–76]. The main traffic-related pollutants are PMs, CO, NOx, hydrocarbons [77,78]. Due to the increased traffic emissions and/or adverse dispersion conditions [27], pollutants can accumulate to reach very high levels in street canyons in comparison with background concentrations [29–33,79–86]. Traffic-related pollutants like $PM_{10}$, CO, benzene and toluene in street canyons were reported to frequently exceed the safety thresholds suggested by local or WHO air quality standards [87,88]. High levels of traffic-related pollutants can seriously deteriorate urban air quality and cause damage to human health [89,90].

Similar with flow pattern, air quality in skimming-flow deep canyons [23] was mostly investigated, as they represent the worst condition for pollutants dilution [91]. Under a specific environmental condition, a narrower canyon generally corresponds to a worse street-level air quality [92]. Dispersion and dilution of airborne pollutants in a street canyon rely strongly on the exchange rate of flow between a canyon interior and its upper atmosphere [93,94]. When the ambient wind speed above a canyon is too low to establish the coupling between the canyon interior and its upper atmosphere (see Section 2.1), pollutants accumulate in the street canyon [46,95–97]. On the contrary, when the ambient wind speed is sufficiently high to establish such a coupling, pollutants can be effectively diluted to the upper atmosphere. The pollutant concentrations and pedestrian exposure levels in street canyons are closely associated with the traffic intensity [98–101]. Typically, high concentrations of traffic-related pollutants, such as $PM_{2.5}$, $PM_{10-2.5}$, black carbon (BC) and monocyclic aromatic hydrocarbons, in street canyons were reported in rush hours on workdays [102–104].

Fig. 5 presents schematically a spatial concentration distribution inside a street canyon. In general, horizontally, traffic-related pollutants maintain relatively high concentrations in a region near the leeward side of a canyon [95,100,105,106], while concentrations decrease vertically along height above the ground on both sides of the canyon [27]. Vakeva et al. [107] reported that the concentrations of submicron particles and gaseous pollutants emitted at street level decrease by 80% at the height of 25 m. Concentration gradients in vertical profiles of fine particles are still obvious [27]; it is 12% between two measurement levels at 2.5 m and 8.9 m. They explained that the decrease of canyon concentrations in the upper part of the canyon is due to the enhanced turbulence and mixing. In contrast to fine particles and gases, due to the gravitational effect, significant vertical concentration gradients were reported for larger-sized particles [108].

Table 2 summarizes the reported ratios of pollutant concentration measured in a street canyon to that in a corresponding background location, such as urban park and suburban area. These concentration ratios are mostly between 1.0 and 3.0, indicating high contrasts of pollutant concentration between traffic streets and background locations. However, dependent on traffic intensity, the concentration ratios should vary in both space and time. In addition, owing to the limited number of on-site measurement, the influence of climate characteristics and the measurement period cannot be revealed from the results summarized in Table 2. Large-scale and long-term measurements would be useful for cross comparison and influencing factors analysis.

### 2.4. *Traffic noise*

Noise is another serious environmental issue in urban areas. Although a combination of many environmental noise sources contributes to shaping an urban soundscape, road traffic noise is usually the most important contributor. Exposure to excessive noise levels could result in a series of negative health effects [112], particularly hypertension [113–115].

Noise levels in street canyons are strongly associated with traffic intensity [36]. Previous on-site measurements (see Table 3) indicate that road-side noise levels in street canyons frequently exceed the legislated limit of 70 dBA [34]. Note that one study [116] reports median noise levels, while others report mean values. Exception are those reported by Morelli et al. [116], who measured noise levels in three European cities, which are all below though still close to 70 dBA. Owing to the uneven distribution of traffic intensity, these reported traffic noise levels in specific street canyon(s) could not represent the average noise level in a city, which, however, are sufficient to demonstrate the severe sound environment in urban areas. Such high levels of traffic noise would certainly lead to a deteriorated indoor sound environment.

**Table 2**
Ratios of pollutant concentration measured in a street canyon to that in a corresponding background location; climate classification is made according to Köppen–Geiger Climate Classification System [52]; PAHs is the abbreviation of polycyclic aromatic hydrocarbons, while Cr, Cu and Fe for chromium, copper and iron, respectively.

| City/climate | Measurement period | $PM_{10}$ | $PM_{10-2.5}$ | $PM_{2.5}$ | BC | Cr, Cu and Fe | NOx | $NO_2$ | NO | CO | VOCs | PAHs | Benzene | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Guangzhou/Warm temperate (Cwa) | Feb. 1–2, 2002 | 1.2 | – | – | – | – | – | – | – | 4.7 | – | – | 1.4 | [86] |
| Hong Kong/Warm temperate (Cwa) | Jan. 1 – Dec. 8, 2005 | – | 1.3 | 1.5 | – | – | – | – | – | – | – | – | – | [102] |
| 5 Dutch cities/Maritime temperate (Cfb) | 6-month beginning in Jun. 2008 | 1.2 | – | 1.2 | 1.9 | 2.0–3.0 | 1.8 | 1.5 | – | – | – | – | – | [31,109] |
| Copenhagen/Maritime temperate (Cfb) | Jan.–Mar. 1992–1994 | – | – | – | 2.4 | – | – | – | – | – | – | 3.2–5.3 | – | [110] |
| Raleigh/Warm temperate (Cfa) | Aug. 11 – Sep. 20, 1988 | – | – | – | – | – | – | – | – | – | 1.7 | – | – | [111] |
| Los Angeles/Dry-summer (Csa) | Feb. 14, 20, Apr. 7, 16, 24, 2003 | – | – | – | – | – | – | 2.0 | 13.9 | 2.6 | – | – | – | [99] |

**Table 3**
Traffic noise levels measured in urban areas.

| City | Description | Mean noise level (dBA) | Variation (dBA) | Reference |
|---|---|---|---|---|
| New York | 329 samples at 99 street sites | 73.4 | 55.8–95.0 | [36] |
| New York | 6-day measurements near a major urban highway | 74.5–76.9 | Standard deviation: 1.4–1.6 | [35] |
| Valencia | 5-year measurements at a square | 72.3–73.4 | 69–77 | [119] |
| Curitiba | 100 samples at several locations on two traffic streets | 73.1 | 68–78 | [120] |
| Athens | Short-term measurements at 9 street canyons | 75 | 66.1–81 | [117] |
| Basel | 20-min measurements at 60 street sites | 62* | 55–66 | [116] |
| Girona | 20-min measurements at 40 street sites | 64* | 60–68 | |
| Grenoble | 20-min measurements at 41 street sites | 67* | 62–69 | |

Note: * indicates median value.

Nicol and Wilson [117] measured the vertical variations of noise level in nine street canyons with AR varying from 1.0 to 5.0. Based on these measured data, they then developed a mathematical model to predict noise levels inside a street canyon as a function of street width and height above the street (see Fig. 6), which are intended to provide guidances for building design. In general, noise level increases with the increase of street width, which is attributed to that a wider street corresponds to a higher traffic intensity. Moreover, noise level attenuates along canyon height. Therefore, noise level is easier to exceed 70 dBA at the lower part of street canyons. In a deep canyon in Hong Kong [118], the noise level at several lower floors (1/F-3/F, 5/F) is greater than 70 dBA.

## 3. Indoor environmental quality in naturally ventilated urban buildings

Microclimate in street canyons would certainly influence the IEQ in nearby buildings (as indicated in Fig. 1). Only air exchange rate (ACH) and indoor air quality (IAQ) are included in this section, whereas indoor temperature and noise level are not. The influence of outdoor temperature and noise on indoor environment is almost instant and easy to be sensed by occupants. When suffering from intolerable temperature and noise level, active control measures, such as closing windows and turning on air conditioners, can be taken immediately. As a result, studies regarding indoor temperature and noise level were paid mostly to exploring subjective sensation and comfortable range, which are out of the scope of this paper. On the contrary, insufficient ACH values and excessive indoor air pollutants are difficult to detect by human body, which thus could cause serious negative health effects to occupants. Compared to temperature and noise level, ACH values and IAQ in naturally ventilated urban buildings have received much more attentions in past decades.

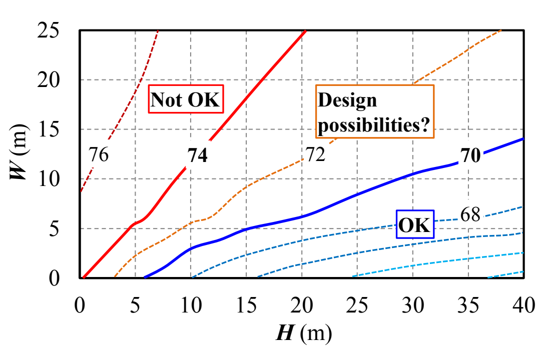


**Fig. 6.** Predicted noise levels (dBA) as a function of street width and height above the street [117]. The region (OK) with noise level lower than 70 dBA is acceptable for natural ventilation design, whereas the region (Not OK) with noise level higher than 74 dBA is unacceptable. There are possibilities for design solutions in the region between 70 and 74 dBA.

### 3.1. Indoor ACH value

#### 3.1.1. Influence of street canyon on indoor ACH value

It has been confirmed in Section 2.1 that wind speed inside a street canyon is significantly decreased compared to that above the canyon. Decreased wind speeds would result in lowered pressure differences around buildings to drive indoor natural ventilation. Therefore, natural ventilation performance in urban buildings drops largely compared to rural areas [121]. van Hooff and Blocken [122] evaluated quantitatively the influence of surrounding buildings on natural ventilation performance of a large semi-enclosed stadium using CFD method. It was found that neglecting the surroundings can lead to overestimations of the ACH up to 96% (see Fig. 7). Gao and Lee [123] worked with a group of high-rise residential buildings and found that the presence of surrounding buildings lowers the wind speed in the vicinity of buildings by 2.5%–86.8%. In addition, Georgakis and Santamouris [25] compared ACH values calculated using climate data measured inside and above a canyon with AR value equal to 3.3. Results show that, inside the street canyon, ACH values for single-sided and cross ventilation are reduced by 82% and 68%, respectively. These studies indicated quantitatively the significant blocking effect of surrounding buildings and thus suggested explicitly the importance of describing the surroundings in detail when assessing natural ventilation performance in buildings [124]. Among influencing factors, a better building disposition, particularly a wider street, is very important to enhance air penetration and movement inside street canyons and thus potentially improve natural ventilation performance in buildings [125,126].

#### 3.1.2. Real-life ACH values in naturally ventilated urban buildings

On-site measurements of ACH values in naturally ventilated urban buildings are valuable to reveal the real-life ventilation condition in such buildings (see Table 4). Analysis of these real-life

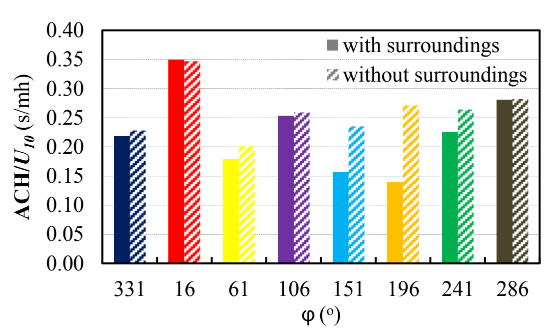


**Fig. 7.** Comparison of the predicted ACH/$U_{10}$ for eight wind directions between cases with and without surrounding buildings [122], where $U_{10}$ is reference wind speed at the height of 10 m and $\varphi$ is wind angle. At the wind angle of 196°, the overprediction of ACH/$U_{10}$ is 96% when the surrounding buildings are not included.

**Table 4**
On-site measurements of ACH value in naturally ventilated urban buildings.

| Building type | Location | AR | Mean ambient wind speed | Indoor/outdoor temperature difference | Location on a building | Opening area | Measurement technique | ACH-SS[a] ($h^{-1}$) | ACH-cross[b] ($h^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Residential buildings | Athens | 1.4 | – | – | 3rd/5 | – | Tracer gas decay ($N_2O$ and $SF_6$) | 2.6–3.1 | 10.2–15.4 | [127,128] |
| | | 2.6 | – | – | 2nd/5 | – | | 3.9–5.8 | 9.8–10.1 | |
| | Athens | 3.3 | Parallel to the canyon 3.2–3.3 m/s | 0.05 °C | 3rd/5 | 1.4 and 1.6 $m^2$ | Tracer gas decay ($N_2O$) | 0.4 ± 0.1 | 1.8 ± 0.3 | [25] |
| | Hong Kong | irregular | 1.9–4.6 m/s | <1.0 °C | 12th/27 10th/22 | 1.2–3.5 $m^2$ | Tracer gas decay ($CO_2$) | 1.5–16.1 | – | [129] |
| | Beijing | – | <0.5 m/s outside windows | <6.0 °C in summertime | Several rooms in a six-story building | 0.4 $m^2$ | Constant tracer gas injection ($CO_2$) | <1.6 | – | [17] |
| Hospital buildings | Bradford | – | 1.0–4.0 m/s | 4.6 °C | 3rd/3 | 0.1 m[c] | Tracer gas pulse injection method ($CO_2$) | – | 3.4–6.5 | [130] |
| | Hong Kong | [d] | 1.3–4.8 m/s | <1.0 °C | – | – | Tracer gas decay method ($SF_6$) | 14–31.6 | 11.9–69 | [121] |
| | Lima | 70 rooms in 8 hospitals | – | – | – | – | Tracer gas decay method ($CO_2$) | – | 18–46[e] | [13] |

Notes: [a] single-sided natural ventilation; [b] cross natural ventilation; [c] windows had a locking mechanism that restricted the maximum opening to 0.1 m; [d] one is located on a hillside surrounded by green environments and another is surrounded by high buildings; [e] interquartile range.

ACH data leads to three important observations.

First, the reported ACH values vary significantly between different measurements and some of them are insufficient (or intermittently insufficient) for maintaining acceptable IAQ, which indicates basically that natural ventilation performance is determined by many factors, such as wind speed and direction, opening configuration, surrounding characteristics, and floor location in a building. This is a well-known disadvantage of natural ventilation technique. Georgakis and Santamouris [25] observed very low ventilation rates, probably because the outdoor wind was nearly parallel to the canyon axis during the measurements. Relatively small ventilation rates obtained by Gilkeson et al. [130] could be attributed to the fact that the maximum opening was 0.1 m due to a locking mechanism. The one-year measurement in four-students dormitories by Li et al. [17] showed that single-sided natural ventilation could not provide sufficient outdoor air to dilute the indoor $CO_2$ in 18% of the measured period, while ACH values were all less than the recommendation (2.3 $h^{-1}$) of IAQ standards [131]. In addition to small window area (0.4 $m^2$), insufficient ventilation rates should be attributed to that during approximately 73% of the measurement period the outdoor wind speed was slower than 0.5 m/s. With similar reasons, Santamouris et al. [132] reported that insufficient ventilation rates occurred during teaching periods in approximately 77% of the measured classrooms and about 52% of the classrooms presented a mean indoor $CO_2$ concentration higher than 1000 ppm. In addition, influence of wind speed and floor location in a building on natural ventilation performance is very significant [133–139], although it is not explicitly revealed in these measurements (listed in Table 4).

Second, despite of being unstable, natural ventilation could potentially provide very high ventilation rates, particularly when cross ventilation is achieved. Hospitals especially benefit from this advantage of natural ventilation, as they normally require a high ventilation rate, namely 6 $h^{-1}$ for general ward environments and 12 $h^{-1}$ for isolation wards [140,141]. Regarding the unstable characteristics, hybrid ventilation combining natural and mechanical ventilations should be a promising option, which is discussed in Section 4.

Third, in addition to wind effect, buoyancy effect due to temperature difference is another driving force of natural ventilation. However, these measurements (listed in Table 4) indicated that indoor/outdoor temperature differences in naturally ventilated buildings, particularly in residential buildings, are very small, less than 6.0 °C even in the cold climatic region, Beijing [17]. Although the indoor/outdoor temperature differences can be much larger in wintertime [17], natural ventilation would not be (fully) used in such conditions. With such small temperature differences, wind-induced pressure differences are mostly the dominated driving force for natural ventilation.

### 3.2. Indoor air quality

#### 3.2.1. Evidences of outdoor penetration

A large amount of literature reported indoor/outdoor (I/O) concentration ratio of PMs and other pollutants, which are intended to reveal the relative relationship of pollutant concentration between the indoor and the outdoor environment. However, I/O ratios of general pollutants that can be generated from both the indoor and the outdoor environment are hardly helpful for understanding the indoor and outdoor concentration relationship, as they vary considerably among different studies [142–144]. Such variations could be attributed to that the I/O ratios depend strongly on indoor and outdoor emission rates, window or crack characteristics and air exchange rates. Studies of PM levels inside and outside naturally ventilated residential buildings [145], commercial office buildings [146] and school buildings [147] indicated that indoor activities are the main contributor of indoor PM levels.

However, there are sufficient evidences demonstrating that outdoor pollutants can easily penetrate into its nearby indoor environment through flow exchanges [146,148–151]. Fischer et al. [152] reported that outdoor $PM_{10}$ and $PM_{2.5}$ concentrations are 15–20% higher at homes located in high traffic intensity streets in Amsterdam than those in low traffic streets, while outdoor concentrations of the particulate components Benzoapyrene (BaP) and total PAHs, as well as the gaseous components benzene and total VOCs are almost 100% higher at high traffic intensity homes. Similarly, I/O ratios for $PM_{2.5}$ were found to be higher at the trafficked site than the residential site [153]. A comparative study by Lai et al. [154] found that the I/O ratio of ozone for using natural ventilation is significantly higher than for using mechanical ventilation with filtrations. Moreover, Rivas et al. [155] reported that the indoor levels of traffic sourced pollutants, such as $NO_2$, equivalent black carbon (EBC), ultrafine particles (UFP) and stibium (Sb), are very similar to those recorded outdoors.

Although many studies confirmed the contribution of outdoor pollutants into the indoor air pollution, only a few studies clarified quantitatively such a contribution. Particularly, Zhu et al. [156] measured UFP in and out of four buildings near a freeway, where there were no indoor UFP generation sources. They found that I/O ratios under natural ventilation with open windows are close to 1.0 (see Fig. 8), which are substantially higher than those under infiltration and mechanical ventilation. Kliucininkas et al. [157] measured indoor and outdoor PAHs in six urban homes. When there is no indoor PAHs source, the I/O ratio ranges from 0.05 to 0.36, which can be regarded as the penetrated portion from the outdoor environment. Amato et al. [158] analyzed the indoor and outdoor sources of $PM_{2.5}$ in 39 primary schools. They found that approximately 47% of indoor $PM_{2.5}$ is generated indoors and 53% outdoors. Among outdoor sources, the traffic contribution was highlighted, suggesting avoiding orienting windows directly to the traffic street. Meier et al. [159] modeled indoor air pollution originated from the outdoor environment using regression models, revealing that the fractions of outdoor pollutants entering indoors are between 30% and 66% except for the coarse particles. These quantitative studies indicate explicitly that outdoor air pollutants are an important contributor of indoor air pollution. However, the amount of penetration is still highly case-dependent.

*3.2.2. Penetration process*

The studies reviewed in Section 3.2.1 measured I/O ratios in practical conditions, where the pollutant sources were uncontrollable and the emission rates were uncertain. A few studies investigated the dynamic process of outdoor pollutants penetrating into the indoor environment under a controlled outdoor pollutant source. Santos et al. [160] experimentally measured the pollutant concentration and its fluctuation in and around a one-story, two-room, compartment building placed on an outdoor open space, with a pollutant source located in front of the building model. The highest concentration and concentration fluctuation intensity were found near the windward walls, while the indoor concentration levels responded quickly to outdoor source and were much higher under naturally ventilated condition than under mechanically ventilated condition. Yang et al. [161] simulated the dispersion of outdoor traffic pollutants into the nearby buildings, focusing on examining the influence of opening ratio (ratio of opening area on a facade to the facade area) of a building on pollutant penetration. Results show that the amount of traffic pollutants entering into buildings through unit ventilation area decreases as the increase of opening ratio.

Apart from pollutants generated outside of buildings, recent studies highlighted that pollutants, particularly toxic gases or infectious biological aerosols, generated inside a room can reenter its nearby rooms in a same building through envelope vents. Such kind of pollutant dispersion is different from purely indoor pollutant dispersion, as the pollutant source is not located in the affected room. It was reported that, driven by wind pressure, CO produced from a house-used natural gas water heater installed in the balcony could diffuse into the adjacent room through crack infiltration [162], where the indoor CO concentration levels could reach a pronounced level under adverse ventilation condition. Motivated by the transmission of Severe Acute Respiratory Syndromes (SARS) within a same building, a series of studies [135–137] were conducted to investigate the pollutant dispersion from one unit to its adjacent unit in same multistory buildings through open windows via airflow route. The dispersion routes and reentry possibilities of such an inter-unit transmission in five-story buildings were revealed quantitatively (see Fig. 9 for examples), which confirmed its validity and severity. In general, these emerging modes of pollutant penetration within a same building pose a serious threaten to IAQ, which should be paid more attentions in the future.

## 4. Discussions and recommendations

Many studies have revealed the significant influence of microclimate in street canyons on IEQ in naturally ventilated buildings in urban areas, which mainly includes decreased ventilation rate and excessive penetration of pollutants and noise. Energy, daylighting, thermal comfort, human adaptation, security and privacy issues involved in naturally ventilated buildings are also very important,

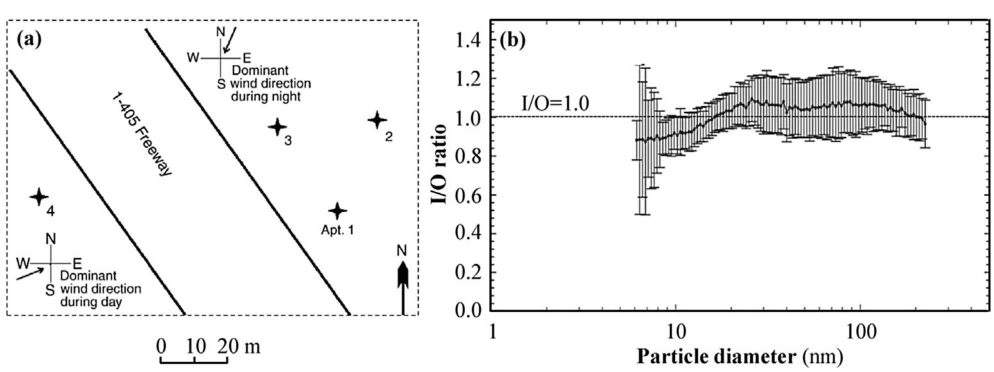


**Fig. 8.** Measurements of indoor and outdoor UFP in buildings within 60 m from the center of a freeway in Los Angeles, CA when there were no indoor UFP generation sources [156]: (a) locations of sampling apartments (Apt. 1–4) and prevailing wind directions; (b) statistical I/O ratio as a function of particle size under natural ventilation condition.

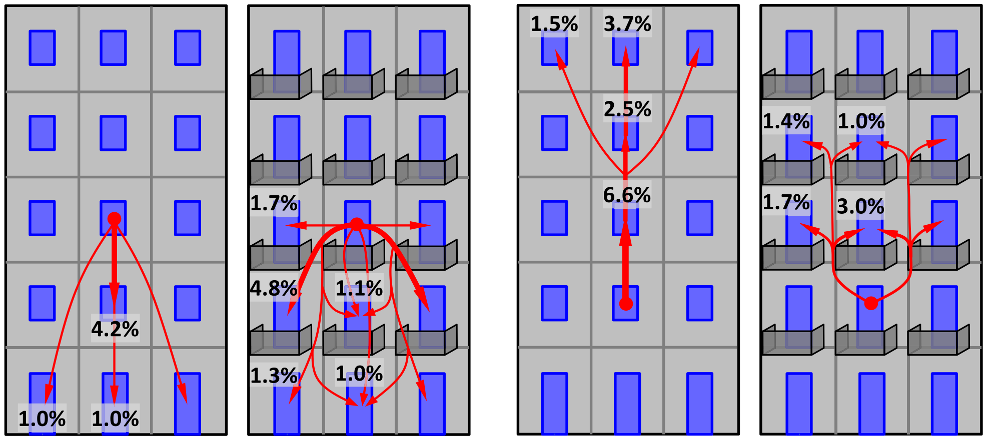


**Fig. 9.** Mean reentry ratios and dispersion routes in two generic five-story buildings without and with balconies under a normal incident wind condition [136]: left two for windward side and right two for leeward side. Reentry ratio is defined as the fraction of pollutant that is generated from an index unit and reenters another unit.

which, however, are not included in this study. Based on the review of microclimate in street canyons and IEQ in naturally ventilated buildings, this section discusses implications and limitations of existing studies and then makes recommendations for future studies.

### 4.1. Ventilation rate

#### 4.1.1. Rethinking existing studies

Existing on-site measurements (see Section 2.1) of airflow in urban street canyons have indicated that wind speeds inside street canyons are relatively small and wind directions are mostly parallel (or closely parallel) to building facades, which are very different from those found in rural areas or open spaces. Existing studies also suggested that building disposition (urban planning) based on local environmental conditions strongly determines the microclimate in street canyons [125,126]. The reason is that a well-planned urban area corresponds to an effective flow exchange between the canyon interior and its above atmosphere, which will not only ensure a moving flow in street canyons but also dilute polluted air. The former is the essential element to produce pressure differences to drive natural ventilation in buildings, and the latter helps to create a good outdoor environment for natural ventilation. Influenced by climate characteristics, meteorological condition, urban morphology, building disposition, and building height, the microclimate, particularly the wind condition, in a street canyon are very complex and are far from well understood from existing studies. In addition, the influence of these factors on the measured results cannot be revealed from existing studies. Particularly, short-term measurements are not useful to reveal the influence of climate characteristics. It is suggested that large-scale, long-term, high-resolution, standardized on-site measurements in typical street canyons should be conducted to accumulate detailed local wind data. Representative measurement campaigns in the past include the European projects URBVENT [11] and RESHYVENT [163], as well as the French project PRIMEQUAL [22]. These data can be (a) summarized and analyzed to find their correlations with other influencing factors, such as AR value, prevailing wind speed and direction and then to optimize urban planning to improve the micro-environment in street canyons, (b) analyzed to directly correlate with natural ventilation performance of nearby buildings, and (c) generalized to provide accurate boundary conditions for further CFD analysis of optimal envelope design to adapt urban environment.

Existing studies (see Section 3.1) have confirmed the significant decrease of ACH values in urban context and have provided examples of the real-life ACH values in naturally ventilated urban buildings. They imply that careful envelope designs can increase the adaptation of buildings to the urban environment and improve natural ventilation performance in terms of increasing ventilation rate and extending its operational time. However, due to the uniqueness of envelope and surrounding characteristics of a specific building in urban areas and the inconstant wind condition, these previous studies are very hard to provide a general conclusion that is applicable to other scenarios. This is the essential reason why (a) different previous studies (Section 3.1.1) reported different percentage decrease of ventilation rate caused by the presence of surrounding buildings and (b) some studies reported well acceptable ACH values but others insufficient (Section 3.1.2). In addition, the influence of environmental parameters, such as wind direction [164,165], on indoor ACH in urban buildings are still unclear. Such knowledge is essential to guiding urban planning and building design. In order to improve our understanding of and provide general information for naturally ventilated building design in urban areas, future studies may pay more attentions on two aspects. First, more on-site measurements of ACH value in naturally ventilated urban buildings should be conducted. Long-term and large-scale measurements are very useful to obtain general knowledge of natural ventilation performance in urban buildings and to analyze influencing factors. Second, future CFD studies should include more realistic boundary conditions. However, CFD studies of naturally ventilated buildings in complex urban context is still a challenge to current computational power, as the large difference in scale between windows and urban area will involve enormous amount of grid cells.

#### 4.1.2. Integration with other systems

Careful urban planning and building envelope design are primary ways to increase natural ventilation performance of buildings in urban areas. However, they alone are limited and insufficient ventilation rates occur sometimes. In view of increasingly stagnant wind flow in high density urban areas, it is important to explore other passive and/or active systems to assist natural ventilation systems to maximize its use.

Hybrid ventilation [163,166–169] that combines natural ventilation system with either mechanical ventilation or even air conditioning systems can ensure a minimum ventilation rate when the purely natural ventilation system cannot provide sufficient airflow exchanges. A more detailed discussion of hybrid ventilation is provided in Section 4.2. In addition, architectural features, such as windcatcher [170,171], balcony [133,134,172], wing wall [173,174] and ventilation shafts [175], are promoted to use in buildings to enhance indoor and outdoor airflow exchange via ingeniously utilizing the aerodynamic flow pattern around bluff bodies. However, their performance and optimal configurations need further investigations.

Combining natural ventilation with other passive cooling technologies, such as thermal mass [176,177], phase change materials [178], solar chimney [179,180], double-skin wall [181,182] and earth-air-tube ventilation [183] attracted more and more attentions in recent years. These advanced passive cooling systems in combination with standby mechanical ventilation systems would definitely improve ventilation rate, reduce pollutant and noise penetration, and be less affected by climate change and more frequent occurrence of extremely climatic events [184]. However, application of these technologies in urban buildings particularly in densely populated urban areas is limited by many factors, such as natural resources availability, integration with buildings, wind safety, cost, operation and maintenance.

### 4.2. Indoor air quality

Existing studies (see Sections 2.3 and 3.2) have revealed that (a) the concentration levels of traffic-related pollutants in street canyons are mostly 1.0–3.0 times higher than urban background concentrations and (b) the fractions of outdoor pollutants entering indoors are dozens of percentages. These results indicate explicitly the importance of taking the outdoor air quality into account when designing buildings with open windows or doors connecting indoor and outdoor. Given that the high pollutant concentration accumulated inside street canyons due to increased traffic-related sources and adverse dispersion condition, the penetration of outdoor pollutants through open windows or doors into the indoor environment should be paid particular attentions. Based on current knowledge, the possible implications and suggestions can be summarized as follows.

First, it has been evident that pollutant dilution and dispersion in street canyons is strongly dependent on the flow exchange between the canyon interior and its above atmosphere. Again, urban planning should be carefully conducted to ensure that coupling between the canyon flow and its above ambient flow can be frequently established. In addition, buildings that frequently use natural ventilation, such as residential buildings, should not be planned in high traffic intensity areas. Building design should consider its surrounding traffic conditions; particularly flow intakes should not orient major traffic streets.

Second, similar with controlling indoor heat load to promote the use of natural ventilation, a reasonable control of indoor activities to decrease indoor pollutants load is very helpful for promoting the use of natural ventilation, as indoor activities are a main contributor of indoor pollutants.

Third, although existing studies provide sufficient qualitative evidences regarding the penetration of outdoor pollutants into the indoor environment, quantitative studies are still very few. More quantitative studies should be conducted to clarify the penetration quantity and its influencing factors. Particularly, the measured indoor traffic-related pollutants should be compared with local IAQ standards.

Fourth, similarly with the third point, the dynamic process of outdoor pollutants penetrating into the indoor environment is far from well understood. Here, particulate and gaseous pollutants should be distinguished. The main objectives of understanding the dynamic penetration process are to clarify the penetration mechanisms and the influencing factors of penetration, which are the fundamental information for formulating effective control measures. In addition to traffic pollutant sources, which are almost volumetric sources, some point sources, such as exhausts of parking garages, restaurant kitchens and laundry shops, as well as even intentional releases by terrorists, are important outdoor pollutants that could have a local effect on their nearby indoor environments. More studies on these aspects are necessary.

Fifth, mechanical ventilation with filters can significantly reduce the penetration of outdoor particulate pollutants. Park et al. [18] reported that, compared with use of natural ventilation, use of mechanical ventilation with filters in residential buildings reduce I/O ratios by 26% for submicron particles and 65% for fine particles, which substantially reduces the exposure to outdoor particles. The rationale of a hybrid ventilation system is to allow maximum use of natural ventilation, while mechanical ventilation system works only when natural ventilation cannot provide the required IEQ. Good performance of hybrid ventilation with filters and tempers in residential buildings was reported recently by Turner and Awbi [169]. In general, hybrid ventilation system is a simple, feasible, low energy solution for building design, which (a) ensures sufficient ventilation rates regardless of the magnitude of outdoor wind speeds and indoor/outdoor temperature differences, (b) reduces significantly exposure to particles when the outdoor particulate pollutants' concentration levels are unacceptable for natural ventilation, and (c) can be used in almost all situations where natural ventilation can be used. Further development on hybrid ventilation should focus on its standardized application, particularly with automatic control, in residential and school buildings.

### 4.3. Indoor traffic noise

Existing knowledge (see Section 2.4) has indicated that average noise levels due to road traffic in the lower part of street canyons easily exceed 70 dBA, which would certainly result in unfavorable indoor sound environment in nearby naturally ventilated buildings. In this context, more studies should be conducted to increase the understanding of sound environment in street canyons, particularly the vertical variation of noise level and its relationship with influencing factors. In addition, noise control of naturally ventilated buildings, particularly ventilation openings, is worthy of further investigations [185]. It is evident that the most efficient method to attenuate noise is to locate the building or the windows in an area of low noise levels. Within a high noise area, typical noise control methods at an window is to present barriers, such as screen, balcony and acoustic louvre [185], and to incorporate reactive elements [186], absorptive materials [187] and ceiling-mounted reflectors [188]. These measures can generally lead to a noise reduction of up to 23 dBA [187]. Moreover, Azkorra et al. [189] found that green walls have a weighted sound reduction potential of 15 dBA.

Acoustic performance of an opening system should be provided, together with ventilation performance, to designers so that they could select an approach to satisfy both. Oldham et al. [190] proposed a technique to enable the design of acoustic and ventilation performance of opening systems simultaneously. However, there is still very few information available on the combined analysis of noise attenuation and flow characteristics of a control method. It is to date still difficult to ensure an acoustically comfortable indoor environment and an adequate flow exchange rate simultaneously in a naturally ventilated building in a high traffic intensity area.

## 5. Summary and conclusions

This paper provides a review of past studies on (a) the microclimate in urban street canyons, (b) the potential influence of such microclimate on IEQ in the nearby naturally ventilated buildings, and (c) the real-life IEQ statuses in naturally ventilated urban buildings. Based on existing knowledge, implications for urban planning and building design are summarized and recommendations for future studies are made.

In street canyons with AR greater than 0.65–0.7, wind directions are mostly parallel (or closely parallel) to building facades in both vertical and horizontal directions; wind speeds are mostly less than 1.0 m/s, decreased up to approximately 70–90% compared to those above the street canyons. Dependent on meteorological condition and canyon characteristics, the recorded simultaneous temperature difference between two facades reach up to 19 °C, while air temperature difference inside a canyon is very slight. Street canyons are hotspots for both traffic-related pollutants and noise. Mean pollutant concentrations in street canyons are mostly 1.0–3.0 times higher than corresponding urban background concentrations, while mean noise level in the lower part of a canyon easily exceeds the threshold of 70 dBA.

The ACH value of naturally ventilated buildings is significantly decreased (up to nearly 100%) in urban areas compared to that in isolated conditions. Natural ventilation sometimes fails to maintain sufficient ACH values for acceptable IAQ in urban buildings, although it can potentially provide very high (dozens of) ACH values. Traffic-related pollutants have, up to 100%, higher concentrations in high traffic intensity buildings than in low traffic intensity buildings, where the penetration of outdoor pollutants increases the indoor pollutant concentrations by dozens of percentages.

Existing knowledge suggests that reasonable urban planning and careful envelope design are the primary ways to improve the IEQ in naturally ventilated buildings and thus maximize the use of natural ventilation. For pollutant and noise, naturally ventilated buildings should be planned in low traffic intensity areas and the main windows should not orient heavy traffic streets. Hybrid ventilation using mechanical ventilation with filtrations as a standby system for natural ventilation is a promising ventilation system in urban areas to ensure a minimum ventilation rate and avoid excessive penetration of outdoor pollutants.

However, quantitative studies, particularly on-site measurements, of both the microclimate in street canyons and the IEQ in naturally ventilated urban buildings are still very few, and most of them are short-term measurements under a specific environmental condition. Cross comparison of these studies and analysis of influencing factors are currently impossible. In order to better understand and improve IEQ in naturally ventilated urban buildings, the following recommendations are made for future studies.

- Large-scale, long-term, high-resolution, standardized on-site measurements in typical urban street canyons should be conducted to accumulate microclimatic data, which are fundamental information for urban planning, building design, and even CFD simulations.
- More on-site measurements should also be conducted to increase the understanding of IEQ in naturally ventilated urban buildings. Measured data should be compared to local IEQ standards and should be analyzed to summarize influencing factors.
- Dynamic penetration process of particulate and gaseous pollutants from the street canyons to the nearby indoor environment should be investigated to understand the penetration mechanisms and generate design guidelines.
- Combined analysis of flow characteristics, pollutant penetration, and noise attenuation should be conducted to optimize building envelope design to adapt street canyon microclimate.
- More efforts should be made to solve related issues of combining natural ventilation with other active and/or passive cooling technologies in urban buildings.

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