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A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies

Afiq Witri Muhammad Yazid[1], Nor Azwadi Che Sidik[1], Salim Mohamed Salim[2] and Khalid M Saqr[3]

Abstract

As a result of rapid urbanization in numerous cities around the world, the demand for transportation has increased rapidly, resulting in emission of high levels of exhaust pollutants into the atmosphere. This is a major cause of deterioration in the local air quality, with consequent escalating risk of adverse health conditions amongst urban inhabitants. Understanding dispersion of pollutants in street canyons, local urban configurations, meteorological processes, and other physical factors are essential for predicting and assessing air quality. This article presents a comprehensive review of the state-of-the-art research works relevant to the investigation of flow structures and pollutant dispersion phenomena in urban street canyons. Various factors, including building geometries, local atmospheric conditions, static and dynamic obstructions, as well as chemical reactions of exhaust pollutants, are critically discussed by taking into account field measurements, wind tunnel experiments, operational modeling techniques, and computational fluid dynamics (CFD). The most critical pollutant levels in street canyons under several physical circumstances are identified. Elements leading to discrepancies and resulting in inconsistencies of different research methods are briefly addressed and suggestions for future research are offered.

Keywords

Urban street canyon, air quality, flow structure, pollutant dispersion

1. Introduction

Air quality is of the utmost importance in cities, especially since the numbers of road vehicles are much higher, hence contributing to the deterioration of urban air quality. Over 600 million people worldwide are exposed to traffic-generated pollutants based on estimates by the United Nations.[1] Past studies identified that poor air quality is mainly contributed to by traffic emissions,[2] with the largest pollution level occurring in urban street canyons due to drastically reduced ventilation. These pollutants typically consist of substantial amounts of carbon monoxide (CO), nitrogen oxide (NO), and sulfur dioxide (SO_2), which are dangerous to residents in urban areas. Studies have shown that long-term exposure to traffic-generated pollutants results in various adverse health problems.[3,4]

A few comprehensive reviews are available in the literature, including those by Vardoulakis,[5] Ahmad et al.,[6] Li et al.,[7] and Afiq et al.[8] They discuss the range of techniques currently employed in investigating air quality in urban areas and their contributions towards the understanding of flow structure and pollutant dispersion in street canyons. Each review paper discretely focused on different aspects of interest and did not encompass all contributing factors. For example, Vardoulakis explained the available operational modeling related to the investigation of wind flow and pollutant dispersion.[5] Ahmad et al. focused on wind tunnel investigations,[6] while Li et al. covered studies performed using computational fluid dynamics (CFD).[7]

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The present article differs from previous reviews by collectively accounting for all of the state-of-the-art findings by systematically drawing attention to the production of vortex regimes and the dispersion of traffic-induced pollutants corresponding to different street canyon geometries, wind and thermal conditions, static and dynamic physical obstructions, as well as chemical reactions. The review will discuss both symmetrical and asymmetrical configurations including various roof shapes. This will be followed by looking at the influence of differing wind velocities, atmospheric stratification, differential wall heating, static (trees plantings) and dynamic (moving vehicles) physical obstructions and also chemical reactions. The work aims to provide the insight of the current research status related to the investigation of flow structure and pollutant dispersion benefiting urban planners and policy makers in ensuring that urban development is carried out in a sustainable manner without compromising the air quality.

Once the main aspects influencing the air flow and pollutant dispersion have been discussed, they are summarized in tabular form. These tables can be used as a reference to identify the outcomes due to different building configurations and incoming wind flow conditions.

1.1. Urban flow dynamics and analysis methods

A street canyon is said to be symmetrical if the adjacent building heights are equal. The dimensions of a street canyon are expressed by its aspect ratio, *H/W* (building height to street width) and *L/W* (building length to street width) (Figure 1). Based on the approximate values of aspect ratios, street canyons can be classified (Table 1). On the other hand, a street canyon is said to be asymmetrical if the relative height of buildings on the opposite sides of the street canyon are unequal and can be distinguished into two categories depending on the height of the upwind (H_A) or downwind (H_B) buildings (Table 1) with respect to the approaching wind flow. The classification presented here is conventionally used by numerous researchers.

The interaction of prevailing atmospheric conditions with buildings creates complex flow structures (i.e. separation, circulation, and reattachment) and diverse air ventilation systems in urban street canyons. Due to the generation of these structures, the dispersion of pollutants is hindered and as a consequence, pollutants accumulate near street level, where the majority of human activities take place.

There are numerous methods and tools employed for the study of flow structures and pollutant dispersion processes and these include field measurements, wind tunnel experiments, operational modeling techniques, and CFD.

Field measurements carried out in urban street canyons using hot wire anemometer and pollutant analyzer for wind flow and pollutant concentrations provide real-time data for specific locations.[9,10] However, the major setback of this approach is that the governing parameters simultaneously fluctuate during the measurement intervals due to unpredictable meteorological and other changing conditions such as number of cars.[11] Hence, it is difficult to meaningfully interpret the data obtained.

Small scale measurements via wind tunnel or water channel experiments have advantages over field studies as the influencing factors can be controlled and parameterized. This approach also allows for scalability from simple street canyons up to regional length scales by carefully fulfilling the physical similarity criteria.[12] Due to the high cost of constructing and maintaining experimental rigs, this method is not favored. In addition, the exact full scale conditions are sometimes difficult to obtain in wind tunnels (e.g. thermal conditions via Richardson number).

Another method employed for the investigation of air flow and pollutant dispersion is operational simulation models such as the operational street canyon pollution model (OSPM) and atmospheric dispersion modeling system (ADMS).[13–15] These models use semi-empirical equations based on parameterization techniques deduced from extensive analysis of experimental data and model tests and incorporate meteorological conditions, pollutant concentrations and street configurations. Only a small amount of input is required and the computational cost is relatively

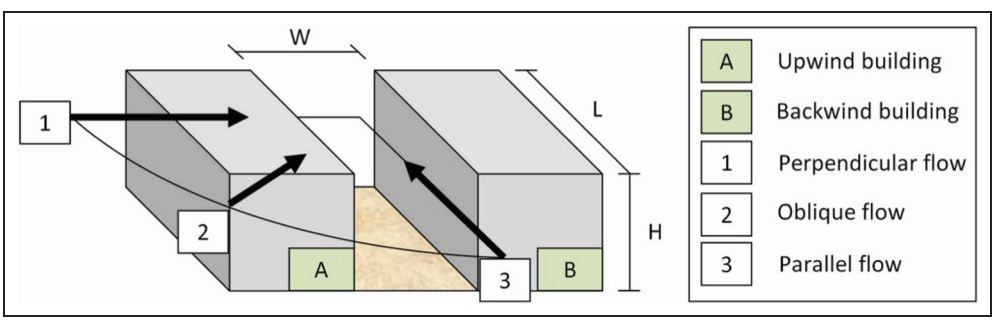

Figure 1. Geometry of a street canyon.

Table 1. Classification of street canyons.

Aspect ratio	Classification
$H/W \leq 0.5$	Avenue canyon
$0.5 < H/W < 2$	Regular canyon
$H/W \geq 2$	Deep canyon
$L/W \leq 1$	Short canyon
$1 < L/W < 5$	Medium canyon
$L/W \geq 5$	Long canyon
$H_A > H_B$	Step-down canyon
$H_A < H_B$	Step-up canyon

low, hence it is attractive to many regulatory bodies.[16] However, the shortcomings of these models are that they fail to accurately predict the flow field and pollutant concentration at different street configurations that have not yet been parameterized, as addressed by Vardoulakis et al.,[17] Di Sabatino et al.,[18] and Murena et al.[19]

1.2. The role of CFD in studying urban flow dynamics

In recent decades, CFD has become popular amongst the academic and industrial research community. In CFD, a series of fluid transport equations such as continuity, Navier–Stokes, and other auxiliary equations are solved using discretization techniques such as the finite volume method. Compared to operational models, CFD models (e.g. ANSYS FLUENT and OpenFoam) are much more realistic as they are based on governing equations of fluid flow systems, whereas the operational models are based on semi-empirical relations deduced from experiments. The CFD method also has the advantage of providing comprehensive data of all variables unlike experiments that are limited by the locations and numbers of sensors and other measuring devices, hence making further analysis feasible. The nature of wind flow is highly characterized by turbulent flows, therefore special additional closure schemes are needed to solve the transport equations. The so-called Reynolds-averaged Navier–Stokes (RANS)-based turbulent models, large eddy simulation (LES), and direct numerical simulation (DNS) are widely used to solve turbulent flows and they differ in terms of computing time and accuracy.

At present, the majority of the wind engineering research community use RANS-based turbulence models, particularly the k–ε closure scheme because it is numerically stable and provides the fastest convergence with the least computational demand.[20–22] But since most of the RANS models are based on the linear eddy viscosity assumption (i.e. Boussinesq hypothesis), the method is inaccurate for situations where turbulence mixing is significant. In such situations, LES and DNS can be adopted. The LES method lies in between RANS and DNS in terms of solution accuracy and computational time. Meanwhile, the DNS approach requires a highly prohibitive mesh resolution accounting up to the smallest eddies (i.e. the Kolmogorov length scale), whereas the LES method is more viable because it models the smaller universal eddies while only resolving the energy-carrying larger eddies. LES has been shown to be superior to RANS, with much better results when validated against an experimental benchmark.[23,24]

2. Canyon configurations and roof shapes

2.1. Symmetric canyon

Due to their design simplicity, symmetric street canyon configuration has been the central topic for the vast majority of researchers in the past few decades. The most prominent flow formation in a street canyon is central dominant vortex first described by Albrecht,[25] which was further analyzed by Georgii et al. and DePaul and Sheih.[9,26]

Another important study appeared in the work of Oke,[27] which describes the formation of three flow regimes inside a street canyon at certain threshold values of aspect ratio (H/W) with the L/W up to 8, namely isolated roughness flow (H/W = 0.1667), wake interference flow (H/W = 0.25), and skimming flow (H/W = 1). Sini et al. refined the threshold value of H/W for infinitely long canyon using CFD techniques,[28] and found that the isolated roughness flow regime occurred at even wider street canyon (H/W) of 0.11. In the isolated roughness flow, two vortices are produced with each located at the leeward corner building and backwind corner building and, due to the wide street, these vortices do not interact with each other. In the wake interference flow, due to the closer gap of the street width, the flow in the street canyon is mixed with the interaction of both vortices. As in the H/W = 1 case, a clockwise recirculation is produced in the street canyon.

Most of the wide street canyons are usually found at suburban area including residential area and small commercial buildings. High-rise buildings on the other hand are mostly located in the city center and the average buildings aspect ratio is more than one. Wind tunnel results has found that two vortices are developed in a deep street canyon (H/W = 2.0), where an upper vortex is driven by the ambient air flow at roof level and a lower vortex is weakly driven in the opposite direction by the circulation above it.[29,30] Numerous numerical investigations also revealed the production of the third vortex, vertically aligned in a deep street canyon typically for H/W = 3.[31,32] For even higher aspect ratio ($H/W >$ 5), more than three vortices are produced, as reported by Li et al.[33,34] The newly created vortices were found to be emerging from the bottom corner of backwind buildings and moved towards the center of the bottom of canyon and this process was repeated again for each increment of aspect ratio (H/W) with the strength of the lower vortices that was relatively weak compared to vortex at roof level.

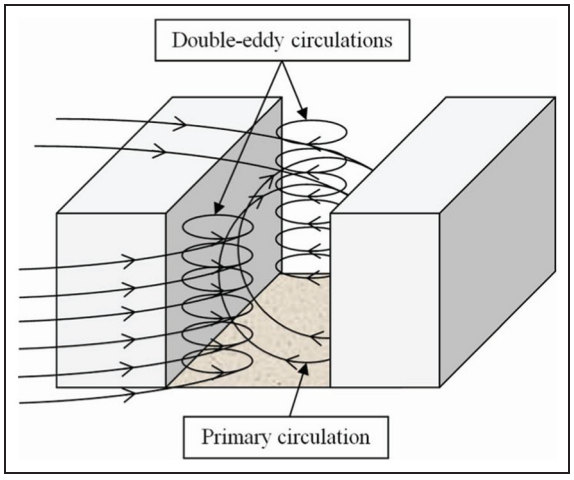

Figure 2. Flow structures in an isolated street canyon with perpendicular air flow.

Besides the formation of cross canyon flow due to shear flow at roof level of street canyon, double-eddy circulations behind a single building, as described by Hosker,[35] were also formed (Figure 2). This was further investigated numerically by Hunter et al. for the street canyon configuration.[36] The results from their findings showed that the formation of double-eddy circulations was maintained along the height in between buildings. Moreover, the extension length of a double eddy on street canyon corresponds to the formation of cross canyon flow, as classified by Oke,[27] which ceased for long avenue street canyons (L/W = 5 and H/W = 0.67). In another numerical finding, the absence of double-eddy circulations at deep street canyon (H/W = 2) was reported by Lee and Kim,[37] which suggested that the flow structure inside a deep canyon was solely affected by the shear flow at street canyon roof level rather than from each side of the buildings.

The production of vortices has direct impact on the air speed leading to the air ventilation, particularly inside a deep street canyon. Most studies have shown that the multiple vortices in a deep street canyon caused reduction of air speed at street level as compared to the roof level wind speed.[32,33] In addition to that, the vertical air flow associated with vortex circulation is more significant in the upper part of deep canyon ($H/W \approx 2.5$) with the descending motion stronger than ascending based on field measurement.[38] Assimakopoulos et al. found similar flow structure in a deep street canyon ($H/W \approx 3.33$) in the city of Athens at different street length,[39] which suggests the insignificant impact of street length on air flow particularly in a deep canyon.

The pollutant dispersion behavior depends strongly on air flow structures in street canyon. Several wind tunnel measurements, including those by Pavageau,[30] Meroney et al.,[11] and Pavageau and Schatzmann,[40] found gradual reduction of pollutant concentration from the bottom of a regular street canyon (H/W = 1), with the pollutant accumulated more on the leeward wall than on windward wall driven by the opposite direction of velocity at street level associated with the vortex circulation. Xie et al. also reported higher concentration at the leeward side with twice the concentration compared to the windward wall and decreased along the height of both side walls based on their measurement in a street canyon.[10]

Numerous findings show the evidence of higher pollutant concentration in street canyon corresponds to the increment of H/W aspect ratio. Using LES, Liu et al. investigated the pollutant concentration in deep canyons ($H/W > 2$) and found that high residue of pollutant resides at the bottom corner of windward wall and decreased along half lower of the windward wall.[41] Moreover, Baik and Kim also reported high pollutant concentration at the upper half of leeward wall based on the RANS turbulence model.[31,42] Recently, Liu et al. employed mathematical models to evaluate the ventilation and pollutant exchange rate.[43] They demonstrated that the maximum pollutant removal was at H/W = 0.8 although the ventilation was enhanced as H/W reduced. This was due to the pollutant re-entrainment particularly at $0.2 < H/W < 0.3$ and $H/W \geqslant 1$. In a deep street canyon, Li et al. demonstrated a very high pollutant accumulation on the bottom street of H/W = 5 compared to H/W = 3 using LES turbulence model.[33,34] This was due to very weak vortex near the ground street which contributed by the dominance of molecular diffusion over advection and turbulent diffusion, and thus causing high pollutant accumulation there. A field measurement at H/W = 5.7, obtained by Murena et al.,[44] found that CO concentration on the two sides of canyon at pedestrian level was very similar to the previous LES results,[33,34] which suggests that the transport of pollutants in deep canyons is not affected by the vortex induced, as occurs at a regular street canyon. A series of field measurements in a deep street canyon of H/W = 5.7 showed as much as three times the concentration compared to the nearby monitoring station reading in a regular street canyon H/W = 1.0 field and recommended the requirement of various monitoring stations at micro scale instead of city scale.[45,46]

Apart from different H/W aspect ratio, a numerical study by Banerjee and Christian reported the influence of street length on the pollutant dispersion.[47] In short street length, the pollutant concentration along the bottom street is almost uniform. However, for longer street canyons, the pollutants were mostly concentrated at the center of the street canyon. They described the production of a jet effect along the street canyon which helped flush away the concentration from the street canyon. Their numerical results were consistent with a field measurement made by Ossanlis et al.,[48] who found a higher accumulation time of pollutants at the middle of the street in a longer street

Table 2. Flow and vortex structure within symmetric street canyons.

Reference	Research method	Street canyon shapes		Flow structure
		H/W	*L/W*	
Oke[27]	Review and analysis of literature	Avenue / Regular canyon	Long canyon	• Found three regimes correlated to the geometrical aspect ratio: ○ Isolated roughness flow (*H/W* = 0.1667) ○ Wake interference flow (*H/W* = 0.25) ○ Skimming flow (*H/W* = 1) • The double-eddy circulation was not found.
Sini et al.[28]	CFD (RANS)			• Found refined thresholds values of H/W for different flow regimes: ○ Isolated roughness flow (*H/W* = 0.11) ○ Clockwise recirculation (*H/W* = 1)
Hunter et al.[36]	CFD (RANS)	Deep canyon	Short canyon	• The double-eddy circulation was found.
Chang et al.[29]; Pavageau[30]	Wind tunnel		Long canyon	• At (*H/W* = 2), two vortices were formed in the canyon: The upper was driven by shear flow and the lower was driven by the upper vortex.
Baik and Kim[31]	CFD (RANS)			• At (*H/W* = 3), a third vortex was formed, with its core being vertically aligned with the other two vortices.
Li et al.[33,34]	CFD (LES)			• At (*H/W* > 5), more than three vortices were identified in the flow.
Lee and Kim[37]	CFD (RANS)		Short / long canyon	The double-eddy circulation was not found.

length. Wind tunnel experiments by Dabberdt and Hoydysh found the pollutant dispersion for different building shapes,[49] e.g. square blocks and rectangular models, where the square blocks resulted in an overall decrease in dispersion with the concentrations consistently about one-third less than the rectangular models. Also, the concentration maximum shifts from mid-block for the rectangular models to the edges of the square blocks.

The symmetric street canyon was the earliest street canyon layout to be investigated, based on the above literature. It is still receiving attentions by many researchers due to its spatially huge variable and shape simplicity, which make the parametric study feasible. Some important features of flow structures and pollutant dispersion characteristics identified in the references are summarized in Tables 2 and 3, respectively. In all, the formation of vortex strongly depends on the street canyon ratio (*H/W* and *L/W*) and caused variable pollutant dispersion as follows:

- The number of vortices increases with the increase of *H/W*, whilst their rotational direction depends on vertical location inside the street canyon.
- Double-eddy circulation can only be observed in an avenue/regular canyon coupled with short street canyon.
- The increased number of vortices usually found in a deep street canyon reduces the ventilation, which subsequently increases the pollutant concentration.
- The lowest pollutant accumulation can be found in an avenue/regular canyon with short canyon.

2.2. Asymmetric canyon

With regard to their geometry, buildings comprise a large variety of configurations, as classified in Table 1. One of the most commonly seen in a typical urban city is an asymmetric street canyon. The asymmetric street canyon still holds the unique features of symmetric street canyon, which is the production of recirculation vortex but differs in terms of flow structure (number of vortex, vortex size and strength) and pollutant dispersion (pollutant concentration and accumulation) depending on the buildings height of opposite street canyon and adjacent building height along the street canyon.

An early study by Hoydysh and Dabberdt in a wind tunnel provided pollutant concentration measurements along the mid-block of each building of an asymmetric street canyon.[50] For the symmetric and step-up street canyon, the pollutant concentrations were a factor of two or greater at the leeward than the windward wall, while for a step-down configuration the concentration in the windward façade was slightly greater than leeward. Numerical simulation in a step-down street canyon by Zhang and Huber showed that the pollutant concentration at the windward façade was 2.5 times higher than the leeward façade.[51] Although the asymmetric street canyon showed different locations of pollutant concentrations, the total concentrations were generally a factor of two lower in a step-up canyon than in symmetric and step-down canyons.[50] As far as the results of Hoydysh and Dabberdt are concerned,[50] there is no information regarding the flow structure formation for the asymmetric cases.

Table 3. Pollutant dispersion in symmetric street canyons.

Reference	Research method	Street canyon shapes		Pollutant dispersion characteristics
		H/W	*L/W*	
Liu et al.[43]	CFD (LES)	Avenue canyon	Long canyon	• Found the ventilation was enhanced as *H/W* reduced but the maximum pollutant removal was at *H/W*=0.8.
Pavageau;[30] Meroney et al.;[11] Pavageau and Schatzmann[40] Xie et al.[10]	Wind tunnel Field measurements	Regular canyon	Long canyon	• Pollutant concentration was reduced in the windward side.
Banerjee and Christian;[47] Ossanlis et al.[48]	CFD (RANS) Field measurement			• Pollutants concentration mostly accumulated at the center ground of street canyon.
Banerjee and Christian;[47] Dabberdt and Hoydysh[49]	CFD (RANS) Wind tunnel		Short canyon	• Pollutant concentration was uniformly distributed on the ground. • Lower pollutant concentration compared to long canyon.
Liu et al.;[41] Li et al.[33,34]	CFD (LES)	Deep canyon	Long canyon	• The maximum pollutant concentration was at the bottom corner of windward wall and it decreased along the lower half of windward wall. • Pollutant concentration in the street level was proportional to the aspect ratio.
Murena et al.;[44] Murena and Vorraro[45,46]	Field measurements			• The concentration in a deep canyon (H/W=5.7) was three times the concentration in a regular canyon (H/W=1).

The CFD method proved its capability by providing comprehensive data of flow structure and had observed similar patterns with Hoydysh and Dabberdt for step up and step down based on numerical studies.[50] For the case of step-up notch, Garcia Sagrado et al. and Assimakopoulos et al. observed that the main vortex was extended towards upwind building roof and thus weakened the vortex intensity.[52,53] Although the vortex was weakened, the direction of the rotation remained unchanged and because of that, the pollutants was accumulated at the leeward buildings driven by vortex near the ground and easily disperse out due to the shorter upwind building. Therefore, the pollutant level within the street canyon was reducing. Assimakopoulos et al. also reported the extension of the main vortex to just above the downwind building and the formation of a weak secondary vortex with rotational direction opposite to the main vortex,[53] located at the lower downwind building corner. The pollutant emitted at the ground was recirculated by this weak secondary vortex causing high pollutant accumulation at the downwind building wall. Hence, the pollutant was concentrated more in this case than the symmetric case caused by the reduction of ventilation inside the canyon.

Xie et al. extended the numerical study of asymmetric canyons with numerous building aspect ratios according to the building aspect ratio of the upwind building height and the street width (H_A/W),[54] and the ratio of the upwind building height and the backwind building height (H_A/H_B) (Figure 3), where three regimes were defined to denote the vortices and pollutant dispersion characteristic in street canyons.

The classification of the flow regimes observed by Xie et al. is as follows:[54] for Regime I there were two co-rotating vortices in the street canyon, for Regime II a main vortex was generated in the canyon and there was one or two tiny vortices with opposite flow direction to the main vortex at the lower corner of the street canyon, whereas for Regime III there were two or three vortices. It was found that the pollutant transport and diffusion was strongly dependent upon the type of flow regime inside the canyon and exchange between canyon and the air above roof. The most favorable configuration for pollutant dispersion was in Regime II, followed by Regime I and Regime III.

Another configuration of asymmetric street canyon is the uneven buildings height of adjacent buildings along the street canyon. This configuration is also usually present in a typical street canyon having different types of buildings such as apartments, shopping complex and others. Gu et al. studied this configuration numerically using LES and observed complex flow structures which were not observed in symmetric street canyons,[55] such as the wind streamline tilting, horizontal divergence, and

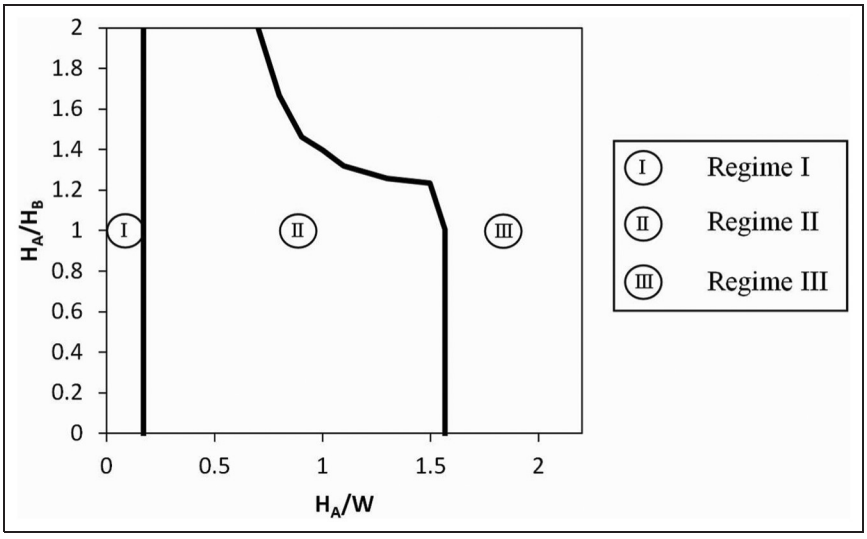

Figure 3. Flow structures in a street canyon with perpendicular air flow (after Xie et al.).[54]

convergence of air flow. These flow structures have resulted in the enhancement of air exchanges between, in, and out of the street canyon. Hence, the pollutant can be dispersed easily compared to the symmetric street canyon.

Unlike the previous sub-topic (symmetric street canyons), the asymmetric street canyon is a technically complex shape. As explained in Section 1.1, the asymmetric street canyon layout involves the relative height of buildings on the opposite sides of the street canyon and the homogeneity of the adjacent buildings height along the street, which is the most realistic representation of a typical street canyon having different types of buildings, such as apartments, shopping complexes, and others. The investigation on this layout via real scale measurement was not found, wind tunnel measurement is scarce, whereas many researchers preferred numerical simulation to analyze the specific street canyon parameters (relative buildings height on the opposite sides of street canyon or adjacent buildings). It is therefore crucial to analyze the flow structure combined with pollutant measurement in a real asymmetric street canyon to prove such findings by wind tunnel measurement and numerical simulation. Some important features of flow structures and pollutant dispersion identified in the reference are summarized in Table 4. The following notes can be drawn from the literatures of flow structure and pollutant dispersion in asymmetric street canyon:

- For the step-down or step-up canyon, the number of vortices increase with the increase of H/W and H_A/H_B, whilst its rotational direction depends on its vertical location inside the street canyon.
- The increasing number of vortices in step-down canyon, especially with deep street canyon reduces the ventilation, which subsequently increases the pollutant concentration.
- Uneven buildings enhanced pollutant dispersion by the effect of divergence and convergence of the main flow passing through it.

2.3. Roof shape

The previous topic only discussed the street canyon having flat shape on the roof. Most modern houses in urban areas have their roof with slanted shape at a certain angle and these unique features have impact on the ventilation of flow inside street canyon. The first study to investigate this aspect was initiated by Rafailidis,[56] where they made a comparison between flat roof and slanted roof through a series of wind tunnel measurement. Based on their experiments, the slanted roof shape was found to be more effective compared to flat roof in terms of air ventilation above street roof due to the turbulent shear intensification above urban fetch. However, the study by Rafailidis was not comprehensive as they did not mention any information of the flow structure within the street canyon.[56] Kastner-Klein and Plate extended the study by performing numerous wind tunnel experiments with more varieties of roof shapes.[57] The shapes are shown in Figure 4.

The distribution of pollutants along the midblock of each buildings wall are somewhat varied. By focusing on the bottom one-fifth of the building height, the roof with shape 2 yields the highest pollutant accumulation along the leeward mid-block while on the other side of the wall, roof with shape 1 yields the highest pollutant accumulation, which suggests that the backwind roof shapes coupled with the upward slanted roof at upwind buildings is the worst shape combination. The observation in similar wind

Table 4. Flow structure and pollutant removal in asymmetric street canyons.

Reference	Research method	Street canyon layout	Remarks
Hoydysh and Dabberdt;[50] Zhang and Huber[51]	Wind tunnel CFD (RANS)	Step-down canyon	• Pollutant concentration near the windward wall was greater than leeward wall.
Garcia Sagrado et al.;[52] Assimakopoulos et al.[53]	CFD (RANS)	Step-up canyon	• The main vortex was weaker than such of the symmetric street canyon. • The direction of rotation was similar to such of the symmetric street canyon. • The main vortex extends above the shorter building leading to a secondary vortex. • Pollutant removal was enhanced.
Xie et al.[54]	CFD (RANS)	Regular and deep canyon combined with step-down and step-up canyon	• Three flow regimes were identified based on the canyon aspect ratio (Figure 3). • Canyon layout within Regime III caused high pollutant accumulation.
Gu et al.[55]	CFD (LES)	Uneven buildings	• Flow was complex and characterized by: ○ streamline tilting ○ horizontal divergence and convergence of air flow • Pollutant removal was enhanced.

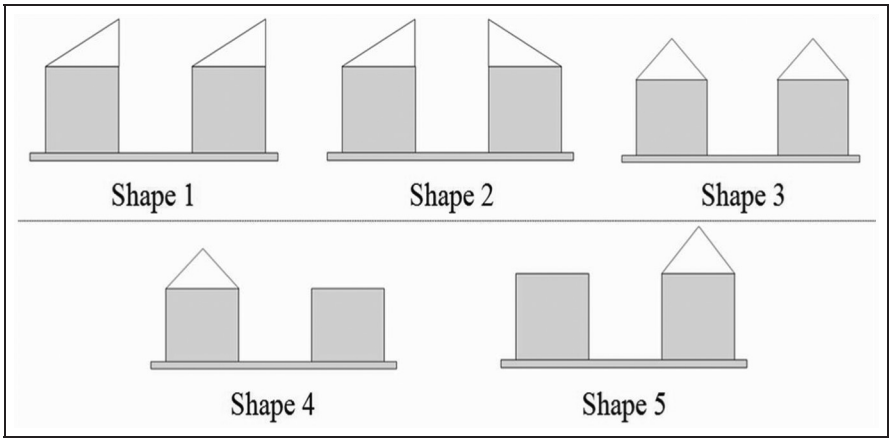

Figure 4. Various roof shapes investigated by Kastner-Klein and Plate.[55]

tunnel experiments by Kastner-Klein et al. showed that the typical street-canyon vortex did not develop for all the cases studied with pitched upwind roof (shape 3 and 4).[58] Instead, a recirculation zone formed at the upwind building ridge and spans across the downwind building, while the flow became almost stagnant inside the canyon, which explains why the pollutant dispersion pattern deviates from the reference case (flat roofs). The pollutant concentration for the flat roof at upwind coupled with pitched roofs at the backwind buildings showed similar results with flat roofs street canyon. Pitched backwind roof (shape 5) showed very similar pattern with the reference case. In general, the upwind building roof shape plays vital role in the production of flow structure in street canyon rather than the backwind building roof regardless of the shape. However, based on a comprehensive numerical investigation by Huang et al. for 17 roof shapes,[59] the height of the upstream corner of the downwind building is also equally important factor deciding the in-canyon flow pattern when a slanted shaped roof is placed on the downwind building of a canyon.

Cross referencing by the authors found no field study has ever been conducted for the investigation of flow structure and pollutant dispersion for different roof shapes. Based on numerous wind tunnel and numerical simulations, there is evidence of flow induced by the roof shapes which affects the flow structure and pollutant dispersion. Therefore, this topic can be further studied via field measurement to validate numerical simulation. The following notes can be drawn from the literature of flow structure

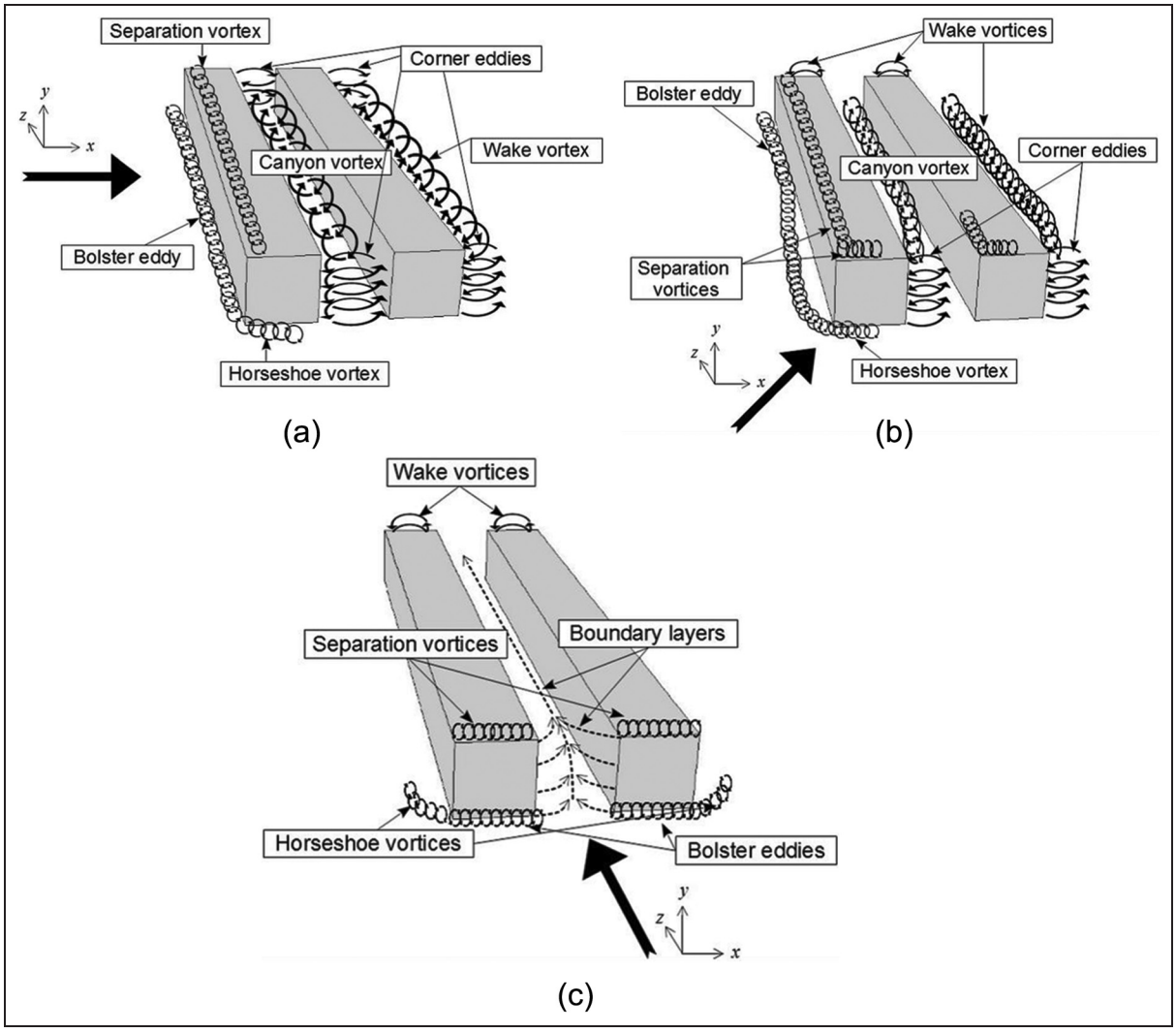

Figure 5. Flow structures around buildings and inside a long street canyon with (a) perpendicular, (b) oblique, and (c) parallel wind flow.

and pollutant dispersion in street canyon with different roof shapes:

- Slanted roof on both buildings helps to promote better air quality compared to pitched or flat roof.
- For more complex roof shapes, which involve different roof shapes on either upwind or backwind building, the air quality is highly dependent on the roof shape of the upwind building.

3. Wind conditions

3.1. Wind direction

For perpendicular wind, double-eddy circulations located along the corner of street canyon end are seen to form, driven by shear flow at each side of street canyon alongside a primary circulation or vortex, which is generally found in a street canyon due to shear flow at street roof (see Figure 5(a)).[36,60] Detailed numerical results show the complexity of the flow structure transition from perpendicular flow to oblique flow within regular ($H/W = 1$) and short canyon ($L/W = 1$).[61] The double-eddy circulations usually observed in perpendicular flow were shifted towards the flow direction, while horseshoe vortex was observed to emerge and stretched along the bottom of windward wall. In case of oblique flow in long canyon ($L/W > 4$), other features of flow structures were also identified. Early studies based on wind tunnel investigation have shown the development of a helical flow in the canyon when oblique wind was blowing.[62,63] Later, field observation by Nakamura and Oke and Santamouris et al. also reported the same patterns,[64,65] where the oblique flow induces a spiral vortex with a corkscrew type action along the length of canyon. They observed the angle of incidence on the

windward wall was similar to the angle of reflection of the wall, which explains the formation of spiral vortex across the street canyon. Yamartino and Wiegand explained that the three-dimensionality of the helical vortex was maintained by the product of both the transverse and parallel components of the incoming ambient wind.[66] The transverse component was responsible to drive the canyon vortex while the parallel component was responsible to stretch the vortex along the street canyon. In this wind condition, the strength of the vortex was about an order of magnitude lower than the wind speed above based on numerical study reported by Lee et al.[67] Czader et al. provided good visualization of the flow structures within the street canyon and around the adjacent buildings,[68] as illustrated in Figure 5(b).

When the flow is parallel to the street axis, the flow inside the street canyon and above the roof is in the same direction due to channeling effect,[64,69] whilst the mean vertical velocity is almost zero.[70] The same flow condition was measured in a deep street canyon.[65] Moreover, the channeling effect creates two regions of boundary layer within a long street canyon depending on the influence either by side wall or by the ground, as observed in numerical studies by Soulhac et al. and Soulhac and Salizzoni (see Figure 5(c)).[69,71] These boundary layer formations lead to the higher longitudinal velocity along the bottom of the avenue street canyon compared to deep canyon. Besides, the longitudinal velocity along the canyon with $H/W < 0.5$ was found to be independent of the aspect ratio. Numerical results obtained by Hang et al. also confirmed the formation of a fully developed region and its effect to the flow capacity in different street width,[72] where the normalized flow rate in an avenue canyon (H/W = 0.5–0.25) was larger than that in a regular canyon (H/W = 1). The formation of a fully developed flow region and the normalized flow rates was also maintained at certain values in all sufficiently long regular street canyon (L/W = 21.7, 43.5, 72.5).[70]

There are few studies of the pollutant concentration within broad range of street canyon configurations and of arbitrary angle of approaching wind. For a long street canyon, the wind tunnel study by Hoydysh and Dabberdt found the concentration distribution on the surface of leeward and windward walls with even, step-up, and step-down canyons for different wind angle (perpendicular, oblique, and parallel).[50] They observed that the pollutant concentration distribution on the leeward wall was higher compared to the windward wall with a gradual decrease from the bottom of street canyon as the wind was blowing in perpendicular and oblique directions. In the case of parallel flow, the pollutant concentration was identical on both of the leeward and windward walls with a gradual decrease from the bottom of the street along both walls. Analytical models by Hargreaves and Baker using Gaussian puff models found the lowest pollutant concentration when the wind was in oblique direction,[73] which is in line with previous study, whilst the pollutant concentration distribution for perpendicular and parallel was closely identical. Another analytical model, namely OSPM, was developed by Berkowicz et al. with parameterization based on an earlier field study.[74,75] This found that the lowest concentration was when wind was blowing oblique to the street axis. The lowest pollutant concentration in the oblique direction obtained by numerous results was explained by the presence of the helical flow structure and therefore has a strong influence on the local concentrations within the canyon and consequently exposure.

There have been a limited number of studies of the pollutant concentration within broad range of street canyon length configurations (L/W) combined with arbitrary angle of approaching wind. For the case of a short street canyon, a numerical analysis by Kim and Baik showed that the pollutant concentration in a short street canyon (L/W=1) was increased from perpendicular wind direction (θ = 90°) to oblique wind direction (θ = 45°) particularly along the leeward wall.[61] These numerical results are backed up by other research, where the high concentration at oblique direction wind was found at the leeward wall as compared to other wind directions measured in real urban area by Tomlin et al.[76] Kim and Baik also found that the pollutant tends to accumulate at the end of a street canyon when the wind was perpendicular to the street canyon,[61] which was also found through wind tunnel experiments by Dabberdt and Hoydysh,[49] In comparison with long street canyon, Dabberdt and Hoydysh found that the pollutant concentrations along the mid canyon height for the short canyon case (L/W = 1) were consistently about one-third less than the case of the long canyon (L/W = 10) for all wind directions,[49] indicating that the long street canyon has low ventilation which in turn trapped the pollutant inside street canyon. For parallel wind in a long street canyon, previous studies showed some contradictory outcomes. The concentration contours along the street length for both short and long canyons were very similar, where the concentration contours along the street length were essentially parallel to ground level.[49] However, other wind tunnel study observed different location of accumulation of the pollutant in long canyon. Kastner-Klein and Plate conducted a series of tunnel experiments to investigate the pollutant concentration inside longer regular street canyons (L/W = 5, 10, and 15) at different wind angle and found relatively high concentration at the end of long canyons compared to short canyons for parallel wind direction.[57] A numerical investigation by Banerjee and Christian confirmed such findings,[47] where the pollutant accumulates at the end of street canyon rather than at the middle. For the case of parallel flow with the deep street canyon ($H/W > 1$), Soulhac and Salizzoni have shown that the concentration along the street canyon increased as street canyon was narrowed down (deep canyon) due to the reduction of longitudinal

Table 5. Effect of wind direction on the flow structure and pollutant removal in long street canyons.

Reference	Research method	Wind direction	Remarks
Hunter et al.[36]	CFD (RANS)	Perpendicular wind	• Flow was mainly shear driven, characterized by a central main vortex and double-eddy circulation located along the street canyon corners.
Hoydysh[60]	Wind tunnel		
Hoydysh and Dabberdt[50]	Wind tunnel		• Pollutant concentration was higher on leeward wall compared to windward wall with gradual decrease from the ground.
Dabberdt et al.[62]	CFD (RANS)	Oblique wind	• Three-dimensional helical flow was developed.
Wedding et al.[63]	Wind tunnel		
Nakamura and Oke;[64] Santamouris et al.[65]	Field measurements		
Berkowicz et al.[74]	Operational model		• Results in the lowest concentration inside the street canyon.
Berkowicz et al.[75]	Field measurement		
Arnfield and Mills[70]	Field Measurements	Parallel wind	• The flow exhibited channeling effect and the vertical velocity component was approximately zero.
Soulhac et al.[69]	CFD (RANS)		
Soulhac and Salizzoni[71]			• Two regions of boundary layer within a long street canyon can be identified.
Hoydysh and Dabberdt[50]	Wind tunnel		• Pollutant concentration was identical on both of the leeward and windward wall with gradual decrease from the ground.
Kastner-Klein and Plate[57]	Wind tunnel		• Pollutant accumulation at the end of street canyon.
Banerjee and Christian[47]	CFD (RANS)		

velocity along the street canyon,[71] which was attributed to the formation of a boundary layer along the wall of the building and street canyon, as discussed in the previous section.

As summarized in Table 5, it can be seen that the change in wind direction will cause changes in the structure of the wind and the dispersion of pollutant in a long street canyon. The discovery of the helical vortex while the wind was oblique indicates the enhancement of air ventilation by this unique flow structure and enhances the air quality inside the street canyon. Other than that, when the length of the canyon was taken into consideration, the pollutant is varied, where the short canyon is much more preferable layout for the pollutant reduction when the wind is blowing in perpendicular and parallel to the street canyon. The following notes can be drawn from the literature on wind direction effects on flow structure and pollutant dispersion in street canyons:

- Perpendicular and oblique wind exhibit higher pollutant accumulation along the leeward wall compared to the windward wall.
- The lowest pollutant accumulation in street canyons can be found with oblique wind, whilst the highest pollutant concentration in street canyons is when the wind is blowing in parallel and becomes worst if coupled with a long street canyon.
- Short street canyons exhibit high accumulation of pollutant when the wind is blowing in an oblique direction.

3.2. Wind speed

The deterioration of air quality reported in the previous section is usually found when the approaching wind flow is perpendicular or parallel to the street canyon. Varying wind speed approaching the street canyon has different effect on the resultant flow structure and pollutant dispersion. A few field measurements in a street canyon, by DePaul and Sheih with $H/W = 1.5$ and Mazzeo et al. with $H/W = 0.8$,[9,77] have observed the disappearance of vortex for wind speed above street canyon of less than 1.5–2.0 m/s. In this condition, the air inside street canyon is almost stagnant, which in turn reduces air ventilation and results in a more homogeneous distribution of pollution across the street canyon.[78,79] In addition to that, low wind speed shows no significant effect on the flow structure and pollutant dispersion when the wind blows from any direction.[74,75] Under the low wind speed condition, the pollutant is mostly transported either by mechanical induced of moving vehicle or thermally induced under unstable atmospheric condition.

When the above canyon flow speed is more than 1.5–2.0 m/s, vortices are formed and the vortices structures

Table 6. Effect of wind speed on the flow structure and pollutant removal in street canyons.

Reference	Research method	Wind speed	Remarks
DePaul and Sheih;[9] Mazzeo et al.[77] Jones et al.[78] Kukkonen et al.[79]	Field measurements	< 1.5–2.0 m/s	• The central vortex disappeared in regular street canyons (AR = 0.8-1.5). • Air was stagnant and ventilation quality was reduced significantly. • Distribution of pollutant concentration was more homogenous than in cases exhibiting central vortex.
Baik and Kim;[31] Nazridoust and Ahmadi[80]	CFD (RANS)	High wind speed (> 2.0 m/s)	• Intensification of primary vortex. • Enhanced overall air quality particularly near the leeward building. • Improved ventilation efficiency of pollutants.
Hargreaves and Baker[73]	Operational model		
Tsai and Chen[82]	Field measurements and CFD (RANS)	Low wind speed (< 1 m/s) High wind speed (2~4 m/s)	• Pollutant concentration ratio between leeward and windward wall increased with the increase in wind speed.

may be described in terms of three regimes based on the dimensions of the street canyon as previously explained.[27] The vortex produced will cause pollutant to be advected from the bottom of the street towards the leeward wall, which in turn accumulated the pollutant near this wall. For high wind speed above street roof level, numerical studies for avenue, regular, and deep street canyons, by Baik and Kim and Nazridoust and Ahmadi,[31,80] respectively, observed the convergence of multiple vortices (primary vortex at the upper street and secondary vortices at the bottom street), becoming only one vortex due to the intensification of primary vortex. The intensification of a vortex is seen to enhance air quality in a street canyon, particularly at the leeward wall by enabling pollutant to flush out from the street more effectively, as measured by Berkowicz et al. and as calculated using the Gaussian puff model by Hargreaves and Baker.[73,81] Besides the overall reduction of pollutant reported before, the concentration ratio between the leeward and windward wall also varies, as reported by Tsai and Chen.[82] They found that pollutant concentration at the leeward wall was about 64–107% higher than the windward wall under high wind speed condition (2–4 m/s) compared with the condition of low wind speed (< 1 m/s).

Based on the literature, the effect of wind speed on flow structure and pollutant dispersion in street canyon is obvious (Table 6). By taking perpendicular wind direction for example, low wind speed does not produce the typical vortex in a regular canyon and the pollutant will remain near the source. This will cause a high pollutant concentration near the ground and has adverse effect on people living in the vicinity of pollutant source. The following notes can be drawn from the literatures of wind speed effect on flow structure and pollutant dispersion in street canyon:

- High wind speed will maintain the flow structure in street canyon (e.g. vortices, boundary layer), which helps to disperse the pollutant out of the street canyon.

4. Thermal effects

Most studies of air flow structure and pollutant dispersion explained before only consider the atmosphere to be under neutral condition or isothermal. In daytime, the atmospheric condition is also affected by temperature, where the solar radiation from the sun will heat up building facades, ground surfaces, and building roofs, which in turn heats up the ambient temperature in the vicinity of buildings and creates thermally unstable conditions. In current trends, the assessment of thermal effects on air flow and pollutant dispersion is increasing due to its contribution towards the understanding of human comfort, especially for pedestrians, air quality, and energy performance of buildings. Previous studies have shown that the stability condition of atmosphere and different heated building walls also contribute to the changes of air flow and pollutant dispersion in street canyons.

4.1. Thermal stability

The thermal stability can be categorized in general as stable, neutral, and unstable. The stability criterion requires parameters such as wall temperature, air and wind speed to distinguish different thermal stability regimes based on equations such as those for Richardson number, *Ri*, or Froude number, Fr, i.e.

$$Ri = \frac{gH(T_{ref} - T_w)}{(T_{ref} + 273){U_{ref}}^2}$$

$$Fr = \frac{{U_{ref}}^2}{gH\left(\frac{T_w - T_{ref}}{T_{ref}}\right)}$$

Table 7. Stratification of air flow at different atmospheric stability regimes.

Stability regime R_i	Unstable $R_i < -\infty$	Neutral $R_i \approx 0$	Stable $R_i > \infty$
Remarks	Air motion is dominantly induced by buoyant flows	Air motion is induced by both forced convective flow and buoyant	Air motion is dominantly induced by forced convective flow

Stability regimes based on Richardson number can be used when determining to what extent the flow is dominated by stratification, as shown in Table 7. In the same way, the characteristic of the flow based on Ri can also be determined as follows:[83]

Laminar flow becomes turbulent when $Ri < R_c$
Turbulent flow becomes laminar when $\mathrm{Ri} > R_T$

where R_c is the critical Richardson number for the onset of turbulence and R_T is the critical Richardson number for the termination of turbulence. The typical values of R_c and R_T are 0.21–0.25 and 1.0, respectively. Based on the relationship above, high value of Ri leads the flow field to become laminar, which indicates very weak wind speed in this regime.

Early investigations of flow structure and pollutant dispersion under different thermal stability were applied to a single building or structure.[84,85] Wind tunnel studies by Uehara et al. provided the first insight on how thermal stability could affect flow and turbulent structure in urban street canyons with an array of cubic buildings (street canyon with $H/W = 1$; $L/W = 1$) with thermal stability ranging from stable ($R_b = 0.79$) to unstable ($R_b = -0.21$).[86] Note that the similarity condition of R_b, which is the bulk Richardson number used by Uehara et al.,[86] was assumed to be in agreement with Ri. The outcome of the wind tunnel study showed that the primary vortex formed in between buildings became weaker when under stable atmosphere. In contrast, the intensity of the vortex became stronger when atmospheric conditions were unstable as a result of enhancement of turbulence. In particular, the wind speed at ground level was half of the wind speed above street canyon under neutral condition, while increment of wind speed of up to 60% was observed when under high unstable condition. Furthermore, the wind speed in the street canyon dropped to nearly zero, as observed when $R_b \approx 0.8$. The studies by Uehara et al. have become pivotal in the understanding of thermal instability;[86] since then, numerous numerical studies have been conducted.[87–89] The numerical results obtained by Bohnenstengel et al. confirmed the results of Uehara et al.[86,87] Later, a few numerical studies were carried out using LES with similar geometry by Kikumoto et al. and $L/W = \infty$ by Cheng and Liu,[88,89] which include detailed investigation of pollutant dispersion mechanism at different thermal stabilities. In both studies, the low intensity of the primary vortex during stable case will create stagnation of the flow at the bottom of canyon, which in turn prevents the pollutant from being transported upward. Hence, the pollutant concentration for stable case was much higher compared to neutral and unstable cases near the bottom of a street canyon. The specific location of the accumulation of pollutant also varied. For the stable case, the pollutant was seen to accumulate at the windward wall, whilst for neutral and unstable cases, the accumulation of pollutant was higher near the leeward wall, with the latter having less concentration. Despite the similarity of results for both studies, the magnitude of stream-wise velocity obtained by Cheng and Liu was smaller than that of Uehara et al. as a result of the different L/W configurations adopted in both studies.[86,89]

As explained in the above paragraph, the atmospheric conditions under thermal stability showed significant effects on the flow structure and pollutant dispersion. In particular, the stable atmospheric conditions weakened the vortices inside the street canyon and causes high pollutant accumulation while the unstable atmospheric conditions are the most favorable conditions by intensify the vortex and enhance pollutant dispersion. The following notes can be drawn from the literatures for thermal stability variation on flow structure and pollutant dispersion in street canyon:

- Unstable atmospheric conditions intensify the flow within the street canyon and thus help in better pollutant removal.

4.2. Different wall heating conditions

Nakamura and Oke found that conditions in a street canyon during the day or night remained thermally unstable;[64] they found that the maximum temperature difference between the air and the ground surface and building façade could reach 12–14°C and 8–9°C, respectively, with a typical wall of a house made from concrete and road surface made from asphalt. Meanwhile, Louka et al. found a large temperature gradient in the near-wall region in which the temperature difference between building façade and air often exceeds 10°C.[90] In summer climatic conditions, Offerle et al. found the temperature difference between the surface temperature of building facade and ambient

temperature was more than 15°C.[91] All of these measurements imply that weak or strong buoyancy forces occur in a street canyon depending on the time of the day. In addition to the thermally unstable atmospheric conditions, different heated surface wall may cause different buoyancy effects due to the interaction of heated air circulating inside the street canyon with the incoming fresh air flow into the street canyon. This is caused by the diurnal heating conditions during daytime resulting from different incident angle of sun radiation, which leads to a different surface location of the wall being heated.

The first paper to report the effects of different wall heating was the numerical study by Sini et al. using a RANS-based turbulent model with buildings aspect ratio of $H/W = 1.12$ and temperature difference of $\Delta T = 5$°C.[28] They demonstrated that in the case of ground or leeward wall being heated up, the intensity of primary vortex was strengthened due to the upward motion near the leeward wall or ground surfaces, resulting in better air quality. For windward wall heating, the primary vortex was split into two due to the buoyancy force on the windward wall, which opposed the circulation motion resulting to reduction of air quality. Kim et al. revisited the numerical study by focusing on the flow pattern and pollutant dispersion by widening the range of street canyon aspect ratio ($0.5 < H/W < 3.5$) with the combination of different wall heating conditions.[92] The resultant flow pattern inside the street canyon with different heating conditions and aspect ratios was characterized by the circulations produced. Interestingly, the vortex structure remained the same for the case with the leeward wall heated whilst for ground or windward wall heated cases, threshold H/W values were identified before more vortices produced with different rotating direction and location. Later, using the same approach, Kim and Baik studied the in-depth ground heating case at different temperature difference between ambient air and heated surface.[93] They identified about five flow regimes which were explained in terms of counted vortices produced with corresponding circulation direction attributed to the buoyant or force convective force. Both studies showed that as temperature difference increased, more complex vortices structures were produced. On the other hand, Xie et al. determined pollutant concentration,[94] and their results pattern was in line with what was calculated by Sini et al.[28] Besides symmetric street canyon configuration, Xie et al. also included the investigation for asymmetric street canyon with step-up and step-down canyons.[94] The ground heating in either the step-up or step-down canyon has relatively lower concentration compared to symmetric street canyon. For the case where the leeward wall is heated, the step-down canyon gave higher pollutant concentration whilst step-up gave lower results, which were in contrast with the windward wall heated. The results indicated that the buoyancy force plays an important role in the pollutant dispersion even when combined with an asymmetric street canyon.

Xie et al. ($H/W = 1$ with ground heating) and Cheng and Liu ($H/W = 1$ with all surface heated including roof) investigated the characteristics of air exchange rate based on temperature difference and Reynolds number in terms of Gr/Re^2 and Ri, respectively.[89,95] Air exchange rate was found to increase as temperature difference increased but decreased with increasing Reynolds number. Xie et al. also found a second-order polynomial relationship for air exchange rate with Gr/Re^2,[95] while Cheng and Liu found that the retention time was shortened for decreasing Ri,[89] which helps to promote better ventilation and air quality under unstable condition.

In contrast to the CFD method, very few small-scale experiments have been conducted in the last 10 years in the investigation of thermal effects in street canyons. Wind tunnel experiments for unstable atmospheric conditions have a difficulty in the attempt to generate physical model, which is similar to the actual atmospheric condition because certain parameters do not completely satisfy real physical conditions, leading to incorrect representation of thermal flow.[12,97] However, few wind tunnel experiments were successfully conducted within a limited range of thermal conditions. Kovar-Panskus et al. investigated the effect of windward wall heating in $H/W = 1$; $L/W = 8.8$ with different wall temperature of 80°C and 120°C corresponding to $Fr = 2.03$ ($Ri = -0.1$) and $Fr = 0.27$ ($Ri = -0.92$).[98] Their results showed formation of very weak secondary flow close to the ground and reduction of velocity near the ground and leeward wall with up to 50% as Fr decreased. Besides unity aspect ratio, different aspect ratios were also investigated by Garbero et al. through wind tunnel measurements with heated windward and leeward walls at $Fr \approx 60$.[99] The study indicated that the vortex structure in deep street canyon ($H/W > 1$) with heated windward wall was found to be significantly influenced by buoyancy force. Recently, Allegrini et al. conducted a wind tunnel experiment similar to that of Kovar-Panskus et al. but within wider range of Froude number ($Fr = 0.65$–17.3) in unity street canyon with different heating cases,[98,100] including isothermal and all heated surfaces cases. Their results showed the significant impact of free-stream speed on the vortex intensity, where for low speed free-stream air the ground heating condition causing the most vortex intensifications followed by all surfaces heated, leeward wall heated and windward wall heated, whilst for high speed of free-stream air, there was no significant changes of differential wall heated cases on the vortex intensity. However, result for the all surface heated case showed the strongest increase of turbulent kinetic energy within the street canyon followed by ground, leeward, and windward heating. Although they obtained a wide range of Froude numbers, the lowest Froude number

did not achieve Reynolds independent, which is the most important flow characteristic which needs to be fulfilled for a reduced scale measurement.

As an alternative to the wind tunnel experiment, water medium via a water laboratory can be used where it can maintain parameters of flow speed and thermal conditions effectively.[101] A few water tank measurements have been done for a street canyon of $H/W = 1$ in a circulating water channel,[102] and for a street canyon with various H/W in a water tank,[103] where the bottom of the canyon was heated for both experiments. Vortex intensification was observed in both experiments and in particular, Huizhi et al. found that,[103] under near-zero ambient wind, the flows in the street canyon were completely driven by buoyancy force.

Previous wind tunnel and CFD works assumed the wall to be heated uniformly along the surfaces, either in an avenue or deep street canyon. In reality, the incident angles of solar radiation are time variable and some areas of wall did not receive solar radiation due to the shadowing from the opposite building. This phenomenon was observed in a field measurement by Offerle et al. in a deep canyon ($H/W = 2.1$).[91] In their measurement, the upper portion of one side of building surface received solar radiation while the lower portion did not during early morning and late afternoon due to the shadowing from the opposite building. The surface that receives direct sunlight tends to heat up the air close to the heated wall and strengthen the upward/downward motion depending on the location of heated building compared to the air close to shadowed surface wall. Besides individual surface heating, the multi-surface heating case, vis-à-vis leeward and ground heating, windward and ground heating combined with ground heating, as well as all-heated surfaces in street canyons ($H/W = 0.1$–2) were investigated numerically by Xie et al.[104] They found that the intensity of the vortex with a combined heated surface was increased compared to only one surface being heated. However, if the windward wall was a part of the multi-surface, the vortex was weakened. Recently, the inclusion of a rough surface by Cai,[105] through parameterization of the wall function in LES models, demonstrated that the air temperature in a street canyon is significantly influenced by the near-facet process as the primary factor, while other processes such as in-canyon mixing and roof-level exchange were secondary.

Table 8 shows more complex flow and its attributes towards pollutant dispersion are determined by further analyzing the unstable conditions, in which the differential wall heating effect is taken into consideration. As discussed in the previous paragraphs, the adoption of water experiments instead of wind tunnel could help tremendously on fulfilling the similarity criteria of thermal condition. Hence, the validation of numerical simulation for a large temperature variation flow conditions can be done properly. The following notes can be drawn from the literatures for differential heated walls on flow structure and pollutant dispersion in street canyon:

- For a single wall heated or multiple walls heated, the leeward and/or ground heating intensifies the flow within the street canyon and promotes better pollutant removal.
- If the windward wall is involved in multiple wall heating, the vortex intensity is slightly weakened and reduced pollutant removal.

5. Tree plantings

Past studies have shown numerous benefits of trees in absorbing and thus removing chemical pollutants from the atmosphere. Nowak et al. and Tallis et al. estimated through mathematical modeling that urban air quality in the United States and United Kingdom had improved drastically through the removal of large amounts of air pollutants in the presence of urban vegetation.[106,107] One of the key elements of trees is the foliage, which has the capacity to trap and hold particle pollutants (dust, ash, smoke particulate matter) through a process called dry deposition, which in turn removes airborne particles from the atmosphere.[108,109] In addition, trees absorb a variety of traffic-induced pollutants such as SO_2, NO_2, and CO_2, which prove to be harmful to humans.[110–112] Trees also act as shade from solar radiation, helping to reduce the urban heat island effect in which the urban geometry has the capacity to increase the absorption of solar radiation, thereby increasing the air temperature within a street canyon. Despite the stated benefits of trees, they can also be detrimental in a way that they reduce the natural ventilation in street canyons, thus increasing street level pollutant concentration as they act as obstacles that block the air flow in open environments,[113] or built-up environments,[114,115] as illustrated in Figure 6.

Following the explanations above, there are both advantages and disadvantages of planting trees in an urban area. On the one hand, vegetation can remove pollutants and has a positive influence on air quality, but on the other hand, it may also inhibit street ventilation and lead to deterioration of air quality in certain locations. In fluid mechanics, the area of interest is the aerodynamic mechanism of air ventilation and its potential towards the removal of pollutants. In addition, the building configuration and microclimate conditions strongly influence these processes. Therefore, this section will only review the available literature regarding the potential of air flow ventilation and pollutant removal due to tree plantings in built up environments.

The earliest study of tree-like obstruction in a street canyon was idealized by Gavey and Savory through wind tunnel experiments,[116] where they placed a few standing cylinders with different configurations along the street.

Table 8. Effect of differential wall heating on the flow structure and pollutant removal in street canyons.

Reference	Research method	Heating conditions	Remarks
Sini et al.;[28] Allegrini et al.[100]	CFD (RANS) Wind tunnel	Leeward heated	• The central vortex was intensified compared to isothermal condition • Found lower pollutant concentration compared to isothermal or windward heated.
Kim et al.[92]	CFD (RANS)		• The central vortex remained at the center of street canyon plane for different *H/W*.
Sini et al.;[28] Kim and Baik[102]	CFD (RANS)	Ground heated	• Vortex intensification. • Found lower pollutant concentration compared to isothermal or windward heated.
Kim et al.[92]	CFD (RANS)		• Identified production of more complex vortices at threshold *H/W*.
Kim and Baik[93]	CFD (RANS)		• The increments of temperature difference produced more complex vortices.
Xie et al.[94]	CFD (RANS)		• Found relatively lower pollutant concentration in step-up or step-down compared to symmetric street canyon.
Kovar-Panskus et al.;[98] Allegrini et al.[100]	Wind tunnel	Windward heated	• Found a formation of very weak secondary flow close to the ground and reduction of velocity near the ground and leeward wall as R_i increased.
Garbero et al.[99]			• Found significant effect on vortex structure in a deep street canyon.
Kim et al.[92]	CFD (RANS)		• Identified production of more complex vortices at threshold *H/W*.
Sini et al.;[28] Xie et al.[94]	CFD (RANS)		• Highest pollutant concentration in symmetric street canyon. • Found high accumulation of pollutant in step-up canyon compared to step-down canyon.
Xie et al.[104] Allegrini et al.[100]	CFD (RANS) Wind tunnel	Multiple wall heated	• Found the intensity of vortex higher than that of single heated wall. • Found the strongest turbulent kinetic energy within the street canyon when all walls were heated. • Pollutant was reduced compared to only single heated wall. • If the windward wall was involved in multiple wall heating, the vortex intensity was slightly weakened and reduced pollutant dispersion.

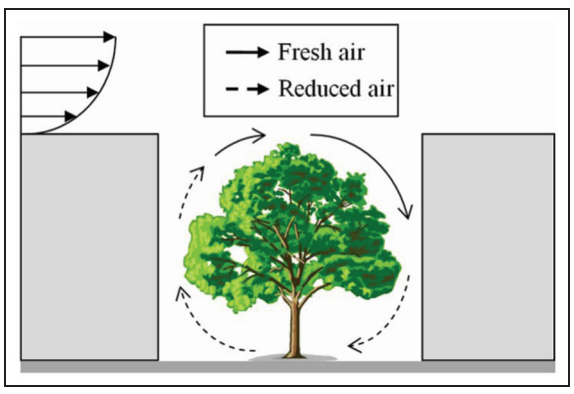

Figure 6. Air flow in a street canyon with a planted tree.

Reduction in air velocity and an increment of velocity fluctuation of between 50–200% inside the street canyon were measured. Full incorporation of tree-like plantings for wind tunnel measurements are well documented in the Concentration Data of Street Canyons (CODASC) at the University of Karlshure,[117] where they presented the wind tunnel results for $H/W = 0.5$ and 1 with $L/W = 8$ for different tree stands and crown configurations based on stand density/crown porosity, as well as wind directions.

The application of CFD in simulating the air flow and pollutant dispersion and the influence of the presence of trees was initiated by Ries and Eichorn using a micro-scale air pollution model (MISCAM) developed assuming a two-dimensional idealized street canyon.[118] They observed that the wind speed in the street canyon was reduced while the pollutant concentration was increased. Based on the results of CODASC, Gromke et al. used FLUENT 6.3 with the RSM turbulence model and obtained results that were qualitatively consistent with the experimental studies,[119] but the quantitative discrepancy was large especially for the pollutant concentration magnitude. Salim et al.

incorporated a more computationally intensive simulation (i.e. LES) and found that the results produced were much better than the previously determined calculation based on RSM.[24,120] LES was able to resolve the intermittent and unsteady fluctuations of the flow fields, resulting in better predictions of the distribution of pollutants by accounting for the turbulent mixing process. Buccoleri et al. further analyzed a street junction adjacent to four buildings mimicking the geometry of a real city in Italy,[121] where tree configurations and meteorological condition data were available. They demonstrated the importance of accounting for the presence of trees in computational modeling when performing simulation of real-life scenarios.

Based on these studies, tree plantings are shown to exhibit a static obstruction which reduces the air ventilation, hence resulting in poor air quality. These observations have motivated researchers to begin looking for strategies to efficiently utilize appropriate tree planting configurations and geometries. One way is to study the effect of different sizes of trees (i.e. crown density), as demonstrated by Kikuchi et al. where they investigated a simple way to improve air quality in street canyon with roadside trees using CFD.[115] They found that the trees under trim condition helped to increase the ingoing/outgoing air flow rate and thus improved the air ventilation and less pollutant were trapped. Another useful strategy is to look for different types of trees and optimum spacing between them. Wania et al. performed extensive investigation on different types of vegetation based on crown density at street junction with various street canyon aspect ratio,[122] as well as microclimate conditions using the microclimate model ENVI-met. In their simulation, they observed that the sparsely foliated trees did not result in any changes either in widely space or in continuous row arrangement. However, the densely foliated trees led to the overall increase of pollutant concentration and stronger effect was observed for continuous row of densely foliated trees. Hence, the hedge and sparsely foliated trees was recommended and densely foliated trees should be avoided especially when planted in a continuous row.

Recently, Park et al. conducted a field measurement campaign at a scale model site to measure the wind speed and temperature in a street canyon with the presence of trees at sidewalk and median strip in summer time.[123] They found that wind speed reductions of up to 51% were obtained in the presence of more sidewalk trees. The sidewalk trees layout also decreased the ambient temperature inside the street and this was attributed to the shading effect from solar radiation. In contrast, the median strip effect on the wind speed and air temperature was not discernable compared to the sidewalk trees.

Based on the literature above, there is a lack of investigations on pollutant removal due to the combined effect of trees and thermal variation. The analysis could help urban planners and environmental policy makers to identify the best tree types/configurations that are able to mitigate the urban island effect through the benefits of trees by creating shadowing effects, but at the same time not posing health risks to pedestrians due to the accumulation of pollutants. The current studies include identifying types of vegetation that are optimum to be planted in urban street canyons. The following notes can be drawn from the literature on tree planting effects on flow structure and pollutant dispersion in street canyons:

- The presence of trees exhibit roughness effects in street canyon that could reduce air ventilation and ultimately increase pollutant concentration levels.

6. Moving vehicles

The previously mentioned individual physical factors are based on the assumption that the traffic pollutant is represented as simple line sources that emit pollutants uniformly. In the actual situation, however, each vehicle moves at a certain speed and direction and at the same time emits pollutant source corresponding to moving point sources. The aerodynamics of flow around vehicles also induces turbulence by the formation of near wake and far wake. The near wake is the region of separated flow just behind the body characterized by both the region of recirculation and the formation of a pair of stream-wise longitudinal vortices.[124] The far wake is an area of general turbulence downstream of the near wake, which has little discernible flow structure.[124] All of these flow structures will generate turbulence when the vehicles move along the street canyon.

There are few literature studies, e.g. Baker and Carpentieri et al.,[125,126] explaining intensively the effect of moving vehicles. However, most literature studies are limited to the investigation of vehicular scale effects in open terrain and no information regarding the interaction of near wake or far wake with the vortex flow associated with the parallel or crosswind usually perceived in a typical urban street canyon. It should be noted that open terrain and street canyons have different effects on the wake structure behind a vehicle, under low wind speed in particular, due to atmospheric turbulence, where according to Baker,[125] the translation and diffusion processes on the vehicle wake are different. For the sake of abbreviation and practical importance of this review, only the resultant flow interaction between the turbulence generated by the vehicle with the approaching wind in street canyon will be discussed.

The investigation of the impact of moving vehicles on the flow structure and pollutant dispersion is not new and many examples can be found in the literature. According to Jicha et al.,[127] traffic influences mixing processes in the proximity of traffic paths within the canopy layer, especially in the situation of very low wind speed. Moving vehicles intensify both micro- and large-scale mixing

processes in the environment by inducing turbulence and enhancing advection by entraining masses of air in the direction of vehicle motion.

An early field measurement showed that moving vehicles considerably affect pollutant dispersion in a typical street canyon under isothermal condition with variable wind and vehicle speeds.[128,129] The most critical location in a street canyon was found to be near the bottom of the canyon; vehicle wake was generated here and hot exhaust gases were dominant.[130,131] Different ambient wind directions coupled with moving vehicles were also reported to have an influence. In all these cases, Holscher et al. observed a decrease in pollutant concentration when vehicle movements were opposite to the wind flow directions.[132] A series of wind tunnel experiments for the investigation of variable ambient wind speed perpendicular to the street canyon, traffic velocities, and traffic density by Kastner-Klein et al. is also interesting to note.[133] The reduction of ambient wind speed, the increment of vehicle speed, as well as traffic density helped to subsequently reduce pollutant concentration along the mid-block of a street canyon. This result indicated that in all of the cases being studied, the turbulence generated by the vehicle was dominant and resulting in the enhancement of street canyon ventilation. The study also confirmed the validity of the traffic-to-wind turbulence production ratio as a similarity number for the regime of turbulent diffusion in an urban street canyon, as proposed by Plate.[134]

Meanwhile, Jicha et al. used an Eulerian–Lagrangian approach where they assumed a continuous stream of moving vehicles one-way and two-way traffic in four lanes of traffic.[126] Their results showed that one-way traffic has a favorable impact on the concentration field where it showed lower values of concentration than in two-way traffic. Kastner-Klein et al. also reported the same results using two-lane traffic and suggested that air motion under one-way traffic created a piston effect associated with the reinforced mean flow component along the street canyon and thus enhanced cross road ventilation in the middle of the street.[135] For the case of two-way traffic, Kastner-Klein et al. and Ahmad et al. found that two-way traffic generated the same flow pattern with no traffic case,[135,136] where the pollutant distribution was the similar due to the non-existence of significant mean flow component along the street canyon. Nevertheless, the pollutant concentration near the bottom edge of the leeward wall and windward wall was slightly lower, which indicates the existence of the additional diffusion of tracer due to the vehicle-induced turbulent motions. For one-lane traffic, the results showed contradiction with previous studies. Hargreaves and Baker demonstrated the operational method in modeling of moving vehicles by simplifying the mathematical formulation developed by Eskridge and Hunt on pollutant dispersion due to a vehicle-induced turbulence in open terrain and street canyon using Gaussian puff model in computer program called PUFFER.[73,137] They found that the increase of density and speed of vehicles caused high pollutant concentration at the leeward wall of a building. This inconsistency was related to the only one-lane traffic adopted in this study. Using CFD by means of standard k–ε turbulence model, Solazzo et al. explicitly modeled vehicular motion in a street canyon,[138] where the condition was similar to Kastner-Klein et al. for comparison.[135] They split their study into two parts. The first part dealt with moving building wall and floor, while the vehicle was stationary, creating condition of vehicles under motion without ambient wind. Then, using the velocity and turbulent field developed behind vehicle in first part of study, they placed it in the computational domain of the second part of study by including ambient wind flow perpendicular to the street canyon. Comparison of CFD with wind tunnel data showed a very good agreement for the turbulent kinetic energy and mean horizontal velocity. However, some limitations of the model to reproduce the mean vertical velocity components were observed.

Due to the limitation and difficulty of numerical and small-scale experiment, more detailed and structured studies are needed. As suggested for further study and due to the absence of studies in literature, the moving mesh approach in CFD could be initiated, although it is computationally expensive. Since vehicle-induced turbulence is seen in the lower part of a street canyon, while the wind above the canyon is responsible for the formation of a vortex, further study on different building layouts and arrangements for example on deep street canyon and street junction layout could also be explored to quantify the air quality in a street canyon, particularly at pedestrian level. In all, the effects of moving vehicles on the air quality can be distinguished into two conditions: the wind speed condition coupled with traffic speed and the traffic direction. The following notes can be drawn from the literature of moving vehicle effects on flow structure and pollutant dispersion in street canyons:

- Under low wind speed, higher speed traffic increases the vehicle-induced turbulence, which helps to spread the pollutant from being stagnant on the ground.
- For different traffic directions, the one-way traffic yields better air quality as it produces a piston-like effect within the street canyon and subsequently enhances pollutant removal.

7. Chemical reactions of exhaust pollutants

Previous physical factors assume the pollutant to be non-reactive. However, many past studies have shown that there are many complex chemical reactions taking place as a result of various chemical from vehicle exhausts

mixing with atmosphere gases. According to Vardaloukis et al.,[5] most traffic-related pollutants (e.g. CO and hydrocarbons) can be considered as practically inert species because the reaction time is longer than the retention time of pollutant species in a street canyon. However, this is not the case for NO_2, which dissociates extremely rapidly in the presence of light, or for NO, which also reacts very rapidly with O_3. As an example, NO_X reacts in the presence of ozone (O_3) quickly to form nitrogen dioxide (NO_2). Under sunlit conditions, NO_2 is dissociated back into NO and O_3 according to the chemical reaction equation: $O_3 + NO \rightarrow O_2 + NO_2$.[139] In addition, NO_x with the dominant fraction being nitric oxide (NO) is mainly emitted by most road vehicles.[140]

Field measurement by Xie et al. in a street canyon of $H/W = 1.1$ showed a distinctive O_3 concentration distribution with chemically produced pollutant as a result of the dispersion by the primary vortex typically found in urban street canyon.[10] They observed that CO, NO, NO_2, and NO_x concentrations decreased on the vertical section of a leeward wall driven by the primary vortex. In contrast, the O_3 distribution on the leeward wall was quickly consumed by the already accumulated vehicle pollutants which contribute to the low concentration, while at the windward side, distinctive diurnal fluctuation characteristic and increased with height, which was explained by the supplement of O_3 from above street canyon driven by the primary vortex.

The first CFD method applied to further analyze this phenomenon was reported by Baker et al.,[141] where they simulated reactive gases using LES. The results of their study showed significant impact of reactive pollutant on the distribution of individual levels of NO, NO_2, and O_3 in a street canyon. Moreover, their preliminary tests were consistent with previous results obtained by Xie et al.[10] They demonstrated that the mixing of chemical species was stable at the center core and the ground level windward corner of the street canyons, while along the windward wall and near emission source, the chemical species were unstable. Using the same method, Grawe et al. extended the investigation of Baker et al. by including the effect of shaded windward/leeward walls in a street canyon,[141,142] in which the photolytic dissociation process took place and resulting in the occurrence of chemical decomposition due to the heat energy from sunlight.

Meanwhile, Baik et al. and Kang et al. adopted a RANS-based turbulence model to investigate the effect of bottom heating corresponding to the variation of temperature difference.[143,144] The budget analysis of NO and NO_2 concentration showed that the magnitude of the advection or turbulent diffusion term was much larger than that of the chemical reaction term and that the advection term was largely balanced by the turbulent diffusion term. On the other hand, the budget analysis of O_3 concentration showed that the magnitude of the chemical reaction term was comparable to that of the advection or turbulent diffusion term. Moreover, the O_3 concentration was affected by the photolysis rate and reaction rate due to the different temperature distribution in street canyon. Liu and Leung developed a chemistry box model,[145] coupled with previous results of ACH obtained by Liu et al.,[40] to calculate the chemical reaction processes in idealized street canyon. They found that high formation of ozone concentration when concentration of volatile organic compounds (VOCs) was 10 times or more than the concentration of NO_x under calm wind similar to the worst case scenario.

Recently, Kikumoto and Ooka revealed the results for various urban configurations (regular canyon, step-up canyon, and deep canyon) performed under isothermal conditions.[146] Based on the evaluation of ventilation efficiency of respective street canyons, they found that the step-up street canyon, which was known to provide the highest ventilation efficiency amongst others, produced the lowest concentration of NO and product, whilst increasing O_3 due to the shortening of reaction time with NO. Despite the considerable effort of previous studies, Kim et al. recently applied full chemistry simulation and compared with steady-state solution obtained by previous studies where they found considerable difference in O_3 concentration in a street canyon.[147] They also further investigated the reactive species concentration by applying an online photolysis computation module to take account of the effect of diurnal variation of solar radiation where they obtained good results for CO while the remaining chemicals were varied due to the limitations and simplifications of the model used.

By analyzing all of the above, the resultant chemical reaction increases the chemical products over the reactants and the distributions of the products are spatially varied as a result of intense mixing by vortices, photochemical processes due to the solar radiation, and the presence of other chemicals in the street canyon. However, the flow structure in the street canyon remains unchanged, which indicates the insignificant impact of reactive pollutant on the resultant flow structure. In addition, NO and NO_2 have their own pros and cons. For example, NO has direct implication in acid rain whilst NO_2 is considered toxic by inhalation. By taking the reaction of NO for example, the vortex in a typical street canyon will enhance the mixing of these chemicals and subsequently increase NO_2 and deplete O_3. In the presence of heat due to solar radiation, photochemical processes will dissociate these chemicals into their original components. However, the reaction is varied with the presence of other species. Future prospects of this aspect will be on the inclusion of more chemicals and with different building layouts and solar radiation.

Table 9. Summary of favorable atmospheric conditions or canyon layouts for better air quality in street canyons.

Factors	Conditions
Symmetric street canyon	Avenue street canyon coupled with short street canyon
Asymmetric street canyon	Step-up street canyon; uneven building heights along the street
Roof shapes	Slanted roof shape is better compared to pitched or flat roof. For more complex roof shapes, the air quality is highly dependent on the roof shape of upwind building
Wind conditions	High wind speed; oblique wind direction
Thermal conditions	Under unstable atmospheric conditions with the exception of windward heated wall
Trees planting	Planting low foliated trees and align discontinuously along the canyon
Moving vehicle	High vehicle speed during low wind speed; one-way traffic
Chemical reaction	Strongly dependent on the street canyon layout, atmospheric conditions and presence of other chemicals

8. Conclusions

This article has presented a review of the state-of-the-art research relevant to the investigation of flow structure and pollutant dispersion in an urban street canyon. In particular, various significant physical factors, including various building geometries, local atmospheric conditions, static and dynamic obstructions, as well as chemical reaction of exhaust pollutants, are critically discussed and field measurements, wind tunnel experiments, operational modeling, and computational fluid dynamics (CFD) are also taken into account. A few factors leading to the difficulty and resulting inconsistency of research methods are briefly addressed in the introduction, and some issues as well as suggestions for future research are shown below:

1. Operational models are accurate for a simple street canyon configuration (ADMS, OSPM, and others). Therefore, more research collaborations are needed in identifying or modifying the current models, including parameterization for a more complex building configuration.
2. It is worth mentioning that the numerical simulation of turbulent flow using RANS shows acceptable agreement with field measurement for the prediction of pollutant dispersion at different wind speeds, as reported by Tsai and Chen.[82] On the other hand, the prediction of wind field at different wind directions by Assimakopoulos et al. shows some discrepancies with RANS compared to field measurement,[39] especially for the perpendicular case due to the existence of complex flow structures. This is attributed to the simplifications of models and boundary conditions in addition to the steady-state assumptions, which do not portray the case under the real atmospheric conditions. However, it is interesting to note that all the important flow structures are able to be captured by RANS. In recent publications, few studies have shown that LES is more accurate due to its formulation in capturing eddies and periodicity of the flow including pollutant dispersion under isothermal, tree planting, and thermal effects.[41,105,120]
3. The investigation of thermal flow around building complex via wind tunnel experiments is difficult to perform due to the similarity issues, specifically in fulfilling the real physical models. As an alternative, a water tank experiment can be conducted where few previous studies have shown promising similarity. In addition, the methods of field measurement and wind tunnel experiment can also be good choices as demonstrated by Park et al.[123]

By categorizing these physical factors, we can identify which conditions are favorable for the residents living in the vicinity of roadsides and can provide guidelines for urban planners, as shown in Table 9.

Hence, we can conclude that wind flow fields and pollutant dispersion mechanisms are strongly affected by variations in street canyon geometry, wind speed and direction, thermally stability conditions, tree planting, and moving vehicles, with chemical reactions as an exception in wind flow fields. Since there are some aspects of research which still lack of attention, future prospects of air quality assessment in street canyons are expected to focus more on comprehensive thermal investigation (convection, conduction, radiation), moving vehicles (numerically), and study the effect of combining various physical factors to identify which factors are the most pronounced. The authors are hoping that this article can provide a general guideline for the urban planner, urban developer and local authorities on how to utilize buildings configuration and local atmospheric conditions as an important mechanism in the overall strategy of making the urban areas to be more breathable and consequently minimizing pollutant accumulation for the better health of its residence. If possible, construction of buildings which contribute to the worsening of air quality should be avoided.

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