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Impact of Wind Direction on Long Street Canyon Airflow and Pollutant Dispersion

Sanjay Bhat

Lead Product Specialist – CFD and Batteries, ALTAIR, USA

ABSTRACT: This study investigates the influence of thermal effects and aspect ratio on airflow and pollutant dispersion within urban street canyons. Using simulations with an unsteady Reynolds-Averaged Navier-Stokes (RANS) model, various aspect ratios ranging from 0.5 to 3.0 were analyzed under isothermal conditions. The research reveals distinct flow regimes based on aspect ratio: shallow canyons (AR = 0.5) exhibit flow patterns similar to wind-driven scenarios, while deeper canyons (AR = 3.0) show complex vortex structures with up to four counter-rotating vortices. Pollutant concentrations were found to be highest at an aspect ratio of 1.0, especially with heating on the windward side, and generally decrease as the aspect ratio increases. The study highlights the importance of canyon geometry in determining airflow patterns and pollutant dispersion, though it also identifies gaps in current models that link aspect ratios and Richardson numbers to flow regimes. The research underscores the need for further studies on asymmetric street canyons and the development of more comprehensive models to enhance urban air quality management.

KEYWORDS*:* Pollutant dispersion, Urban airflow, Wind direction, Wind speed, Solar radiation, Airflow dynamics, Stagnation zone, Building morphology.

I. INTRODUCTION

Environmental pollution is increasingly recognized as a critical global issue, especially in urban areas where population growth and rising traffic levels contribute significantly to air pollution. The World Health Organization (WHO) reports that over 80% of city dwellers in areas with air quality monitoring are exposed to pollution levels that exceed recommended limits. Alarmingly, ambient air pollution is linked to 4.2 million deaths annually worldwide [1]. This makes understanding how traffic pollutants spread in cities a crucial aspect of urban design.

A common urban structure known as an "urban canyon," which consists of buildings and the spaces between them, plays a significant role in this context. Properly arranging buildings can enhance natural ventilation and help reduce the concentration of pollutants within these canyons. Researchers have extensively studied how different factors in urban areas affect air circulation and the spread of traffic-related pollution. Methods like numerical simulations and wind-tunnel experiments are particularly effective for addressing these environmental challenges [2]. Key factors influencing air movement and pollutant dispersion in urban canyons include the presence of trees, viaducts, wind direction, roof shapes, balconies, and other structural elements. Among these, balconies have a notable impact on airflow near buildings and the distribution of pollutants [3].

The spread of pollutants from emission sources is affected by a wide range of factors, including environmental conditions, the characteristics of the source, the shape and design of buildings, and the presence of obstacles around these structures. Researchers have extensively studied how environmental factors such as wind speed, wind direction, incoming turbulence, and thermal stratification influence airflow around buildings. In particular, the role of heat from environmental sources, like solar radiation, on building exteriors has gained attention as a key driver of airflow. In urban settings, buoyancy effects, mainly caused by solar heating of building facades and the ground during the day, significantly influence airflow. For example, street surfaces can heat up to 64°C on a hot summer day due to direct solar radiation, and the temperature difference between an exterior wall and the surrounding air can be as much as 18°C. In conditions without wind, the upward buoyant forces caused by this heating can counteract the downward inertial forces, making buoyancy an important factor in airflow dynamics.

Airflow and pollutant dispersion in urban areas are categorized into four scales: regional, city, neighbourhood, and street scales. Most studies on urban airflow driven by buoyancy effects have focused on neighbourhood and street scales. Both wind speed and the location of the pollutant source are crucial in determining how air moves and how pollutants disperse around isolated buildings, especially under conditions where the temperature is not uniform. Typically, when wind blows directly against a building, a stagnation zone forms at about two-thirds of the height of the

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windward side. Above this zone, the air flows upward to the roof, while below it, the air moves downward toward the ground.

Understanding the effects of wind direction on airflow and pollutant dispersion within urban environments is crucial for addressing air quality issues in densely populated areas. Urban street canyons, characterized by rows of buildings flanking narrow streets, are common in cities and play a pivotal role in determining how pollutants from traffic and other sources are dispersed. These canyons can trap pollutants, leading to elevated concentrations of harmful substances such as particulate matter (PM), nitrogen oxides (NOx), and volatile organic compounds (VOCs) at street level, which can significantly impact public health [4]. The configuration of buildings, street geometry, and meteorological conditions, particularly wind direction, are key factors that influence the airflow patterns and, consequently, the distribution of pollutants within these urban canyons.

Wind direction is a critical factor in determining how air circulates within a street canyon and how pollutants are transported or trapped. When the wind blows perpendicular to the canyon axis, a vortex is typically generated within the canyon, which can lead to the recirculation of air and the entrapment of pollutants. This phenomenon, known as "recirculation," can result in higher pollutant concentrations within the canyon, particularly on the leeward side of the street [5, 6]. Conversely, when the wind is parallel to the canyon axis, pollutants may be more effectively dispersed along the length of the canyon, potentially reducing local concentrations but spreading pollution over a larger area. The complexity of these interactions highlights the importance of understanding wind effects to inform urban planning and design strategies aimed at mitigating air pollution.

The orientation and shape of the buildings lining the street, the aspect ratio of the canyon (height to width), and the presence of street-level features such as trees and vehicles also interact with wind direction to influence airflow patterns. In deeper canyons, for example, the wind may have a more limited ability to penetrate and ventilate the street, leading to poor air quality [7]. The presence of trees can either enhance or hinder airflow, depending on their placement and density. Similarly, the shape of building roofs, balconies, and other architectural features can alter wind patterns, either promoting the flushing out of pollutants or contributing to their accumulation [8]. Understanding these dynamics is essential for developing effective strategies to reduce exposure to harmful pollutants, particularly in cities where high traffic volumes and dense construction are common.

Balconies significantly impact airflow and pollutant concentration around buildings due to their unique structural characteristics. However, the combined effect of balconies and wind direction has been insufficiently explored. Most existing studies have focused on analyzing the flow field and pollutant concentration near building walls, with limited attention to the overall ventilation within the canyon or at the pedestrian level. This study aims to investigate how different balcony arrangements (on the leeward side, windward side, and both sides) affect canyon ventilation, particularly for discontinuous balcony structures under varying wind directions. The ventilation efficiency of the canyon is assessed by calculating the air exchange rate (ACH) and the net escape velocity (NEV) in the pedestrian zone.

The study of wind direction effects on pollutant dispersion within street canyons is not only important for urban environmental management but also for public health. Poor air quality in urban areas is linked to a range of health problems, including respiratory and cardiovascular diseases, and exacerbates conditions such as asthma and bronchitis [9, 10]. By gaining a deeper understanding of how wind direction and other factors influence pollutant behavior in street canyons, urban planners and policymakers can design cities that promote better air quality, ultimately leading to healthier living environments for urban residents. Therefore, ongoing research into these interactions is essential for advancing our knowledge of urban air pollution dynamics and for developing practical solutions to this pressing global challenge.

II. LITERATURE REVIEW

The influence of wind direction on airflow and pollutant dispersion within urban street canyons has been the subject of extensive research, given its critical implications for urban air quality and public health. Various studies have explored how different wind directions impact the distribution of pollutants, providing insights that are vital for urban planning and design. One of the early studies on this topic was conducted by Oke (1988), who introduced the concept of urban canyons and examined how wind direction influences the formation of vortices within these spaces [11]. Oke's work demonstrated that when the wind blows perpendicular to the canyon axis, a primary vortex forms, leading to the

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recirculation of air and pollutants within the canyon. This recirculation effect can trap pollutants on the leeward side of the street, resulting in higher concentrations of harmful substances.

Later, Baik et al. (2000) [12] expanded on Oke's findings by investigating the detailed flow patterns within street canyons using numerical simulations. Their study confirmed that the perpendicular wind creates a stable vortex that can significantly impact pollutant levels at different heights within the canyon. Baik and his colleagues also noted that the strength and structure of this vortex are influenced by the aspect ratio of the canyon, with deeper canyons (higher aspect ratios) showing more pronounced recirculation zones.

In a study by Kim and Baik (2001) [13], the authors explored how varying wind directions affect pollutant dispersion using a two-dimensional numerical model. They found that when the wind direction is parallel to the street canyon, pollutants tend to disperse more evenly along the street's length, reducing the concentration of pollutants in specific areas but potentially spreading them over a larger area. Their research highlighted the importance of considering wind direction in urban design to mitigate localized pollution hotspots.

Further research by Sini et al. (1996) [14] used large-eddy simulation (LES) techniques to investigate the effects of wind direction on pollutant dispersion. Their findings indicated that oblique wind directions could create complex flow patterns, including secondary vortices, that further influence the distribution of pollutants within the canyon. Sini et al. emphasized that these complex flow structures are critical for understanding pollutant transport mechanisms in urban environments.

Li et al. (2006) [15] conducted an experimental study using wind tunnel simulations to analyze the impact of wind direction on pollutant dispersion in street canyons with varying aspect ratios. Their results showed that the angle of wind incidence significantly affects pollutant concentration levels, with perpendicular and oblique wind directions leading to higher concentrations near the ground level due to limited ventilation. They concluded that optimizing building orientation relative to prevailing wind directions could enhance air quality in urban canyons.

A more recent study by Salim et al. (2011) [16] examined the influence of building geometry and wind direction on pollutant dispersion using computational fluid dynamics (CFD) simulations. Their research confirmed earlier findings that wind direction is a dominant factor in determining the efficiency of pollutant dispersion. Additionally, they noted that the presence of architectural features such as balconies and roof shapes could modify the wind flow, either enhancing or obstructing pollutant dispersion.

Gromke and Blocken (2015) [17] contributed to the literature by exploring the combined effects of wind direction and vegetation on airflow and pollutant dispersion in street canyons. Their study highlighted that while trees can provide shading and reduce thermal load, they can also obstruct airflow, leading to higher pollutant concentrations in certain scenarios. The authors recommended careful consideration of tree placement and species selection to balance the benefits of greenery with the need for effective pollutant dispersion. These findings have important implications for urban design, suggesting that building orientation, street layout, and the strategic placement of vegetation should be carefully planned to mitigate air pollution and improve urban air quality.

Y. D. Huang (2019) [18] This study explores the impact of wind direction on airflow and pollutant dispersion within a long street canyon using computational fluid dynamics (CFD). A three-dimensional CFD model is developed using the FLUENT software to predict flow and dispersion within the canyon, and the model is validated against results from wind tunnel experiments. The study simulates airflow and traffic pollutant dispersion in an isolated canyon with a street-length-to-building-height ratio of 10, across seven different wind directions ($\alpha = 0°$, 15°, 30°, 45°, 60°, 75°, and 90°, where α represents the angle between the approaching wind and the street axis). The findings show that both the mean air exchange rate (ACH) and the turbulent air exchange rate (ACH′) are similar when the wind direction is between $\alpha = 0°$ and $\alpha = 60°$. However, when the wind direction shifts to $\alpha = 75°$ and $\alpha = 90°$, ACH′ becomes significantly higher than ACH. The ACH reaches its peak at $\alpha = 30°$ and its lowest point at $\alpha = 90°$. The computed velocity and concentration fields illustrate how the flow patterns and pollutant distribution within the canyon change with different wind directions. Specifically, the study reveals that on the leeward wall, the average concentration increases substantially as α increases, with the highest wall-maximum concentration observed at $\alpha = 75°$ and the lowest at $\alpha = 0°$. Conversely, on the windward wall, both the average and maximum concentrations are highest when $\alpha = 0°$. At the human breathing height, the highest pollutant concentration on the footpath near the leeward wall occurs at $\alpha = 75°$, while the highest concentration near the windward wall is seen at $\alpha = 0°$.

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III. METHODOLOGY

In real-world urban environments, both wind and buoyancy forces are always at play simultaneously, influencing how air flows through these areas. The flow pattern in urban settings is determined by the relative strength of these two forces—wind and buoyancy. Researchers have introduced several dimensionless parameters to quantify this relationship, such as the Froude number (Fr) and the Richardson number (Ri).

The Froude number and the Richardson number are inversely related, meaning that the Froude number is the reciprocal of the Richardson number, expressed as

Fr = 1/Ri. This relationship allows these parameters to indicate the balance between buoyancy and wind forces in urban flows. The Richardson number is specifically defined based on the ratio of buoyancy to wind effects, and it helps to predict how these forces will interact to influence airflow patterns in urban areas.

$$Ri = \frac{Gr}{Re^2}$$

$$Gr = \frac{g\beta H^3 \ T_W - T_{ref}}{\nu^2}$$

$$Re = \frac{u_0 H}{\nu}$$

In urban airflow studies, several key factors and numbers help understand how wind and buoyancy forces interact. Two important dimensionless numbers are the Grashof number (Gr) and the Reynolds number (Re), which are used to describe the effects of buoyancy and wind on airflow.

Grashof number (Gr): This number relates to the buoyancy effects caused by temperature differences between the building surfaces and the surrounding air. It is calculated using the external wall surface temperature (TW), the ambient air temperature (Tre f), gravity (g), the thermal expansion coefficient (β), and the reference height (H).

Reynolds number (Re): This number indicates the relative importance of inertial forces compared to viscous forces in the flow of air. It is calculated using the ambient wind velocity (u0) and the air's kinematic viscosity (ν).

In urban aerodynamics, it's important to consider Reynolds independence, which means that scaled models used in studies need to reflect the same flow characteristics as in real environments. Studies have proposed different critical Reynolds numbers for ensuring accurate modeling. For example:

Castro and Robins (1977) suggested a critical Reynolds number of 4000, based on the velocity at building height. Hoydysh et al. (1994) proposed a critical Reynolds number of 3400, based on the free stream velocity. Snyder (1991) suggested a widely adopted critical Reynolds number of 11,000, which helps maintain dynamic similarity in models.

The Richardson number (Ri) is another key parameter used to compare mechanical (wind-driven) and buoyant (thermal) forces in the flow. It is defined as the ratio of buoyancy-driven forces to mechanical forces. Typically:
When Ri is less than 0.1, mechanical forces (wind) dominate.
When Ri is greater than 10, buoyant forces (temperature differences) dominate.
For idealized building setups, selecting a reference height for calculations is straightforward. However, in street canyons with buildings of varying heights, defining the reference height can be more complex and might differ between studies.
Therefore, cross-comparisons between studies should be made with care in the choice of length scales and temperature differences. It should be noted that some expression features of Ri might be used in the studies.

$$Ri_b = \frac{gH \ T_{ref} - T_w}{T_{ref} U_{ref}^2}$$

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where Ure f is the mean wind speed at the reference height, and the temperature used in the equation is the average temperature. The value from formula (4) is a negative number for the heating wall and a positive number for formula (1).

IV. RESULT

The design and layout of a street canyon, including factors such as the architectural style, building shapes, and the dimensions of the canyon, play a crucial role in determining how pollutants are transported and how airflow behaves within the canyon. One of the key indicators used to describe the geometry of a street canyon is the aspect ratio, which is the ratio of the canyon's height to its width. This ratio helps to classify the different flow patterns and pollutant dispersion characteristics that can occur in urban canyons.

In two-dimensional street canyons under isothermal (uniform temperature) conditions, researchers have identified four main types of flow regimes. These include:

Fully Isolated Roughness Flow: This regime occurs when the street canyon is sufficiently deep, causing the flow to be dominated by the roughness of the buildings and not significantly affected by the surrounding flow. In this case, the flow within the canyon behaves independently of the flow outside the canyon.

Wake Interference Flow: This flow regime is observed when the flow is influenced by the wakes (turbulent regions) created by the buildings. These wakes interact with each other, leading to complex flow patterns within the canyon.

Skimming Flow: In this regime, the wind flows over the top of the canyon rather than through it, leading to reduced air exchange and pollutant dispersion within the canyon. This typically happens when the canyon is shallow relative to the wind direction.

Multivortex Flow: This is observed in deep canyons where multiple vortices (rotating flow patterns) are generated. These vortices can significantly affect pollutant dispersion and airflow within the canyon.

While the descriptions of the first three flow patterns are generally consistent across different studies, the fourth regime, the multivortex flow, has shown some variation in experimental observations. For instance, in wind tunnel experiments with an aspect ratio of 2.0, researchers observed two contra-rotating vortices, which means that two swirling patterns of air rotated in opposite directions. This was observed in controlled 2D models of street canyons. On the other hand, full-scale street canyon studies with an aspect ratio of 2.7 identified a different pattern: a single dominant vortex structure. This indicates that the scale and specific configuration of the canyon can influence the type and number of vortices present.

These variations highlight the complexity of airflow and pollutant dispersion in street canyons and emphasize the importance of considering both the scale of the canyon and the specific geometric characteristics when studying urban airflow dynamics.

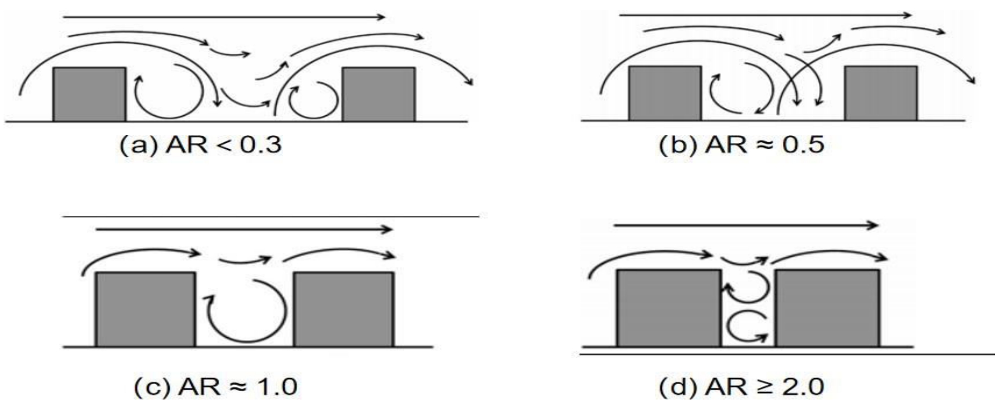

Figure 1: Flow regimes in street canyons with various aspect ratios under isothermal conditions adapted with permission.

Research into the impact of thermal effects on airflow in street canyons has focused on how different aspect ratios influence the flow patterns. Aspect ratio (AR) refers to the ratio of the canyon's height to its width. Several studies have explored this by simulating street canyons with various aspect ratios, ranging from 0.5 to 3.0.

For instance, an unsteady Reynolds-Averaged Navier-Stokes (RANS) model to simulate these canyons under heated conditions. Their findings revealed different flow patterns depending on the aspect ratio:

In a shallow canyon with an aspect ratio of 0.5, the flow pattern resembled that found in wind-driven scenarios.
For a canyon with an aspect ratio of 1.0, they observed two diagonally positioned, counter-rotating vortices.
In canyons with aspect ratios between 1.5 and 2.5, they noted three vertically stacked vortices. These canyons also exhibited similar vortex patterns to those influenced by wind alone.
In deeper canyons with an aspect ratio of 3.0, four counter-rotating vortices were present, with one of the anti-clockwise vortices split into two separate vortices.

The concentration of pollutants within the canyon is closely tied to the number and strength of these vortices. For example, when the heating source is on the windward side of the canyon, the highest pollutant concentration was observed with an aspect ratio of 1.0. As the aspect ratio increased from 1.0 to 3.5, the concentration of pollutants generally decreased. However, when heating was on the leeward side or at ground level, the aspect ratio had less effect on pollutant concentration.

Despite these findings, there is a lack of simple equations connecting flow patterns, aspect ratios, and Richardson numbers (Ri). This gap means that adjusting for changes in geometric shapes or wind conditions still requires extensive processing and computational effort. Most research has focused on symmetric street canyons, but in reality, urban areas often have asymmetric canyons due to varied building geometries.

V. DISCUSSION

The investigation into the effects of thermal influences on airflow within street canyons, particularly concerning varying aspect ratios, highlights several important findings that offer both practical insights and raise ongoing challenges in urban airflow studies. The research conducted by Mei et al. using an unsteady Reynolds-Averaged Navier-Stokes (RANS) model provides a comprehensive look into how different aspect ratios impact the formation and behavior of vortices within street canyons. These findings are crucial for understanding how heat from buildings and the ground influences pollutant dispersion in urban environments.

The study's observations indicate that as the aspect ratio of a street canyon changes, the flow patterns and the number of vortices present also vary. In shallower canyons (with an aspect ratio of 0.5), the flow pattern remains similar to what is seen in wind-driven scenarios, suggesting that the thermal effects have less impact on the vortex formation in such cases. However, as the aspect ratio increases, distinct flow regimes emerge. For instance, with an aspect ratio of 1.0, the presence of two diagonally positioned counter-rotating vortices highlights how relatively shallow canyons can still exhibit complex flow patterns influenced by thermal effects. As the aspect ratio grows from 1.5 to 2.5, the emergence of three vertically stacked vortices demonstrates a more complex interaction between thermal forces and airflow, which becomes evident in the richer vortex structures that develop in these canyons. In deeper canyons with an aspect ratio of 3.0, the formation of four counter-rotating vortices, including the splitting of the anti-clockwise vortex into two, underscores the increased complexity of vortex dynamics in larger canyons. These findings reflect how thermal effects can lead to significant changes in the airflow patterns and pollutant dispersion characteristics, highlighting the intricate interplay between canyon geometry and thermal influences.

The correlation between vortex structure and pollutant concentration is particularly noteworthy. The study finds that the highest pollutant concentrations occur when the aspect ratio is 1.0, especially with heating on the windward side. This suggests that specific aspect ratios can exacerbate pollutant accumulation, which is critical for designing urban spaces that minimize air quality issues. Conversely, as the aspect ratio increases, the pollutant concentration tends to decrease, which indicates that deeper canyons might offer some degree of dilution or improved dispersion of pollutants, though this effect is not uniformly observed across all scenarios.

The complexity of these findings is compounded by the current lack of straightforward models linking aspect ratios and Richardson numbers (Ri) to flow patterns and pollutant concentrations. This gap underscores the need for further research and development of more precise models that can predict airflow and pollution dispersion based on geometric

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and thermal factors. The reliance on extensive computational simulations and empirical studies to account for changes in geometry and wind conditions remains a significant challenge.

The focus of most studies on symmetric street canyons does not fully address the real-world conditions where urban canyons are often asymmetric due to varied building designs. Asymmetric canyons introduce additional complexity, potentially altering vortex patterns and pollutant dispersion in ways that are not fully captured by current models. This gap in research highlights the need for more studies on asymmetric configurations to better understand and manage air quality in diverse urban environments.

VI. CONCLUSION

The research into thermal effects on airflow within street canyons underscores the significant impact that aspect ratio and canyon geometry have on vortex formation and pollutant dispersion. The study by Mei et al. highlights how varying aspect ratios influence the number and structure of vortices, with deeper canyons generally exhibiting more complex vortex patterns. These vortices, in turn, affect the concentration and distribution of pollutants within the canyon. Specifically, the findings suggest that while shallower canyons (with lower aspect ratios) may retain flow patterns similar to wind-driven scenarios, deeper canyons (with higher aspect ratios) exhibit more intricate vortex dynamics, which can lead to variations in pollutant concentrations.

The research reveals that pollutant concentrations are highest with an aspect ratio of 1.0, particularly when heating is applied to the windward side, emphasizing the importance of canyon geometry in urban air quality. As the aspect ratio increases, pollutant concentrations generally decrease, indicating potential benefits of deeper canyons for pollutant dispersion. However, this effect is not uniform and depends on the specific heating conditions and canyon configurations. There is a notable lack of simple models that connect aspect ratios, Richardson numbers (Ri), and flow regimes with pollutant dispersion. This limitation highlights the need for further research to develop more accurate and practical models. Additionally, the focus on symmetric street canyons in existing studies does not fully address the complexities of asymmetric urban environments, where varied building geometries can significantly alter airflow and pollutant dispersion patterns. The study contributes valuable knowledge to the understanding of how thermal effects and aspect ratios influence urban airflow, it also points to the need for continued investigation into asymmetric canyon geometries and the development of improved models. Addressing these research gaps will be essential for advancing urban planning strategies aimed at optimizing air quality and managing pollutant levels in diverse urban settings.

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