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Diffusion Characteristics of Particulate Pollutants Across Street Locations

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Abstract

Street canyons, as a key component of the urban built environment, strongly influence the diffusion and retention of particulate pollutants due to their complex airflow structures. To investigate the diffusion mechanisms of particulate matter released from different locations within street canyons, a two-dimensional idealized canyon model without vegetation was employed. A steady-state flow field was simulated using computational fluid dynamics (CFD), and a Lagrangian particle-tracking approach was applied to analyze particle trajectories and transport behaviors at different spatial positions. Results indicate the formation of a stable primary vortex within the canyon. The central region, characterized by low wind speeds and recirculating streamlines, significantly inhibits particle dispersion, whereas the upper canyon and free-flow regions promote rapid particle removal due to higher wind velocities. Particle release location plays a critical role in diffusion efficiency: particles released near the upper region or close to the free-flow boundary disperse rapidly when their initial momentum aligns with the main flow direction; particles in the vortex core are prone to long-term trapping; and particles near the ground can gradually rise due to boundary layer disturbances but exhibit prolonged residence times. Additionally, the alignment between particle initial velocity and local flow structure significantly affects their ability to escape vortex constraints. These findings highlight the sensitivity of particulate dispersion to spatial location and flow structures within street canyons, providing a theoretical basis for optimizing urban ventilation and pollution control strategies.

Keywords

Street Canyon; Particle Dispersion; Lagrangian Particle Tracking.

1. Introduction

Street canyons, as fundamental components of the urban built environment, play a crucial role in residents’ daily activities. Owing to their relatively enclosed geometry, airflow within street canyons is highly complex, and pollutant dispersion is governed by multiple interacting factors. Ventilation conditions directly determine the transport and dilution of pollutants, thereby exerting a significant influence on urban air quality and public health [1,4]. Therefore, a thorough understanding of particulate matter diffusion mechanisms in street canyons is essential for optimizing urban environments and improving living quality.

Existing studies have demonstrated that street geometry is a key factor influencing ventilation efficiency and particulate matter dispersion in street canyons. Zhang et al. [5], through computational fluid dynamics (CFD) simulations and field measurements, found that variations in the aspect ratio of street canyons significantly modify wind speed distribution and pollutant transport pathways, thereby reshaping spatial pollutant patterns. However, pollutant dispersion is not only governed by overall geometric configuration but also strongly dependent on emission source location and spatial distribution. In complex flow fields, particulate transport behavior exhibits pronounced spatial variability across different release positions.

Regarding influencing factors, existing studies have focused on the regulatory role of street vegetation (such as roadside trees) on pollutant diffusion. For example, Lin et al. [6] pointed out based on large eddy simulation (LES) that the aerodynamic effects of trees can alter the spatial distribution of pollutants in street valleys; Buccolieri et al. [7] believed that canopy structure can hinder pollutant diffusion and lead to accumulation; Wang et al. [8] and Hong et al. [9] further pointed out that different canopy densities and structures have different effects on pollutant diffusion. However, most of these studies have introduced vegetation factors, making the flow field structure more complex, thus obscuring the intrinsic relationship between the basic airflow structure of street valleys and pollutant diffusion to some extent.

In contrast, under idealized conditions without vegetation or other disturbances, systematic analysis of particulate matter diffusion at different release locations can help reveal the fundamental mechanisms governing airflow organization and pollutant transport in street canyons. However, existing studies on spatial differences in particle dispersion—such as those associated with near-ground, lateral wall, and central release positions—remain limited, and a comprehensive understanding of transport pathways, concentration distributions, and retention behaviors is still lacking.

Therefore, this study investigates particulate matter dispersion under treeless, idealized street canyon conditions, focusing on the transport behavior and spatial distribution characteristics of particles released at different locations within a typical canyon geometry. The aim is to provide a theoretical basis for urban ventilation design and pollution control strategies.

2. Numerical Methods

2.1. Street Physical Model

This study employs a two-dimensional idealized street canyon model. The buildings are 18 m in height and 9 m in width, with an 18 m wide street canyon between them, resulting in an aspect ratio of 1:1. The computational domain is discretized using a structured quadrilateral mesh, as shown in the figure. A uniform grid resolution of 0.2 m is applied within the street canyon region, resulting in a total of 15,552 cells.

2.2. Mathematical Model

This paper mainly studies the simulation using the following governing equations:

Particle trajectory equations:

This study uses the Lagrangian method to track the trajectory of discrete particles. The equations governing the motion of the discrete phase are:

$$\frac{du_p}{dt} = F_D\left(u + u' - u_p\right) + F' \tag{1}$$

In the formula: $\mathrm{F_D}\left(\mathrm{u} + \mathrm{u'} - \mathrm{u_p}\right)$ is the drag force on a unit mass of particle, and its calculation expression is:

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D R_e}{24} \tag{2}$$

$$R_e = \rho d_p \left| u_p - \left(u + u'\right) \right| / \mu \tag{3}$$

In the above formulation, $\mathrm{R_e}$ denotes the particle Reynolds number, and $\mathrm{C_D}$ is the drag coefficient. $\mathrm{R_e}$ represents the relative Reynolds number. $\mathrm{F'}$ accounts for other forces acting on the particles, with gravity considered in this study.

3. Calculation Methods and Example Settings

3.1. Introduction to Model Simulation Parameters

To simulate the effects of particulate pollutant dispersion within a street canyon, a set of adjustable model parameters is specified to represent key influencing factors. These parameters include the incoming wind speed and particle release location.

(1) Incoming wind speed:

The wind speed at the left boundary inlet is represented by an exponential wind speed profile. The direction of the incoming wind speed is perpendicular to the inlet boundary line.

$$U_z = U_H \left(Z/H \right)^{\alpha} \tag{4}$$

where H is the reference height (18m), α is the power-law exponent, and U_H is the reference wind velocity.

(2) Particle settings

In this study, particles are assumed to be spherical, and each case involves only a single particle, with inter-particle collisions neglected. Particle motion is simulated using a Lagrangian approach by solving the trajectory equations, and particles are treated as independent tracked entities to analyze their dynamical behavior within the flow field.

(3) Initial velocity of particles

This study introduces particles into the street canyon after the flow field has reached a steady state, requiring specification of an initial particle velocity. The initial velocity is set equal to the local wind velocity at the particle release position under the fully developed flow field condition.

3.2. Case Settings

This study investigates the dispersion patterns of particles released from different locations within the street canyon. Particles are injected at 16 uniformly distributed release points along the street canyon, as illustrated in the figure below.

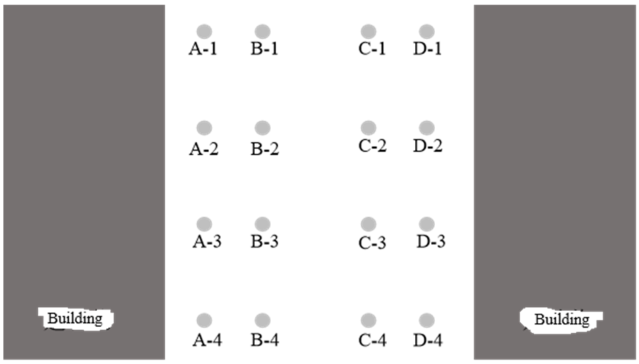


Fig 1. Distribution map of particulate matter

For the two-dimensional computational domain, airflow enters from the left boundary and exits through the right boundary. The top boundary is extended to a sufficient height to ensure a horizontally uniform flow that is not influenced by the street canyon dynamics. The lower boundary consists of the street surface, the side walls of the buildings, and the upper building surfaces on both sides. The boundary conditions are summarized in Table 1.

Table 1. Boundary Condition Settings

variable	Physical boundary conditions			
	inlet	outlet	top	Other boundaries
wind velocity(U_z)	fixedValue	inletOutlet	Slip	fixedValue
pressure(P)	ZeroGradient	fixedValue	Slip	ZeroGradient
Turbulent kinetic energy(k)	fixedValue	ZeroGradient	Slip	kqRWallFunction
Turbulent dissipation rate(ε)	fixedValue	ZeroGradient	Slip	epsilonWallFunction

4. Influence of Particle Position on Diffusion Patterns

In the absence of vegetation or other obstacles, the incoming flow enters the street canyon from above the left building, forming a dominant recirculating vortex in the central region. The vortex is approximately circular, with streamlines gradually becoming more constrained by the geometry toward the core. The velocity field exhibits lower wind speeds in the central region, decreasing toward the vortex center, while higher velocities occur near the building walls and ground surface. To improve computational efficiency, no particles are released during the initial flow development stage. The flow field becomes statistically steady at 80 s and reaches a fully developed state at 100 s. The velocity field at this time is used as the initial condition for particle release, and the local wind velocity is assigned as the initial particle injection velocity at each release position.

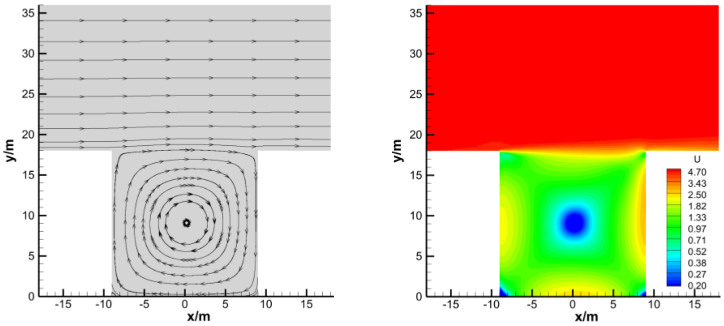
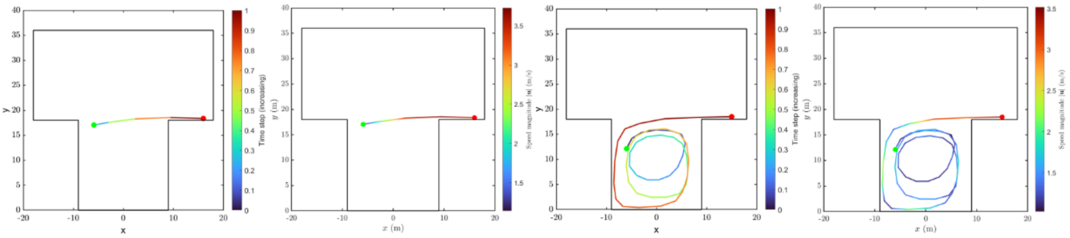


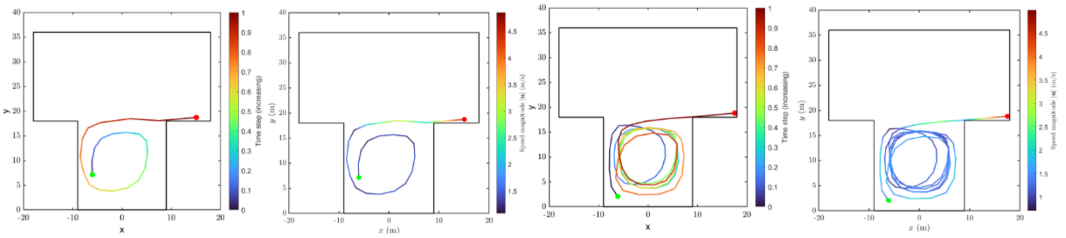
Fig 2. Flow field and wind field within the street

As shown in Fig. 3, the particle trajectories and velocity characteristics near the leeward side were analyzed to evaluate the influence of different release locations on diffusion behavior. A-1 is located at the edge of the free-flow region (y=17 m) and is strongly governed by the mainstream flow, exhibiting a high horizontal velocity aligned with the primary flow direction (Vx=1.025 m/s, Vy=0.433 m/s). As a result, it is rapidly advected downstream and exits the canyon within approximately 10 s. A-2 and A-3 are released within the central vortex region (y = 12 m and 7 m, respectively). Although both are influenced by the recirculating flow, their relatively large upward velocity (Vy≈1.36 m/s) facilitates rapid transport into the upper free-flow layer and subsequent escape. In particular, A-3 exhibits a slightly longer residence time due to its inward horizontal velocity component (Vx=−0.204 m/s), despite its stronger vertical transport capacity, completing dispersion in 144 s. A-4 is located in the low-velocity near-ground region and initially experiences an inward horizontal velocity (Vx=−1.062 m/s), leading to strong entrapment within the vortex structure. It undergoes a prolonged spiral transport process before gradually approaching the boundary, resulting in the longest residence time of approximately 298 s. Overall, these results indicate that release locations near the free-flow boundary and regions with strong vertical transport capacity are more favorable for rapid particle dispersion.

The streamline distribution reveals a stable clockwise primary vortex within the street canyon, with its center located slightly below the mid-height of the domain. A-2 and A-3 are positioned along the upward branch of the vortex, where strong vertical transport facilitates particle uplift. In particular, A-3 can be rapidly advected upward along the vortex circulation, allowing it to reach the upper boundary and disperse at an earlier stage. A-4 is located closer to the vortex core, with its initial horizontal velocity directed inward, causing it to circulate within the vortex and leading to a longer residence time. Nevertheless, under the influence of vertical motion induced by the flow structure, it eventually ascends toward the upper boundary and completes dispersion. Overall, these results indicate that the upward branch of the vortex plays a key role in enhancing vertical transport and promoting particle escape from the street canyon.



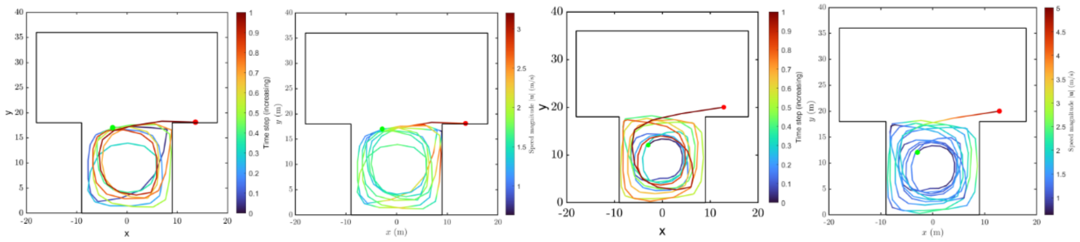
(a1) Case A-1 (a2) Case A-2



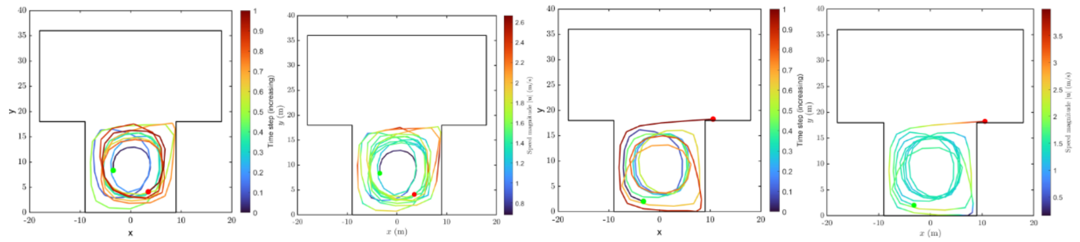
(a3) Case A-3 (a4) Case A-4

Fig 3. Particles located near the leeward side

As shown in Fig. 4 particle motion in the region slightly left of the street center is jointly governed by the initial position and velocity direction. B-1 is located in the upper free-flow region (y=17 m), where its horizontal velocity is strongly aligned with the mainstream (Vx=1.622 m/s). As a result, it is rapidly advected by the high-speed flow and undergoes early dispersion at approximately 300 s. B-2 and B-3 are released in the middle layer (y=12 m and 7 m, respectively). B-2 exhibits relatively low horizontal and vertical velocities but an outward-directed motion, allowing it to gradually approach the vortex boundary and complete dispersion within approximately 400 s. In contrast, B-3 has a negative horizontal velocity (Vx=−0.330 m/s) and is initially located near the vortex core, where it is readily trapped by the clockwise circulation, forming a closed-loop trajectory that prevents escape within the simulation time. B-4 is released near the ground. Although it has a relatively large inward horizontal velocity (Vx=−1.610 m/s), it is initially redirected toward the outer vortex region and is gradually lifted by wall-shear-induced disturbances (Vy=0.279 m/s), eventually dispersing at approximately 316 s.



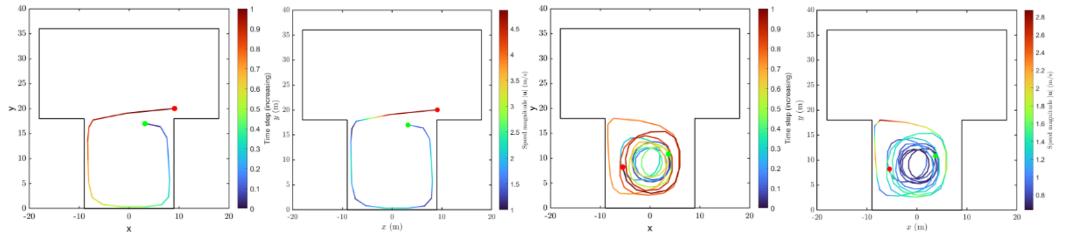
(b1) Case B-1 (b2) Case B-2



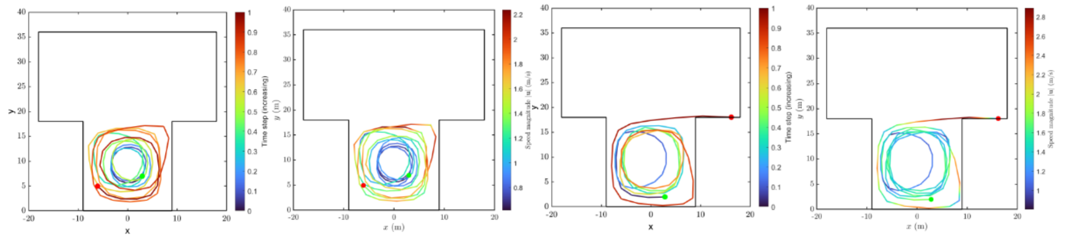
(b3) Case B-3 (b4) Case B-4

Fig 4. shows the particle located slightly to the left of the street center (left side is the time trajectory, right side is the velocity trajectory)

As shown in Fig.5, the dispersion behavior of particles in the region slightly right of the street center is primarily governed by the initial height and whether the particles are located within a closed vortex region. C-1 is located in the upper free-stream region (y=17 m). Although its initial horizontal velocity is relatively small (Vx=0.442 m/s), it is significantly influenced by the superposition of the main flow, enabling it to rapidly escape the local vortex and achieve dispersion at approximately 136 s. C-2 and C-3 are located in the middle and lower vortex circulation region (y=12 m and 7 m, respectively), where the flow field exhibits a closed recirculating structure with relatively low wind speed. C-3, being closer to the vortex core where the velocity is minimal, is more readily trapped within circular trajectories. As a result, neither particle is able to effectively escape within the 400 s simulation period. C-4 is located near the ground (y=2 m). Although its initial horizontal velocity is directed inward (Vx=−0.354 m/s), it gradually expands outward due to disturbances induced by the wall boundary layer and eventually achieves slow dispersion at approximately 302 s.



(c1) Case C-1 (c2) Case C-2



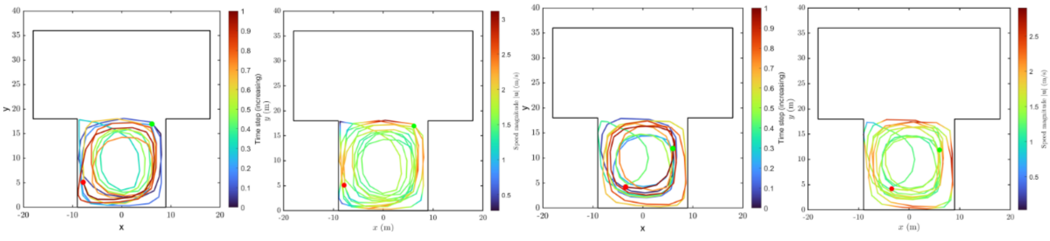
(c3) Case C-3 (c4) Case C-4

Fig 5. shows the particles located slightly to the left of the street center.

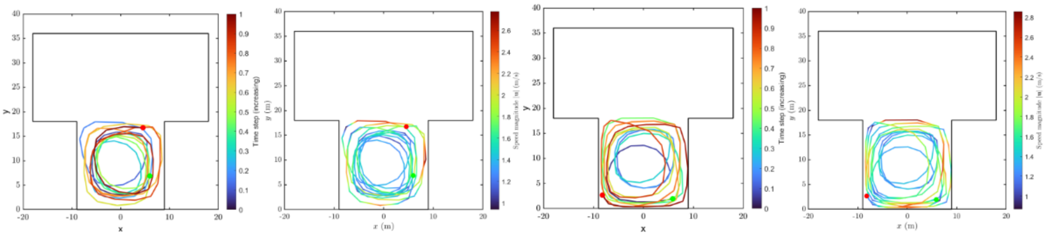
The streamline diagram indicates the presence of a stable clockwise primary vortex within the street canyon, forming a closed recirculation zone extending from the vortex core to the outer boundary. C-2 and C-3 are located near the vortex core and along the main circulation path, where flow velocity is low and disturbances are weak, providing limited additional kinetic energy for particle dispersion. Moreover, their initial velocities are either low or inward-directed, resulting in insufficient momentum to overcome the vortex boundary. Once entrained into this closed flow region, the particles remain trapped in the central recirculation zone for an extended period, making escape difficult.

As shown in Fig. 6, particles in cases D-1 to D-4 do not reach the street canyon boundaries within the 400 s simulation period. This is primarily attributed to the combined effects of a pronounced wind-speed gradient between the canyon and the overlying flow and a stable closed vortex structure. The wind speed within the canyon is significantly lower than that in the above free-stream region (up to approximately 4.7 m/s), resulting in weak vertical exchange and limited particle transport. Meanwhile, a clockwise closed vortex occupying the entire canyon space is formed, causing particles entering the flow to circulate along streamlines and remain trapped, making lateral escape difficult. In addition, the initial conditions further constrain dispersion. In most cases, the initial horizontal velocities are relatively small and, in some instances, oriented opposite to the outward transport direction. In particular, D-3 and D-4 exhibit initial velocities directed toward the street center, which reduces the momentum available for migration toward the boundaries, making the particles more susceptible to vortex entrainment and long-term retention.

The diffusion behavior of particles within street canyons is primarily governed by their initial release location. Particles released in the upper region and near the free-stream flow can rapidly escape the canyon and achieve efficient dispersion due to higher wind speeds and initial velocities aligned with the mainstream flow. In contrast, particles released in the middle and lower regions—particularly those near the vortex core—are more easily trapped by the recirculating flow due to lower local velocities and the presence of closed streamline structures. As a result, they tend to remain within the vortex for extended periods, forming typical low-dispersion or pollutant accumulation zones.



(d1) Case D-1 (d2) Case D-2



(d3) Case D-3 (d4) Case D-4

Fig 6. Particles located near the windward side

5. Summary

Based on a two-dimensional street canyon model and the Lagrangian particle tracking method, this study systematically investigates the diffusion behavior of particles released at different locations under unobstructed conditions. The main conclusions are as follows:

(1) A typical single, dominant clockwise vortex structure forms within the street canyon, which governs the particle transport pathways. The vortex core region is characterized by the lowest wind speed and a closed streamline pattern, making it the primary zone for particle retention.

(2) The initial release height of particles significantly influences diffusion efficiency. Particles released in the upper region of the canyon, close to the free-stream flow, can rapidly exit the canyon under the influence of the high-speed mainstream, resulting in the shortest diffusion times. In contrast, particles released in the middle and lower regions exhibit significantly reduced dispersion capability.

(3) The vortex structure exerts a strong trapping effect on particles in the middle region. Particles located near the vortex core and along the main circulation path tend to follow closed streamlines, making it difficult for them to cross the flow-field boundary. As a result, they may remain within the canyon without escaping over the simulation period.

(4) Particles in the near-ground region are influenced by wall shear and local flow disturbances, allowing them to gradually migrate into higher-velocity regions through slow upward motion. However, this process is delayed, leading to extended residence times.

(5) The degree of alignment between the initial particle velocity direction and the local flow field is a key factor affecting diffusion outcomes. When the initial momentum is consistent with the mainstream flow, particle dispersion is promoted; otherwise, particles are more likely to enter the recirculation zone and become trapped.

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