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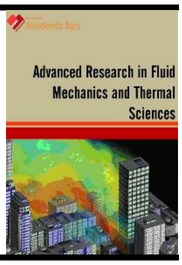


# Effects of Staggered Array of Cubical Obstacles on Near-Ground Wind Environment and Air Quality

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**ABSTRACT**

Deterioration of natural ventilation in outdoor environments due to rapid urbanisation has raised the issues pertaining to pedestrians' thermal comforts and pollutant exposures. There are substantial interests in the recent years to get an insight on how deficient these situations are and later propose the appropriate urban layout for optimum wind ventilation in a dense urban area. The objective of this paper is to numerically study the effects of urban layouts (i.e., staggered arrangements and cubes' densities) on wind ventilation and air quality near the ground subjected to one wind direction; perpendicular to the disposition direction. Computational fluid dynamics simulations were carried out by the use of standard $k$–$\varepsilon$ turbulence model and found to be in fair agreement against the experimental data. Our result showed that loosely packed cubes exhibited lower pollutant concentration and higher wind speed near the ground compared to medium and densely packed cubes. Air quality was improved in closely packed cubes with staggered layout but did not show any improvement in medium and loosely packed cubes with staggered layout. Adversely, disposition of cubes exhibited lower wind speed compared to regular cubes for all street gap sizes. This paper also illustrates a practical strategy in optimising building layouts for wind flow enhancement and air quality improvement in an idealised urban area.



## 1. Introduction

As urban population continues to grow, the demands for living spaces on limited urban area are higher than ever. The importance of future planning is greatly appreciated especially in the efforts to come out with a decent plan of a township to accommodate increasing city inhabitants. Urban planners or developers must consider not only the aesthetic design of house layouts but also from the ventilation perspective. Having a good arrangement of building in an urban area may provide

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sufficient wind ventilation and enhanced air quality, which are beneficial to the communities that live in proximity to tall structures.

The shape of buildings and urban layouts greatly affect wind flow and contaminant dispersion patterns within the urban space, which may impose risks to the well-being and comfort of pedestrians. It is imperative to carry out investigations of the effects of buildings and urban layouts on air ventilation so that the risks associated with the exposure could be assessed. Few studies focused on buildings' densities with infinitely long streets, which assumed a two-dimensional flow within the streets. Oke [1] identified three peculiar flow structures associated with buildings gap; skimming flow, interference wake flow and isolated roughness flow at a certain buildings' height to street width ratio, H/W. Baik and Kim [2] and Mohamad Yusoff and Azawadi [3] further investigated pollutant dispersion patterns and discovered that they are strongly affected by the flow structure. Apart from the above-mentioned factors, the wind flow fields and pollutant dispersion mechanisms are also strongly affected by wind direction and speed [4, 5], thermal stability conditions [6, 7], urban tree [8], and moving vehicles [9]. Detailed discussions on this aspect are available in past studies [10-12].

However, in three-dimensional (3D) flow, the flow is slightly different from two-dimensional (2D) streets due to the influence of flow from the opening at the buildings' sides [13-15]. Arrangements of building clusters are one of the important links to the wind ventilation variations within an urban space. In this regard, staggered arrangement is amongst the parameters that had been investigated by numerous research. One of the earliest studies on staggered building arrangement was experimentally conducted by Meng and Oikawa [16] at a four planar density of up to 40%. Their results showed that at low planar density, the flow underneath the roof layer became an isolated roughness flow. The flow speed is further decreased while the flow structure is identical to skimming flow at higher planar density. Approximately two decades later, Razak *et al.,* [17] conducted a series of large eddy simulations (LES) to predict the wind environment at pedestrian level for five types of uniform staggered block arrays with different aspect ratios and an array with a non-uniform height. They proposed a simple exponential equation and identified the frontal area ratio as the most important parameter in pedestrian wind environment prediction. Another high-resolution simulation of flow structure and pollutant dispersion in arrays of building-like obstacles was performed by Coceal *et al.,* [18] where they observed that highly fluctuating concentration patterns and mean profiles in the near field were strongly non-Gaussian. In the same year, Lin *et al.,* [19] performed CFD for wind assessments of idealised urban canopy layers with various urban layouts and wind direction for the same building packing density. Using the air exchange rate for the assessment of wind ventilation, they suggested that the stronger drag force of staggered urban was the plausible cause for its lower ventilation efficiency. More recently, Yang *et al.,* [20] considered the effect of window opening percentage (WOP) at upstream buildings on air quality within street canyons. Their numerical results showed the potential of cross-ventilation by the upstream buildings on pollutant reduction at higher WOP. Remarkably, they found greater pollutant reduction for staggered arrangements than that for regular arrangements.

As discussed above, the flow and dispersion patterns in urban area are highly responsive to the urban morphology. Based on the brief descriptions of available literature, we found that the effects of staggered building arrangements on wind flow and dispersion patterns mainly considered numerous cluster of buildings, representing a typical urban form at the neighbourhood scale. In reality, urban layouts all over the world are very much different and are too site-dependent. Different from previous studies, our focus in the present study is to investigate the wind environment and pollutant characteristics due to staggered arrangements of obstacles with limited cluster of cubes; a typical urban size that is equivalent to street scale. To the best of our knowledge, the effects of staggered groups of cubes at street scale on near-ground wind environment and air quality has not been systematically explored and fully understood. Here, we adopted Nonomura *et al.,* [21] work for the current investigation by using CFD simulation. The paper has the following structure: Section 1 reviews recent relevant literature and introduces the objective and scope of the present study. Elaboration on the methodology in our study is given in Section 2. Section 3 contains the validation results of our work while the results and discussion of the study are presented in Section 4. Finally, the conclusion of our study is presented in Section 5.

## 2. Methodology

### *2.1 Computational Domain and Mesh Size*

In this study, the array consists of 9 cubes with each cube side is 0.2 m in length. The size of the computational domain is 2.5m x 3m x 1.8m for width, length and height, respectively. The domain size is chosen as such to ensure it is sufficient for the wind flow to be fully developed around the array and to prevent undesirable reverse flow. We considered three different array layouts that are regular and staggered along with three different distances between the cubes. The combination of these parameters results in nine different arrangements. The arrangements are declared by their names. The different distance between cubes are denoted as case D1, D2, and D3. The regular arrangements are defined as R while two staggered arrangements are defined as S1 and S2, respectively. Figure 1 depicts the domain size and the denotation of cube arrangements considered.

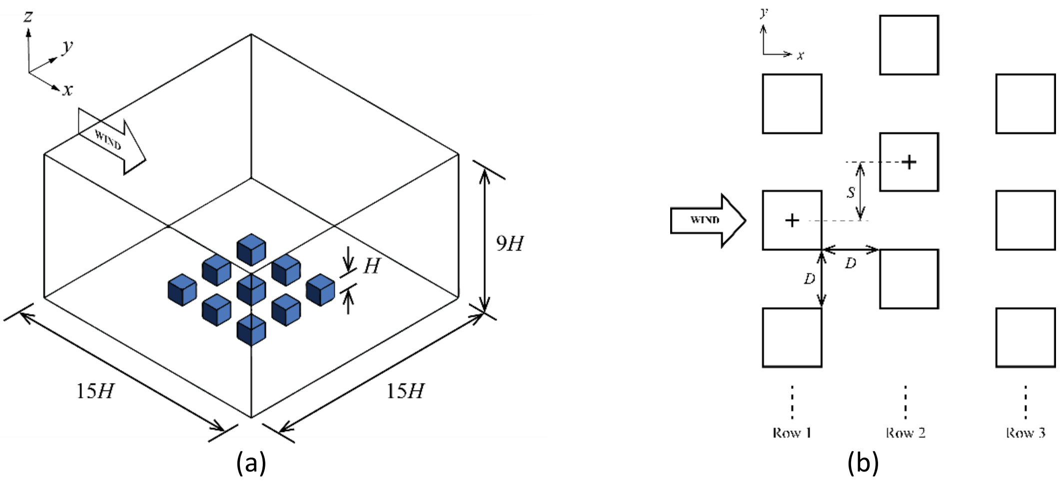


**Fig. 1.** Illustrations of (a) computational domain size, (b) test case descriptions for staggered (*S*) arrangements and distance (*D*) between cubes

In this study, structured and hexahedral type mesh is used to discretise the domain. The reasons are; the geometrical shape of this study is relatively easy to setup using the hexahedral meshing and the beneficial of the hexahedral meshing for minimizing the number of elements. Number of division is used to discretize the grid in the vicinity of cubes while grid stretching is used to minimize mesh elements in the regions far away from the cubes.

### *2.2 Boundary Conditions and Numerical Approximations*

The velocity, the turbulence kinetic energy and the dissipation rate profiles at the inlet have been setup according to AIJ's [22]. The inlet of velocity at the height of the small-scale cube is at 3.65 m/s corresponding to a Reynolds number of 52,000. The outlet has been set to be zero static pressure while the top and the side surfaces are set as symmetry condition.

In order to account for near ground source that is similar to a traffic produced pollutant, one volume source of 0.5 m (x) × 1.8 m (y) × 0.0667 m (z) on each street aligned perpendicular to wind direction are specified on the ground. By assuming a passive and inert airborne pollutant, carbon monoxide (CO) was used as a tracer gas with a constant emission rate $\bar{c}$ = 1 × $10^{-7}$ $kg/m^3s^{-1}$. Here, the Schmidt number is set constant at 0.7.

ANSYS FLUENT is used to predict the air flows under isothermal and steady conditions. For validation, three Reynolds-Averaged Navier-Stokes (RANS) turbulence models are considered to model the turbulent flow which are standard, RNG and realizable $k\text{−}\varepsilon$ turbulence models. The SIMPLE scheme is adopted to couple the pressure to the velocity field. All transport equations are discretized by the second-order upwind scheme for better numerical accuracy. The solutions were analysed after all residuals reached below 1.0 × $10^{-5}$. All numerical schemes were chosen following the recommendations by [23, 24].

### *2.3 Wind Ventilation and Pollutant Concentration Indicators*

Velocity ratio (VR) proposed by Ng, [25] is used in this study to quantify the extent of ventilation capacity of an urban site. The index indicates how much the wind availability experienced by the pedestrians on the ground. It is defined as the ratio of wind velocity at the pedestrian level ($Vp,z$ = 2 m) to that at the top of the boundary layer ($V_\infty$ = 6 m/s). Higher VR corresponds to better wind availability at the study site. In this study, a 1:30 scale model of the urban area is considered, reduced from a 6 m high building that corresponds to a two-storey building. Consequently, the pedestrian level of the current study is about 0.0667 m from the ground ($z/H$ = 0.333).

For consistency, we evaluated the pollutant concentration in the same area with VR discussed previously. However, we consider a dimensionless concentration where the local concentration is normalized by the constant pollutant rate, $\bar{c}$; which known as concentration ratio, CR. This implies how much the concentrations varies with respect to the pollutant source at the origins. The focus of our study revolved around the area where low wind environment and air quality towards urban inhabitants is expected. Thus, the interested area and points at $z/H$ = 0.333 in term of area and vertical lines for post-processing are illustrated in Figure 2.

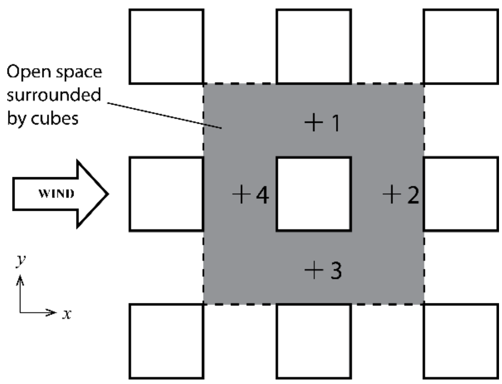


**Fig. 2.** Illustrations of location of interests at at z/H = 0.333 for analysis

## 3. Validation of CFD Flow Simulations with Experimental Data

We have chosen a well-known wind tunnel experiment conducted by Nonomura *et al.*, [21] to validate our numerical method. In all, nine cubes (three rows, three columns) with each cube at about 0.2 m in length were placed in the wind tunnel, as indicated in Figure 1. The building arrangement is of R-D2 case. A series of grid independence test (GIT) have been conducted to determine an optimum mesh for our study beginning from course until fine meshes. The number of divisions for the five meshes is tabulated in Table 1.

**Table 1**
Summary of mesh for GIT

| Test case | Number of grids per building block | Elements counts |
|---|---|---|
| M1 | 4 | 22,000 |
| M2 | 6 | 171,000 |
| M3 | 10 | 585,000 |
| M4 | 14 | 1,120,000 |
| M5 | 18 | 2,500,000 |

The average velocity over 120 points at the roof level plane corresponding to the experimental measurement points has been considered for comparison purposes. Figure 3 illustrates the locations of 120 points around the middle cube.

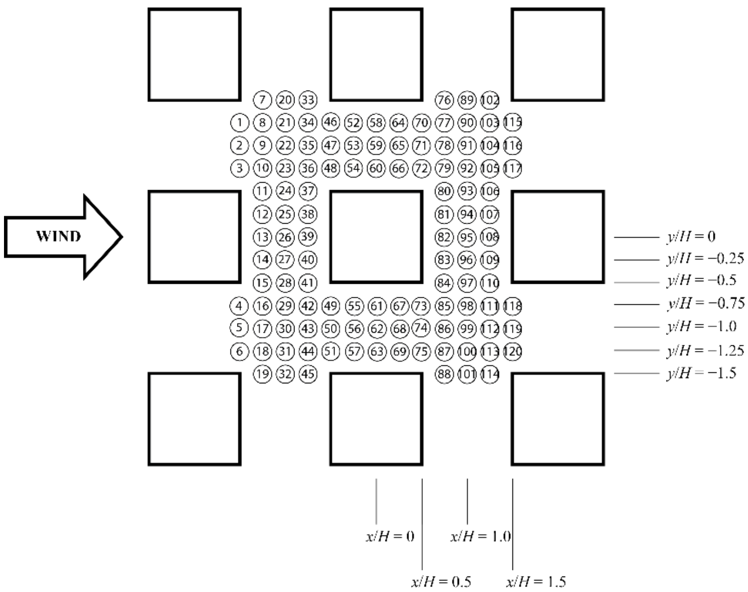


**Fig. 3.** 120 points at roof level (z/H = 1)

The GIT results as depicted in Figure 4 show a reduction on the average velocity of about 0.07 m/s as the mesh density was increased from M1 to M3. However, a slight increment of 0.015 m/s was observed for M4. We can see that the difference from M4 to M5 was about 0.001 m/s, which is lower than 1% difference. Therefore, we can consider that M4 has passed the GIT.

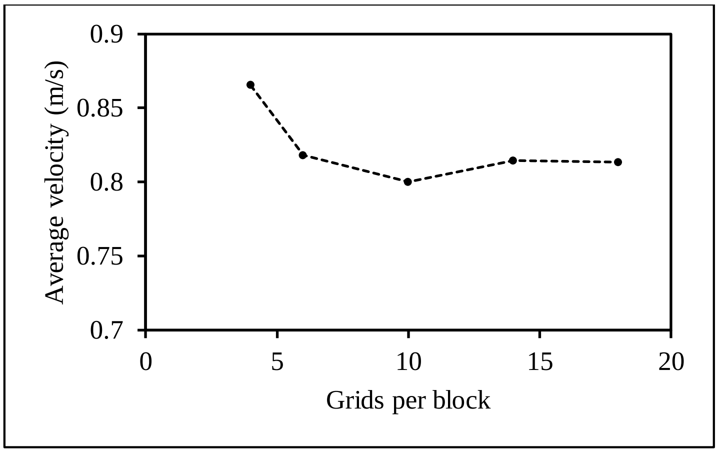


**Fig. 4.** Average velocity over 120 points at roof plane for different grid densities

Herein, the mesh for all test cases was identically constructed with M4 to ensure that the numerical experiment for each case was independent to the spatial discretisation error. Three different types of $k$−$\varepsilon$ turbulence models were tested on the reference arrangement (i.e., R-D2). The results were extracted at 120 points around the centre cube at roof level. Table 2 shows the average percentage error for 120 points for all turbulence models which were standard, RNG, and realisable $k$−$\varepsilon$ turbulence models. The results showed that the standard $k$−$\varepsilon$ turbulence model had the lowest percentage error at 29.87% compared to AIJ, whereas about 34.40% and 34.74% were calculated for RNG and realisable models, respectively.

**Table 2**
Summary of error and average velocity over 120 points for different $k$–$\varepsilon$ turbulence models

| Models | AIJ | Standard | RNG | Realizable |
|---|---|---|---|---|
| Error (%) | – | 30.29 | 34.57 | 33.72 |
| Average velocity ratio (−) | 0.654 | 0.814 | 0.838 | 0.836 |

One can argue the considerably large error of our results compared to the experimental data (error > 20%). To elucidate for the low accuracy, Figure 5 shows the wind flow distribution for 120 points around the centre cube at roof level for all turbulence models. The first 45 points of our results showed a fair agreement with experimental data. For points 46 onwards, significant deviations were evident. Overall, all turbulence models overpredicted the velocity at almost all points. However, the standard $k$−$\varepsilon$ turbulence model was found to be more accurate than other models especially in the wake region of the centre cube.

Our experience with RANS for airflow modelling around a cube indicated that standard $k$−$\varepsilon$ turbulence model performed fairly good over other models including that of $k$−ω turbulence model [26]. In the paper, the standard model was able to reproduce the recirculation in the cube wake, which explained the good result in the wake region of this study. On top of that, other related studies for larger array of cubes such as Lien and Yee [27] and Lin *et al.,* 19] also obtained better prediction of flow in the cube wake regions. The better prediction of flow in the wake region is a central part in our study as the airflow below urban canopy is important to the city inhabitants rather than near the roof and the overlying urban canopy regions.

Based on the best agreement of the standard $k$−$\varepsilon$ turbulence model to the experimental results and findings by others in related and similar studies, we decided to maintain the turbulence model for the rest of the test cases. Apart from the turbulence model, other settings such as mesh scheme, boundary conditions and numerical methods were also kept the same for all test cases with the validation study, ensuring result consistency.

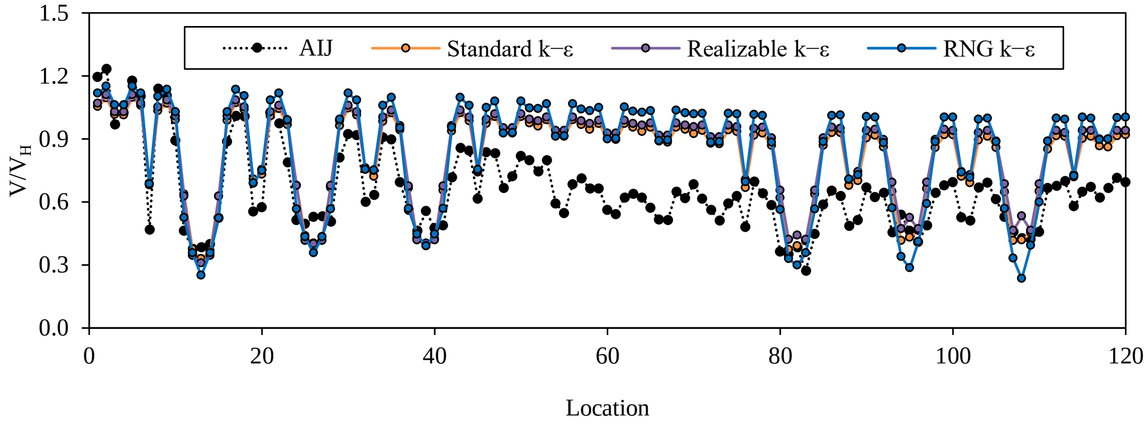


**Fig. 5.** Velocities of 120 points at roof level for different *k–ε* turbulence models

## 4. Results and Discussion

In this section, we discussed how building arrangements and the distance between buildings of idealised building blocks subjected to a parallel approaching wind affected pedestrian wind environment and air quality. A total of nine cases described in Section 2 are simulated and presented here.

### *4.1 Wind Flow Patterns*

Figure 6 shows the VR contours in plan views (horizontal plane) near ground level (z/H = 0.333) for all nine cases. Blue colour indicates lower wind speeds and red colour indicates stronger wind speeds. Focusing first on the cases associated with regular arrangements, large VR is noticeably higher along the streamwise streets. Such outcome is expected, since the approaching wind can flow directly into the streets without disturbance from any obstacles. Due to the flow resistance imposed by the obstacles ahead, VR value was found to decrease along the streamwise streets. However, the VR remained high, exceeding 0.3 for the R-D1 case. Meanwhile, the streamwise streets received high value of VR until the last obstacle row, and increasing the distance between obstacles showed even larger VR; for example, the VR for R-D3 exceeded 0.4.

For obstacles arranged in the staggered manner, a large value of VR was noticeable only in the streamwise streets of the first row of obstacles, while the subsequent streamwise streets showed lower VR compared to the regular case counterparts. The reduction of VR in the middle and last rows of streamwise streets gave rise to enhancement of air flow mixing along the lateral streets and resulted in an asymmetrical flow structure with respect to the incoming wind direction. The enhancement was predominantly high near the windward and left-side surfaces of middle row cubes, which suggested wind deflection to the streets' vicinity by the incoming wind onto the exposed windward face of cubes. Moreover, regardless of distances between the obstacles, increasing obstacle disposition (more staggered) resulted in higher and more uniformly distributed VR along the streamwise streets at the second and third rows as the flow was converged with deflected winds from neighbouring streamwise streets. The results also revealed localised regions of low VR (< 0.3), located behind each obstacle. Circulating vortices in the building wake were the most probable cause for such outcome.

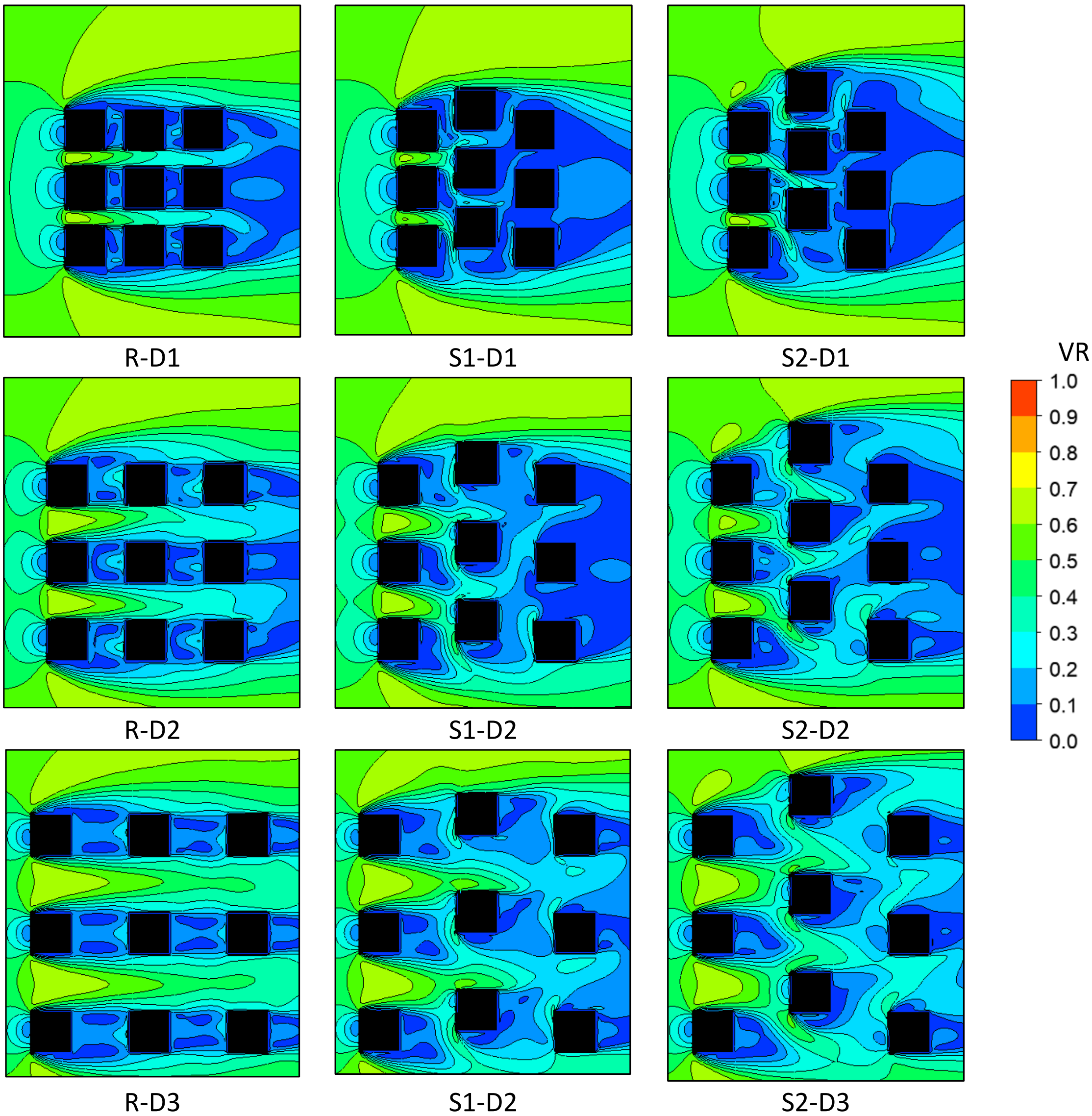


**Fig. 6.** Contours of VR near the ground (z/H=0.333)

Further explanations on the causes of low VR in the block wakes are provided herein based on the streamline plot over a horizontal plane at pedestrian height and coloured in blue for clarity as depicted in Figure 7. It is important to note that the physical characteristics of vortical structures in terms of quantity, size, strength, and others depend strongly on the flow development over the obstacle shape, the proximity to nearby obstacles and their arrangements. A prominent flow feature was the presence of vortical structures formed as the air flowed over and around the cubes. The vortex patterns were different from the typical 2D street canyon flows as the vortical structures near the ground were the results of the flow shearing on both sides of each cube rather than the roof level. In most cases, especially with larger distance between blocks, a pair of counter-rotating vortices were formed behind each cube. In contrast, for smaller building gaps and more staggered arrangements (e.g., S2-D1), there were a few blocks that did not produce circulations in their wakes.

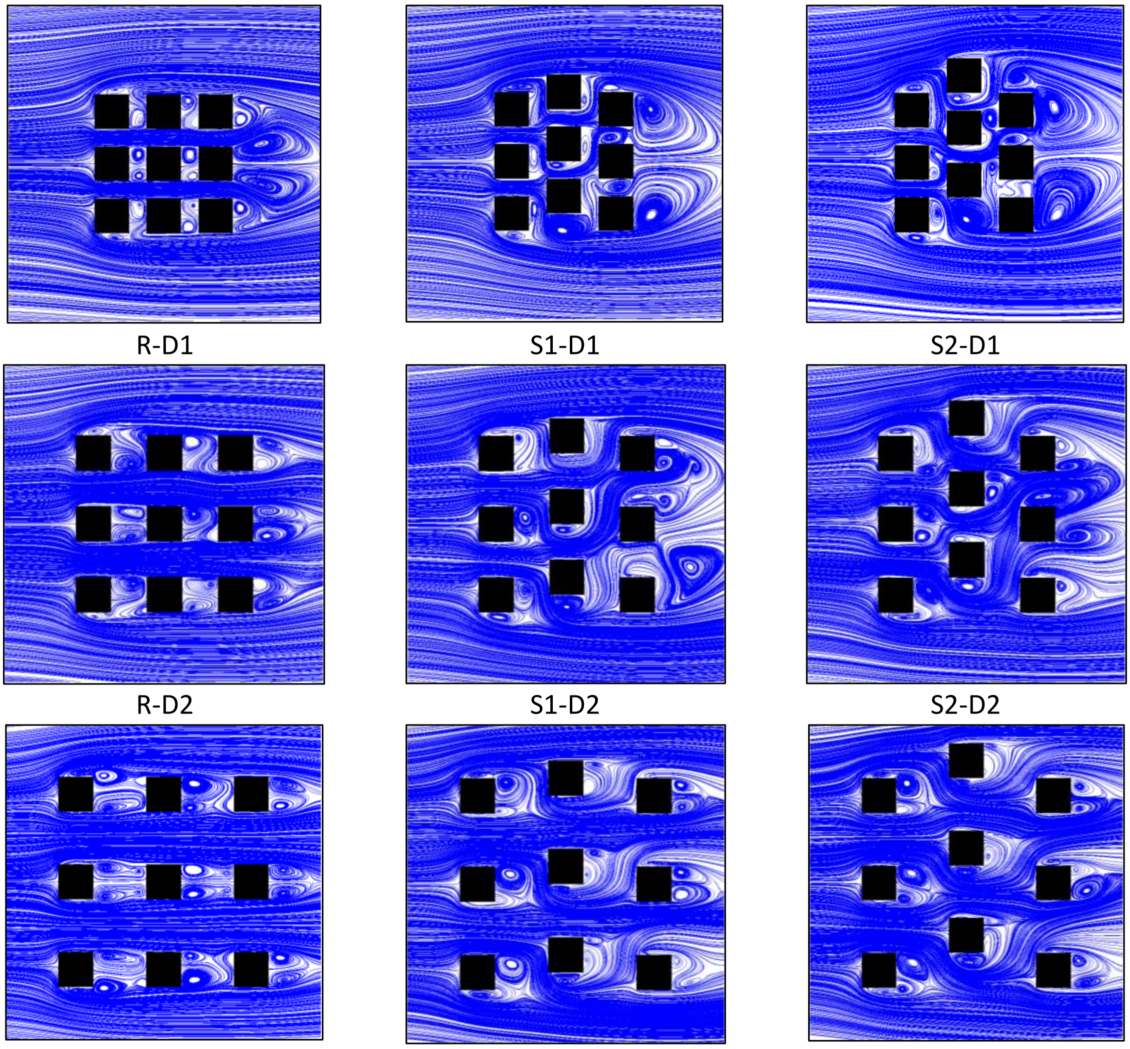


**Fig. 7.** Streamlines plot near the ground (z/H=0.333)

The streamlines presented in the present work correspondingly revealed that for all cases associated with regular arrangements (Figure 7, a channelling-like effect was apparent as fresh air flowed linearly along the streamwise streets. These results confirmed high VR regions along the streamwise streets as observed in Figure 6. In the cases of staggered arrangements, a salient feature of asymmetrical vortical structures with respect to flow direction was observed. Interestingly, each cube in S1-D1 and S2-D1 produced a completely different vortical structure in its wake as compared to S2-D3, which implied the complex flow interactions due to different cube arrangements.

Another interesting flow feature observed in our study was the formation of sizeably large vortices in the wake regions of the last row blocks with increasing cube disposition. Disposition of cubes along the central row that in turn expanded the lateral size of the layout was conceivably the reason. By comparing Figure 6 and Figure 7, we can see that the low VR was predominantly occupied by vortices while the lowest VR location coincided with the centroid of vortex.

Velocity profiles were plotted along the cube's height at the middle canyon for each side of the central cube to further investigate the vertical wind environment within the canyons (Figure 8). Further analysis on velocity components was done, where each of the cube wake had a 3D structure as the vortices structure varied with height due to variations in velocity components (not shown). Herein, we focused only on the wind environment in terms of velocity magnitude.

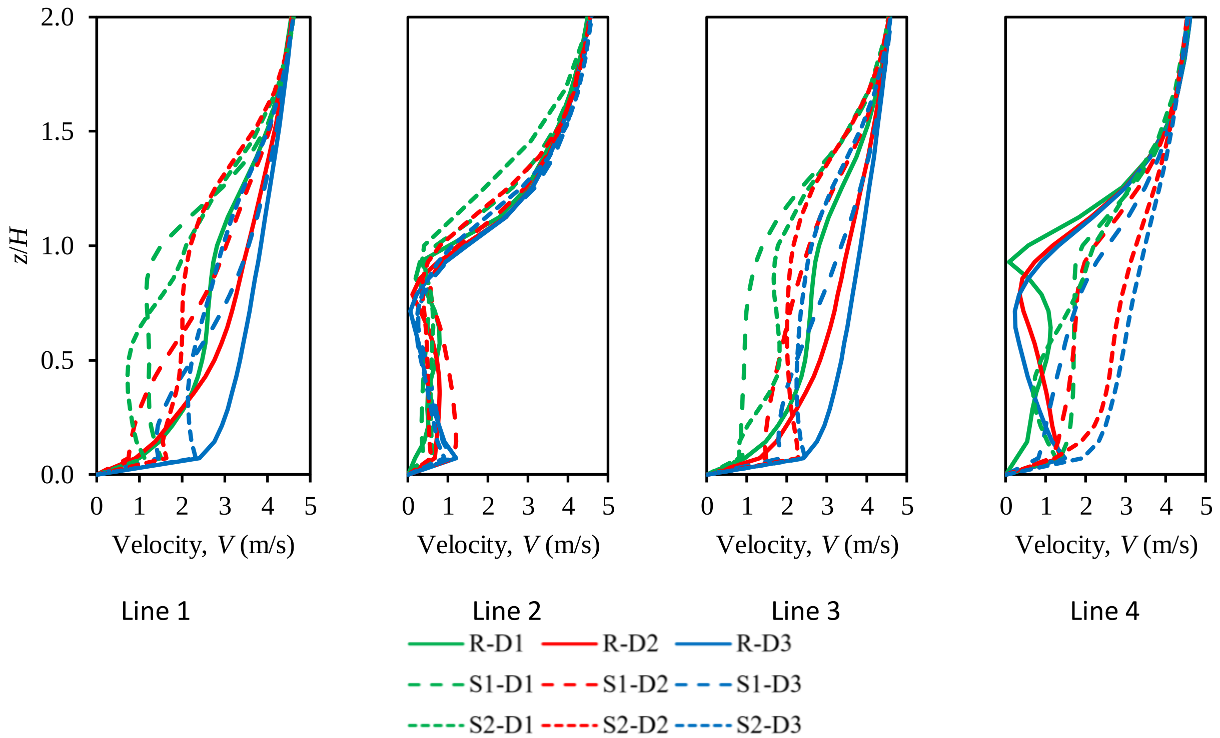


**Fig. 8.** Vertical profiles of the mean velocity, *V* at four locations (see Figure 2 for positions)

For regular arrangements, lines 1 and 3 (see Figure 8) showed identical velocity magnitude from the ground up to about z/H=0.4 for both R-D1 and R-D2. However, distinct enhancement was attained for R-D3, which showed the importance of obstacle distances for wind ventilation. Comparing between lines 2 and 4, we observed that the vertical velocity decreased along the streamwise streets, signifying a relatively large wind resistance exerted by the obstacles. Furthermore, we had found that the vertical profiles of velocity magnitude at line 2 were mostly below 0.5 m/s. From the ventilation point of view, the low velocity all over the canyon height was unfavourable as it may indicate poor conditions for human comfort and health.

Cross comparison of staggered building arrangements for each cube distances showed lower velocity compared to regular arrangement at lines 1 and 3. However, the velocity remained higher than 1 m/s. In contrast, the exposed windward cube to the prevailing winds as the cube was in disposition (line 4) helped to improve wind ventilation.

### *4.2 Pollutant Concentration Patterns*

In our study, pollutant was constantly emitted from two sources near the ground surface that were aligned perpendicular to wind direction in between the first and second streets. Figure 9 displays the CO ratio (CR) contours on a horizontal plane near the ground (z/H = 0.333) for all test cases.

Results showed large CR in all cube wakes as these were the regions that were poorly ventilated (Figure 6). Noticeably large CR was observed in narrow streets as compared to in broad streets. In this case, the dispersion of the CO exhibited a very interesting pattern, especially in R-D1, which was different from other cases, where the CO in R-D1 was highly accumulated in each cube wake of the first row blocks. Based on our inspection (not shown), the tendency of CO accumulation in these regions was due to two counter-rotating vortices that were aligned vertically along the canyon height.

The bottom vortex trapped the pollutants near the windward side of block in the second row and hindered the dispersion of pollutants out of these regions.

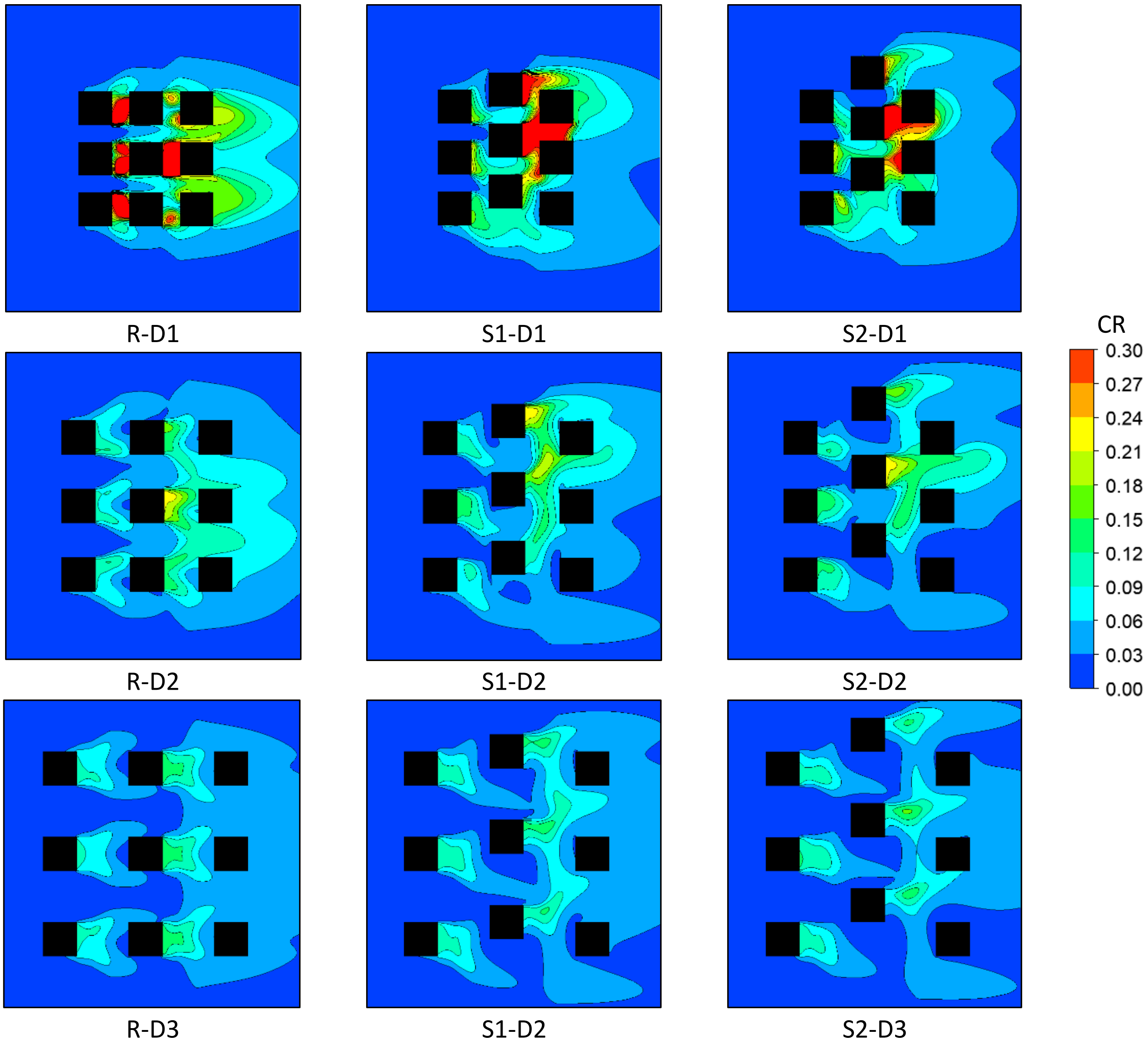


**Fig. 9.** Contours of CR near the ground (z/H=0.333)

Meanwhile, lower pollutant concentration along lateral street behind the first row blocks for cases other than R-D1 was plausibly due to the vertical pollutant exchange through the open street at roof level and the exchange process from the street sides. Higher CR found in the last row streets was partly due to the low VR in these regions. Other reasons were the re-entrainment of pollutant from the second source and the entrainment of pollutant from the top and either sides of the block that originated from the upstream source. In fact, maximum pollutant accumulation in the wake of the central block was attained (not shown) due to the combinations of these effects and the low vertical profile (Figure 8).

In comparison with the regular arrangement, more staggered buildings allowed for more exchange of pollutant in the spanwise direction. As a result, the pollutant tended to spread diagonally in the northeast direction, almost following the central row disposition. From a macroscale perspective, a well-distributed spread of pollutants in streamwise and spanwise directions was seen as the cubes were farther from each other and the middle array was in disposition. Greater flow disturbances in the wake of last array cubes as the cubes were far from each other were the probable reason for the observed trend. The pollutant spread observed here suggested complex interactions between the vortices in the block wake region and the vortices separated from nearby blocks on both sides.

### *4.3 Overall Near Ground Wind Environment and Its Link to Air Quality*

We further analysed the wind environment and air quality on a region surrounded by cubes to understand the impact of staggered arrangement at the street scale. Figure 10 shows the average VR and CR over a horizontal plane near ground level that spanned over the open channel around the centre cube as indicated in Figure 2. The data were mainly sorted according to the array arrangements of regular and staggered, followed by a secondary sorting of cube gap.

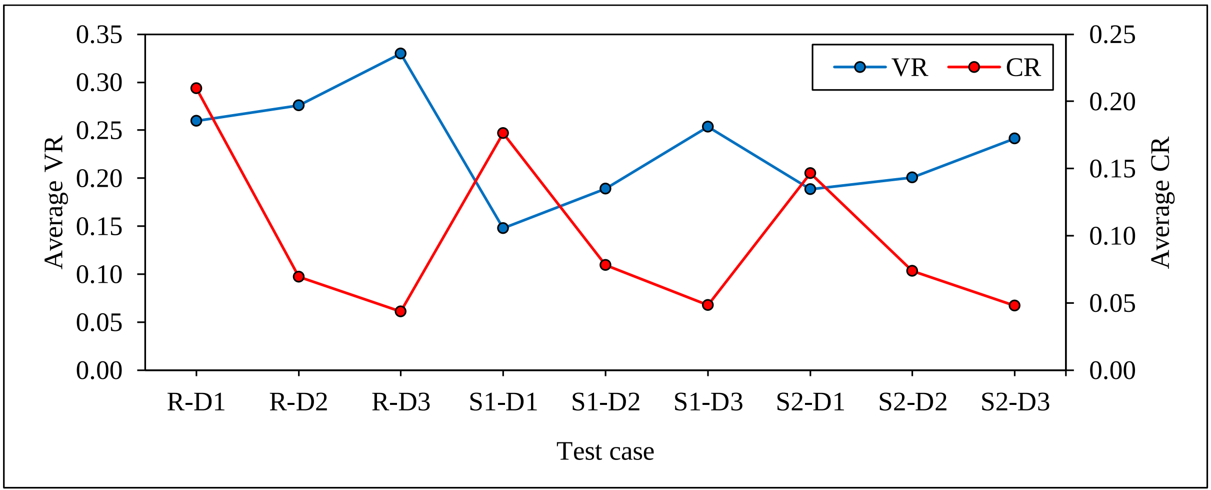


**Fig. 10.** Average VR and CR for all cases evaluated in a horizontal plane near the ground surrounding the middle cube (see Figure 2 for positions)

It was apparent that the larger the gap between cubes, the higher the average VR in regions surrounded by the cube. The significance of cube distance was also observed in S1 and S2 cases. Among these cases, the highest recorded average VR of 0.33 was associated with R-D3 whilst the lowest average VR is almost 50% lower than that; VR of 0.15 for S1-D1. Although staggered arrangement was able to supply a considerable airflow exchange across lateral streets as discussed in Section 4.1, the average VR were below 0.25 compared to the regular arrangement (VR > 0.25) for all cube distances. Surprisingly, the average VR for S2 was just moderate among other arrangements.

Variations in near ground air quality seemed to follow the same trend with that of wind environment. Air quality improvement was the greatest when cube gap was broadened. In this study, the regular arrangement with the broadest cube gap (R-D3) demonstrated the best average CR (CR < 0.05). The worst air quality was also associated with cubes aligned with the incoming wind but with the least cube gap (R-D1), although the average VR was not the worst. This peculiar outcome may be due to the counter-rotating vortices in the cube wake of the first row blocks that hindered the pollutant transfer. While the staggered cube arrangement did not show significant variations of average CR in D2 and D3, it was a different story in D1. The advantage of staggered arrangements in pollutant exchange across the lateral streets in narrow streets was evident as the reduction of average CR was found to decrease linearly with cube disposition; from CR of 0.2 to 0.15.

## 5. Conclusions

The wind flow and pollutant dispersion near the ground surface (z/H = 0.333) through a simple array of nine cubes were examined using numerical results from a CFD simulation. A total of nine cases corresponding to three different street spacings and cube dispositions were numerically investigated. The turbulent wind flow and pollutant dispersion were solved using the standard k-ε model and validated against a wind tunnel data set. In the following, we highlighted a few important findings from our analysis.

The result showed that loosely packed cubes exhibited lower pollutant concentration and higher wind speed near the ground compared to medium and densely packed cubes. Air quality was improved in closely packed cubes with staggered layout but did not show any improvement in medium and loosely packed cubes with staggered layout. Adversely, disposition of cubes exhibited lower wind speed compared to regular cubes for all street gap sizes.

The flow and dispersion patterns presented in this study implied that the wind environment and dilution on the polluted air in the canyon were strongly related to flow structures that depended on both the array's size and layout. Our results offered great insights into the capacity of staggered arrangement and street gap towards outdoor air ventilation and air quality in the region surrounded by cubes. Due to the limited parameters considered in this study, different staggered patterns and wind directions are subjects of further research to understand the effect of cubes in staggered layout on wind environment and air quality completely.

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