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Flow physics of air pollutants dispersion: A case study in an urban street canyon in Baghbazar, Kathmandu

Biraj Khadka*, Binayak Lohani, Arun Bikram Thapa, Bibek Parajuli, Neeraj Adhikari

Department of Mechanical and Aerospace Engineering, IOE Pulchowk Campus, Pulchowk, Lalitpur, 44700, Bagmati, Nepal.

Abstract

The alarming increase of hazardous pollutants in South Asian cities such as Kathmandu, Delhi, Mumbai, Dhaka, etc. risks the life of every individual there. A major source in the production of such harmful pollutants is vehicles and industries. A Computational Fluid Dynamics (CFD) approach is proposed to model the pollutants emitted by vehicles using different Reynolds Averaged Navier Stokes (RANS) turbulence models in the street canyon setup. The primary aim of the study is to understand the effect of turbulence on the transport of gaseous pollutants in the street canyon. RNG $k-\epsilon$ model performed best among other turbulence models with mean FB -0.105, NMSE 0.045, FAC2 0.915 and R 0.93 which is validated with the experimental data. Higher wind speeds allowed the concentration to disperse more effectively in Baghbazar's street canyon, resulting in lower concentrations of pollutants.

Keywords : air pollution, pollutants, computational fluid dynamics, turbulence models, air quality

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Correspondence to: B. Khadka Corresponding Email: Emails: beerazzkhadka12345@gmail.com (B. Khadka), binayaklohani@gmail.com (B. Lohani), arun.thapa@pcampus.edu.np (A. Thapa), 075aer009.bibek@pcampus.edu.np (B. Parajuli), neeraj@ioe.edu.np (N. Adhikari)

1. Introduction

Air pollution is a significant challenge of the 21st century, accelerated by urbanization, industrialization, and the growth in the number of vehicles. The air quality index (AQI) reveals deteriorating air standards, causing health issues like respiratory illnesses and leading to 4.2 million premature deaths annually due to outdoor pollution [1]. South Asia, especially cities like Delhi and Beijing, faces extreme pollution levels. Nepal, situated between them, also grapples with this challenge. Kathmandu, with a growing population density, witnesses over 25% of Nepal's registered vehicles, a major contributor to its air pollution [2] [3] [4]. Many vehicles use poor-quality fuel, are old, and lack maintenance, exacerbating emissions [5]. Other significant sources include industrial activities and residential heating practices. Urban growth has led to more street canyons, trapping vehicular pollution and affecting pedestrian health, especially with perpendicular wind flows that limit pollutant dispersion [6]. Kathmandu's specific urban design, with congested roads and tall buildings, intensifies this problem. Numerical modeling, like the CFD approach, has become essential for simulating and predicting pollutant dispersion in such complex environments.

The vortex present in the street canyon was studied which is typically generated due to shear between the adjacent fluid layers [7]. Most of the street canyon configuration resembles the case with AR > 0.7 i.e, skimming flow where the pollutants remain trapped inside the canyon. A single recirculation vortex is formed in this type of flow. The primary airflow vortex carries the pollutant emitted by the vehicle to the street canyon's leeward wall, and then upward to the top area of the canyon which allows the air exchange and the escaping of pollutants [8]. The pollutant concentration is therefore greater near the leeward wall than it is near the windward wall [8] [9]. The Reynolds number for the street canyon flows is chosen using the height building and the roof velocity as the reference values [10]. Once the Reynolds number exceeds the critical Reynolds number (), the

flow is not dependent on the Reynolds number [11]. For Reynolds number independence, the sufficient critical Reynolds number for the AR: 1, 1.5, and 2 are 11000, 58000, and 87000 respectively. The critical Reynolds number is a function of the AR of the building [12] and by analyzing this a escaping pattern of pollution should identified.

Pollutants like CO2 and NOx are treated as scalar quantities in air. We'll use numerical modeling to simulate their flow in the Baghbazar street canyon. Specifically, we aim to validate the most representative turbulence model for pollutant dispersion using Openfoam. The study will also explore flow patterns in Baghbazar, Kathmandu and how wind speed impacts pollutant dispersion.

2.Materials and Methods

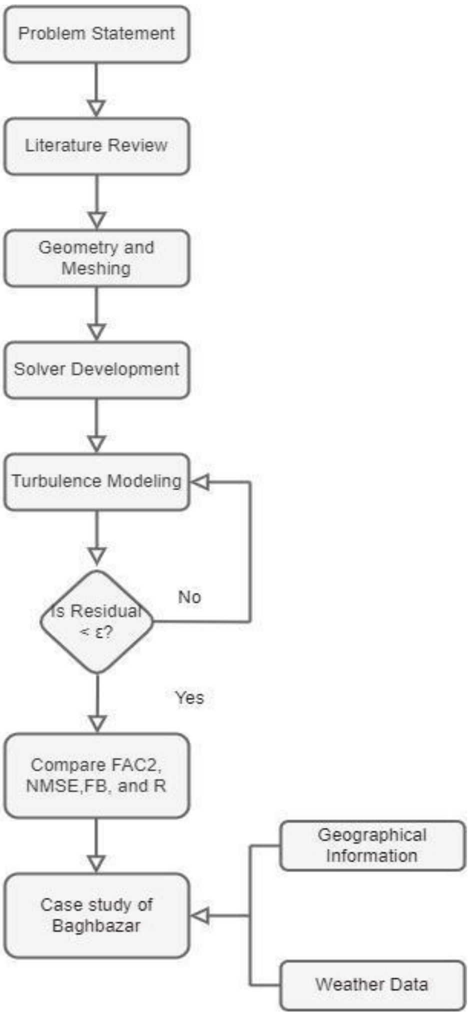

Figure 2-1: Flowchart Methodology

2.1. Computational Domain and Mesh Generation

Laboratory of Building- and Environmental Aerodynamics, Karlsruhe Institute of Technology (KIT), Germany has provided the Concentration Data of Street Canyons (CODASC) database for the validation of different street canyon configurations with/without the presence of trees which is shown in the table below:

Model Parameters	Value
Aspect Ratio (H/W)	1
Height of the building (H)	0.12 m
Width of the street (W)	0.12 m
Length of the street canyon (L)	1.2 m
Reference velocity (	4.65 m/s
Reynolds number (Re)	37,200
Total emission rate from sources	10 g/s

Table 21: Initial data of wind tunnel experiment

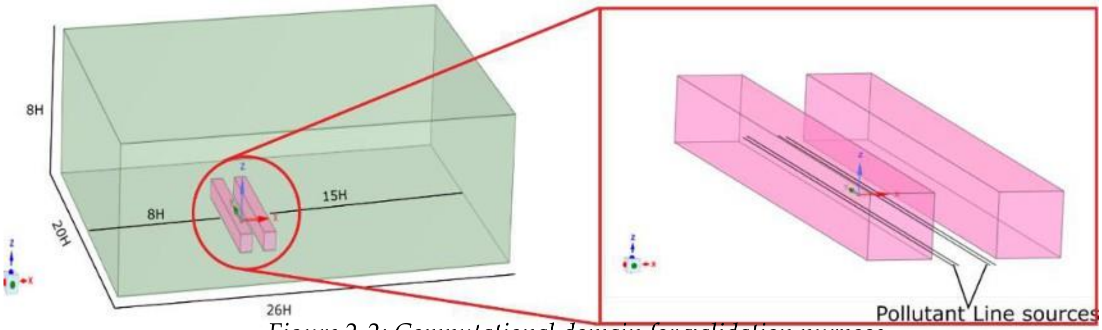

Figure 2-2: Computational domain for validation purpose

The computational domain's size (26H×20H×8H) plays a crucial role in determining the accuracy and computational cost of CFD simulations. The upstream domain length is 8H while downstream domain length is 15H as shown in Figure 2-2.

2.2. Initial Boundary Conditions and Solver

For Boundary condition we require a logarithmic profile of the inlet velocity at the far field known as the atmospheric boundary layer (ABL). ABL is an important concept in urban CFD analysis, particularly in street canyon simulations. The ABL is the layer of air near the earth's surface that is affected by friction with the ground and is influenced by various meteorological factors such as wind speed, temperature, and humidity. The velocity, TKE, and ε logarithmic profile are mathematically modeled using the Equation 2.1, Equation 2.2 and Equation 2.3.

$$U(z) = \frac{u^*}{\kappa} ln \frac{z + z_0}{z_0} \qquad 2.1$$

$$\kappa(z) = \frac{{u^*}^2}{\sqrt{C_\mu}} \qquad 2.2$$

$$\epsilon(z) = \frac{{u^*}^2}{\kappa(z + z_0)} \qquad 2.3$$

Where is the ABL friction velocity, κ is von Karman constant whose value is 0.42, and a constant with value 0.09.

Furthermore, another boundary condition that requires to be initialized at the beginning is zero gradient at inlet, total pressure at outlet and symmetry in the axis. This condition is solved using a finite volume method was used for the spatial discretization along with second-order accurate schemes for the discretization of velocity gradient and divergence (Gauss linear scheme)

3. Results and discussions

3.1. Solver Validation

As discussed, five RANS simulations: SKE, New-SKE, SST, RKE and RNG are simulated. The converged simulations are compared to the normalized concentration wind tunnel data as shown in equation 3.1. The normalized concentration field (C) was used to define the characteristics of the pollutant in the flow

environment given as:

$$C^{+} = \frac{C_p U_{ref} H}{C_s Q_s} \qquad 3.1$$

Where,

C_P=measured concentration in ppm

C_s=source concentration in ppm

U_{ref}=reference velocity at given height

H=Height of the building

Q_s=Source flow rate per unit length in m2/s

The normalized concentration contour of wind tunnel at Wall-A is compared with that of obtained from various turbulence models as indicated in Figure 31. The vortex visible in the street canyon in Figure 32, formed from the shear between adjacent fluid layers, highlights that the pollutant concentration in the leeward area is greater than in the windward area [8] [9].

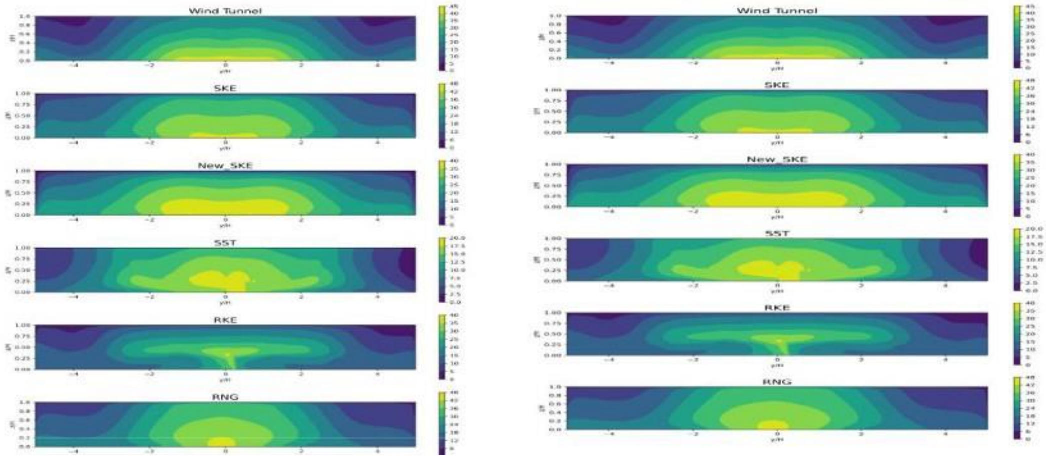

Figure 3-1: Contours of normalized concentration at wall-A

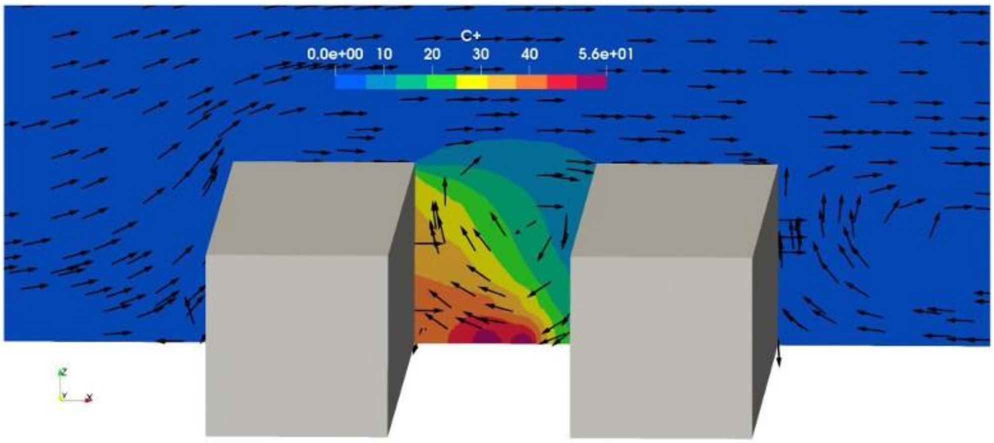

Figure 3-2: Contour of normalized concentration with velocity vector

3.1.1 Statistical Performance Measures

On the basis of four different statistical measures, statistical analysis was carried out. The fractional bias (FB), the normalized mean square error (NMSE), the fraction of predictions within a factor of two of observations (FAC2), and the correlation coefficient (R) were the statistical performance measures (SPM) used for the comparison. RNG k − was chosen in accordance with these SPM.

	SKE	New-SKE	SST	RKE	RNG
FB	-0.16	-0.11	0.59	0.3	-0.13
NMSE	0.07	0.07	0.49	0.2	0.04
FAC2	0.88	0.89	0.69	0.79	0.95
R	0.89	0.85	0.85	0.77	0.93

Table 3-1: Statistical Performance for wall-A

	SKE	New-SKE	SST	RKE	RNG
FB	-0.28	-0.25	-0.13	0.45	-0.08
NMSE	0.13	0.13	0.44	0.39	0.05
FAC2	0.74	0.67	0.29	0.78	0.88
R	0.89	0.84	0.84	0.75	0.93

Table 3-2: Statistical Performance for wall-B

$$FB = \frac{\overline{C_0} - \overline{C_p}}{0.5(\overline{C_0} + \overline{C_p})} \qquad 3.2$$

$$NMSE = \frac{\overline{(\overline{C_0} - \overline{C_p})^2}}{\overline{C_0 C_p}} \qquad 3.3$$

$$R = \frac{\overline{(C_0 - \overline{C_o})(C_p - \overline{C_p})}}{\sigma_{C_p}\sigma_{C_p}} \qquad 3.4$$

$$FAC2 = fraction\ that\ satisfy\ 0.5 \leq \frac{C_0}{C_p} \leq 2.0 \qquad 3.5$$

Here, C_0 are the wind tunnel measured concentrations.

C_p are predicted by the model.

$\overline{C_0}$ and $\overline{C_p}$ are the mean values of C_0 and C_p.

σ_{C_p} and σ_{C_p} re the SD of C_0 and C_p

and are the mean values of and Cp.

and re the SD of and

A measure of mean bias called FB only reveals systematic errors that result in the simulated values being either overstated or underestimated in relation to the measured values. The numerical difference between and , which is employed as the linear scale's systematic bias, is used. The NMSE is a scatter measure that accounts for both systematic and random errors. R just displays the linear relationship between the measured and predicted values, which is a necessary but insufficient condition for a perfect model because it is sensitive to extreme data pairs. Since it only considers pairs with a ratio between 0.5 and 2.0, FAC2 is the simplest simple metric. This circumstance prevents high and low outliers from having a significant impact on FAC2.

The minimum absolute value for FB and NMSE, and maximum value for FAC2 and R statistical measures signify the best models. Therefore, in all aspects RNG k-Є model gave the best results among others.

3.2. Case Study of Baghbazar

Kathmandu's typical street canyon features a two-lane street flanked by three to four-storeyed buildings, forming deep canyons. The surge in old vehicles, many over 20 years old and poorly maintained, elevates air pollution in urban South Asian cities. In Kathmandu's canyons, where tall buildings are near roads, pollutant dispersion is limited, posing health threats. Baghbazar in Kathmandu, with a 12m wide and 116m long street, was selected for analysis due to its high AQI (maximum PM2.5 = 200 µg/m3). Its dense population, high traffic, and narrow street canyon make it a prime location for studying vehicular emissions.

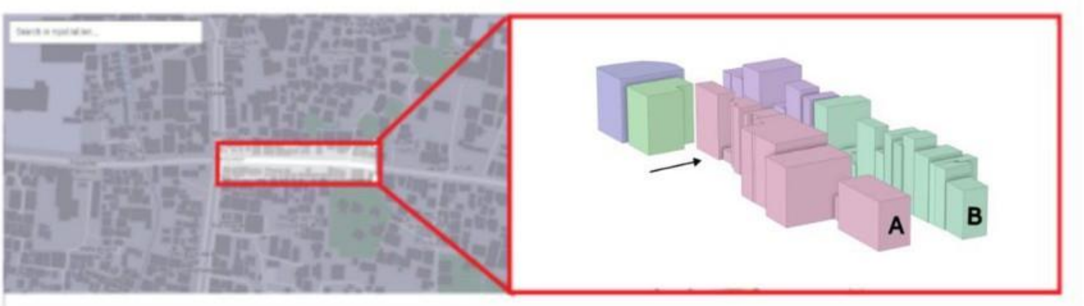

Figure 3-3: Street canyon of Baghbazar

This area comprises 31 buildings altogether which include Medium Rise (6 to 8 Storey) and General buildings (1 to 5 Storey). A two-dimensional sketch of Baghbazar was extracted from Cadmapper. Due to the lack of enough data on the individual height of the buildings in this area, a site visit was conducted to note this data.

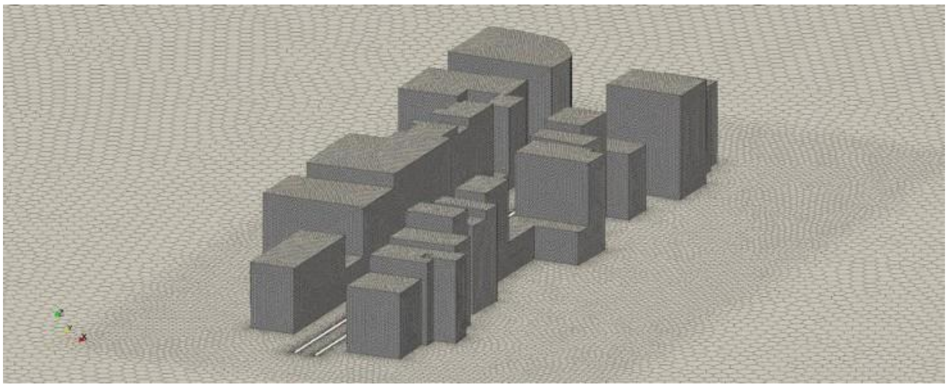

Figure 3-4: Mesh configuration of Baghbazar

Height is crucial for accurate flow pattern replication using numerical methods. Since direct height measurements of buildings weren't feasible, we used a strategy noting each building's storeys. Heights derived from from Table 33 were manually input into the ANSYS designer software, SpaceClaim, as illustrated in Figure 33. The total mesh was 2.3 million which were generated using Ansys Mesher. The total emission rate from the source was taken as 1.5kg/s. While emission rate affects pollutant dispersion modeling, our focus was predominantly on understanding flow dynamics, leading us to rely on this preset value for further analysis.

Type	Storey	Height
General Buildings	1 to 5	Below 16m
Medium Rise	6 to 8	16m to 25m

Table 33: Height Estimation based on storey of the building [13]

Wind speed and direction are important parameters. For this project, we considered wind perpendicular to the street, which creates recirculating zones that trap pollutants in the canyon. While other wind directions can change flow dynamics, they aren't explored here. We studied the effect of four wind speeds: 1, 6, 15, and 22 knots, to understand their impact on flow and pollutant dispersion.

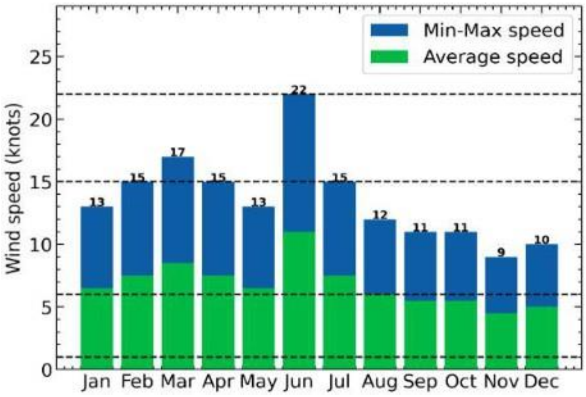

Figure 3-5: Wind speed data in knots measured at 10m AGL, Tribhuvan International Airport [14]

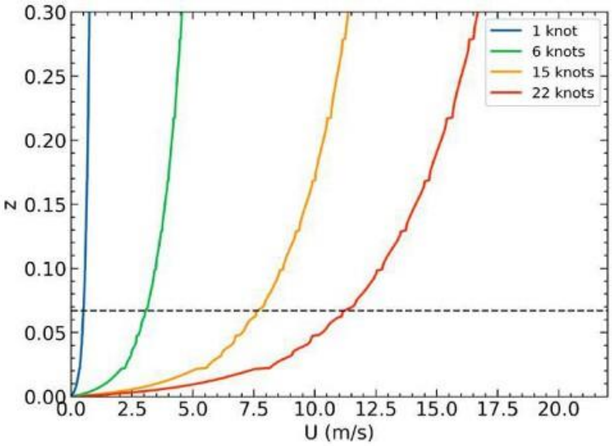

Figure 3-6: Atmospheric boundary layer for different

The atmospheric boundary layer (ABL) for four reference velocities at 10m AGL is depicted in Figure 3-6, showing the wind speed-height plot. With an average building height of 16.28m, we obtained specific Reynolds numbers, all exceeding the critical threshold for H/W=1.35. This confirmed that vortex structures in the scaled model mirrored its prototype. The model was then scaled to 1:150 and simulated in OpenFOAM using the RNG turbulence model, considering wind velocities of 1-22 knots, equating to wind scales from 1 to 9.

In Figure 3-7, as wind velocity rises, the C_P/C_S decreases on both buildings. Higher wind velocities dilute street canyon pollutants more and increase wind pressure on buildings, enhancing natural ventilation [18]. Figure 3-8 reveals pollutant concentrations dropping on both buildings with increased wind velocity. Contour details show higher C_P/C_S values near building A. Due to windward downflow velocity at building B and leeward flow patterns at building A, a large vortex forms, leading to more pollutant accumulation on the leeward side.

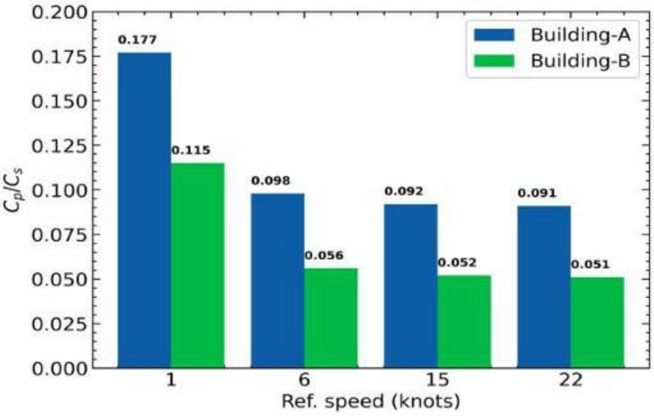

Figure 3-7: Bar-chart diagram for Baghbazar case (vs wind speed in knots ( ))

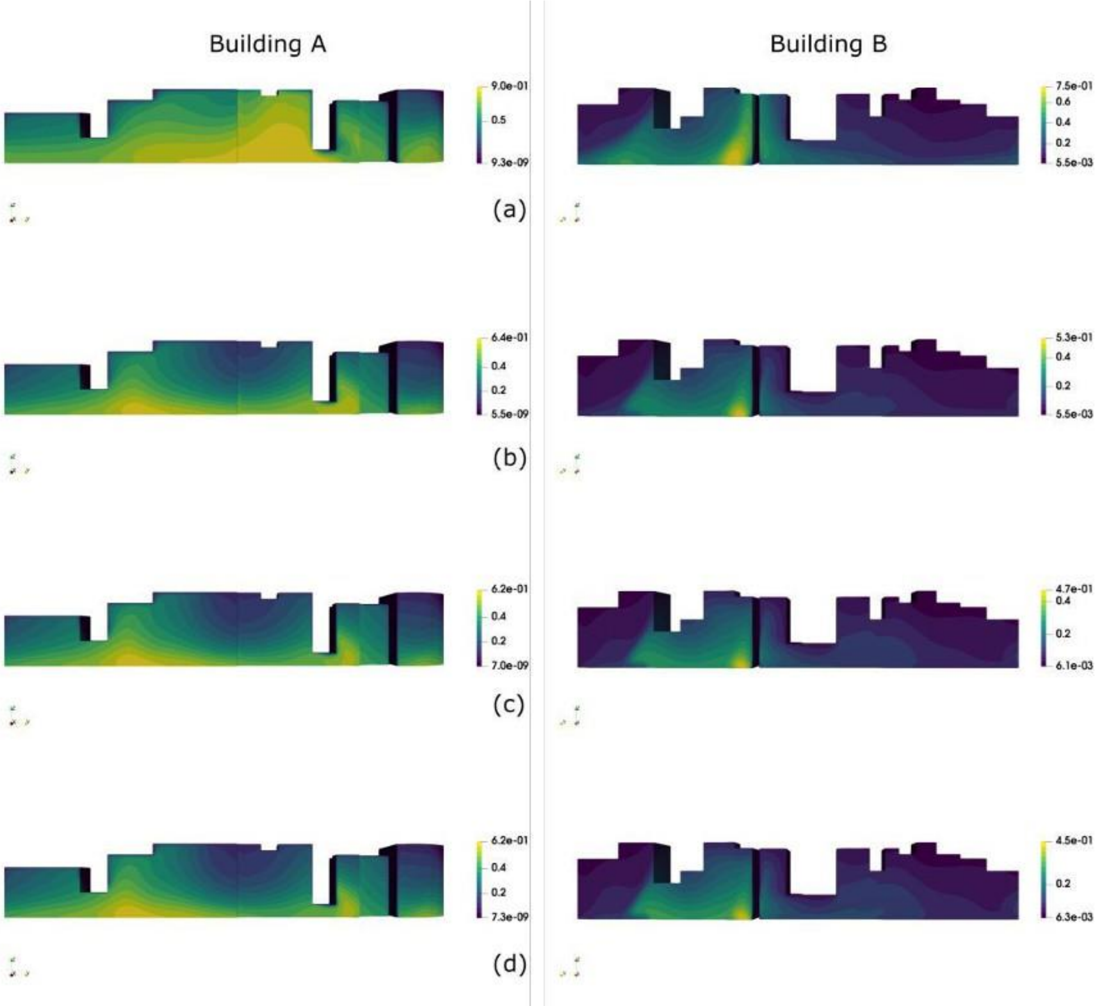

Figure 3-8: Contours of for different (a) 1 knot (b) 6 knots (c) 15 knots and (d)22 knots

4. Conclusions

Five RANS turbulence models were analyzed for pollutant dispersion, with validation against wind tunnel data. Most models closely matched the data, especially the RNG k-ε model. Given the dynamic nature of pollutant flow, the RANS technique proved statistically sound. Accurate modeling can identify pollution hotspots for residents and pedestrians to avoid. Based on this study, the conclusions are:

RNG k-model proved to be the best fit among other standard RANS turbulence models mean FB -0.105, NMSE 0.045, FAC2 0.915, and R 0.93.

Increased wind speeds caused higher dispersion of concentration in the street canyon of Baghbazar and become diluted, resulting in lower concentrations on these buildings. Conversely, when wind speed decreases, pollutants can become trapped and accumulate in specific areas, leading to higher concentrations in buildings.

The numerical model proved reliable for designing buildings in urban cities to minimize pollution risk. To enhance air quality in Baghbazar, it's advised to space buildings apart to improve airflow. This prevents wind vortices and pollutant accumulation. Adjusting balcony structures can further optimize pollutant dispersion, as flow patterns are sensitive to such configurations. The Baghbazar model doesn't account for factors like external pollution sources, flow rates, vehicles, and utility poles due to computational limits. Surrounding buildings are also omitted, as they introduce complexities in flow, affecting pressure and wind speeds in the street canyon.

Conflict of interest

No conflict of interest.

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