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Flow and Pollutant Dispersion Model in a 2D Urban Street Canyons Using Computational Fluid Dynamics

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ABSTRACT

A two-dimensional model is used to simulate temperature distribution, wind speed, and pollutants dispersion within an isolated two-dimensional street canyon using the SIMPLE algorithm in ANSYS Fluent version 16.2. The simulation is based on the Reynolds-averaged Navier–Stokes equations coupled with a series of standard, RNG, and realizable k-ε turbulence models. Simulation domain consisted of a street canyon with two buildings enclosing a street with the aspect ratio of 1. The wind is assumed to be perpendicular to the direction of the street, and the source of the pollution is assumed to be liner. The results showed that the RNG k-ε turbulence model is the most optimum model by comparing with the calculated data under different wind speed patterns and pollutant dispersion model. The improvement of turbulent viscosity term of the RNG k-ε turbulence model provides a more accurate and reliable numerical solution for the present study regarding the pollution dispersion in a street canyon. The simulation results also showed that the dimensionless pollutant concentrations, P, is larger on the leeward side of the buildings and decrease exponentially from floor to top of the upstream buildings. Furthermore, the results showed that the pollutant concentrations on the leeward side of the building are more than that on the windward side due to the pollutant transportation of vortex circulation.

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1. Introduction

The rapid growths of urbanization caused many challenges in urban areas as the urban heat island (UHI) phenomenon and air quality degradation [1–3]. The street canyon indicates a distinct climate where micro-scale meteorological processes have an impact on local air quality and inhabitants comfort and health [4]. The turbulence and pollutant transport in urban street canyons have been investigated in many studies [5–7]. Physical parameters as wind speed and direction, building arrangements, air and surface temperatures, and source of pollutants control the pollutant dispersion process. Measurements, observations, and simulations have been applied to investigate the impacts of aforementioned parameters on pollutant dispersion in street canyons in local scales and regional scales [8–13]. Another important factor that affects the pollutants photochemical formation, coagulation and condensation, transport and dispersion in an area is the increase of temperature due to solar radiation, the release of stored heat by urban canyons, and heat emissions from anthropogenic and biogenic sources [14–18]. Reynolds-averaged Navier–Stokes equations (RANS) assist the understanding of pollutant dispersion in street canyons [19–24]. Kang et al. [25] investigated pollutant dispersion in a street canyon and the NO chain cycle photochemistry considered using a RANS model in the research. The computational fluid dynamic (CFD) methods are capable of representing airflow and pollutant accumulations within the street canyon and show pollutant transport into the atmosphere. The 2D or 3D RANS equations are coupled with the various turbulence models and large eddy simulations to simulate the pollutant scattering.

Here, the effects of air temperature distributions and wind speed on pollutant dispersion are investigated in a two-dimensional canyon with two buildings enclosing a street. The wind assumed to be perpendicular to the direction of the street, and the source of the pollution is considered to be liner. The RANS is coupled with the $k-\varepsilon$ turbulence models namely the standard $k-\varepsilon$ turbulence model, the RNG $k-\varepsilon$ turbulence model [26] and the realizable $k-\varepsilon$ turbulence model [27] to study the effects of wind distribution on pollutant dispersion. Here, the simulations are conducted concerning two different wind speeds (2 and 4 m/s) for the aspect ratio (AR) of 1. (AR) the ratio of buildings height (h) to the street width (b). The other focus is to investigate the increase of discharge rate of Ethane gas in the street canyon. Thus, two scenarios are considered: a low traffic density and a high load of traffic during rush hours (early mornings and evenings). The buoyancy effect is included because the increase of temperature as results of the anthropogenic heat of vehicles play a significant role in the formation of pollutants. The simulation results of the numerical model with ANSYS Fluent version 16.2 are compared with the experiments and calculated results of previous studies. The paper structure is as follows: the methodology includes the numerical approach, computational domain, and boundary conditions; the results and discussion include the effects of temperature distribution and wind speed on pollutant transport and dispersion in a 2-D street canyon; the conclusion includes a summary of the study and future steps.

2. Methodology

2.1. Computational setup

The geometry consists of two buildings surrounded by a street. The wind assumed to be perpendicular to the direction of the street, and the source of the pollution is assumed to be liner. Figure 1 shows the computational domain of AR of 1; where b as the street canyon width is 0.06 m; and has the building height is 0.06 m [28]. The actual physical domain is 0.18 m wide and 0.24 m high. The line source dimension is 0.0011 by 0.01 m. Due to the mesh refinement, the quadrangular meshes are used for the present calculations and set to be 70 in the X direction and 50 in the Y direction.

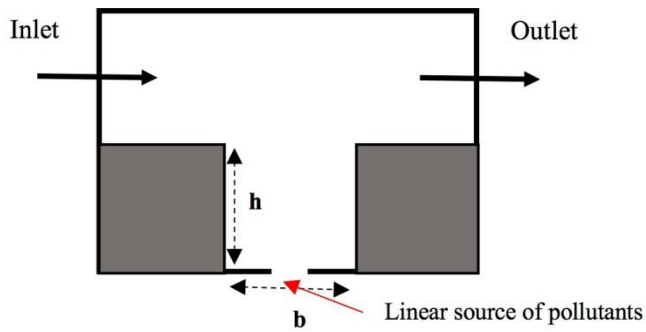

Fig. 1. The computational domain with the AR=1.

2.2. Numerical approach

A 2D computational domain is considered, and the air within the domain is assumed to be incompressible laminar inert flow, and the pollutant compression is assumed to be constant. According to Sini et al. [8] these assumptions are reasonable for the low atmospheric environment but, the thermal and buoyancy effects need to be considered. The set of equations is used to solve the problem: governing equations as continuity (1), momentum equations (2), pollutant transport equations (3), heat equations (4) and K and ε transport equations in the standard $k-\varepsilon$ turbulence model (5 - 6) as follows:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_j \partial x_i} \tag{2}$$

$$\frac{\partial C_i}{\partial t} + u_j \frac{\partial C_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_i}\left[\left(D_i \frac{\mu_i}{S_{C_t}}\right)\frac{\partial C_i}{\partial x_j}\right] \tag{3}$$

$$\frac{\partial \theta}{\partial t} = -u_i \frac{\partial \theta}{\partial x_i} - u_j \frac{\partial \theta}{\partial x_j} + S_\theta \tag{4}$$

$$\frac{\partial k}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \frac{G_k}{\rho} - \varepsilon, \tag{5}$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{1}{\rho} C_{\varepsilon 1} G_k \frac{\varepsilon}{k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{6}$$

whereas; u_i and u_j are the mean velocities in their corresponding x and y arrays; μ is the molecular viscosity; g_i is the gravitation force; μ_t is the turbulence viscosity; G_k is the turbulent kinetic energy production; ∂k and $\partial \varepsilon$ are the turbulent Prandtl numbers for $k-\varepsilon$; ρ is the density; p is pressure; C_i is pollutant concentration; D_i is the diffusivity; S_{C_t} is Schmidt number; and $\frac{\partial \theta}{\partial t}$ represents the local changes in potential temperature. S_θ is the source and sink of heat, which in this study, as a street canyon and is considered to be negligible and zero.

The RNG $k-\varepsilon$ turbulence model and the realizable $k-\varepsilon$ turbulence model are used to validate their numerical performance for the pollutant dispersion modeling in a 2D computational domain. In the RNG $k-\varepsilon$ turbulence model (7) and (8) have a similar form with the standard $k-\varepsilon$ turbulence model, but it provides an analytically derived differential formula in order to determine the effective viscosity. It considers the turbulent Prandtl number, which is the ratio of momentum diffusivity to thermal diffusivity:

$$\frac{\partial k}{\partial t}+u_j\frac{\partial k}{\partial x_j}=\frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+\frac{G_k}{\rho}-\varepsilon \tag{7}$$

$$\frac{\partial \varepsilon}{\partial t}+u_j\frac{\partial \varepsilon}{\partial x_j}=\frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right]+\frac{1}{\rho}C_{\varepsilon 1}G_k\frac{\varepsilon}{k}-\left[C_{\varepsilon 2}+\frac{C_\mu\rho\eta^3\left(1-{\eta}/{\eta_0}\right)}{1+\beta\eta^3}\right]\frac{\varepsilon^2}{k} \tag{8}$$

whereas the α_k and α_ε are the Prandtl number for $k\ and\ \varepsilon$; μ_{eff} is the turbulent viscosity; S is the scalar measure of the deformation force; and the constant of η_0 and β are 4.38 and 0.012, respectively. The difference between the realizable $k-\varepsilon$ turbulence model (9) and (10), is the turbulent viscosity. It is calculated from an analytical formula and the ε equation is derived from an exact equation for the transport of the mean-square vorticity fluctuation:

$$\frac{\partial \varepsilon}{\partial t}+u_j\frac{\partial \varepsilon}{\partial x_j}=\frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_1S_\varepsilon-C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}} \tag{9}$$

$$where;\ C_1=max\left[0.43,\frac{\eta}{\eta+5}\right] \tag{10}$$

The equations are discretized by finite volume method and the SIMPLE algorithm. These numerical calculations are used in the FLUENT code, and the constants of these models are the same as the assumptions in the software.

2.3. Ethane pollution

Ethane is a chemical compound (C_2H_6). It is a colorless and odorless gas at the standard environmental condition. Ethane is a natural gas that is used as a by-product of petroleum refining. In the laboratory, ethane is prepared via electrolysis. Acetate is oxidized to produce carbon dioxide and methyl radicals. Then, the reactive methyl combines to produce ethane [29]. Since Ethane is a free radical reaction; it proceeds through the propagation of the ethyl radical as well. In industry, the complete combustion of ethane releases heat and produces CO_2 and H_2O. The combustion may also occur without the access of O_2, forming a mix of carbon and CO. The series of reaction in ethane combustion is the combination of an ethyl radical with O_2, and the subsequent breakup into other products namely ethoxy and hydroxyl radicals. The release of ethane has negative impacts on people, especially those living near major roads who also suffer cerebral shrinkage. The brain starts aging and thus increasing its dementia risk.

3. Result and discussion

The RANS equations are coupled with the $k-\varepsilon$ turbulence models and are employed to study the effect of wind and temperature distributions as a thermal pattern on pollutant dispersion in the domain of interest. The simulation results as temperature distributions, wind speed pattern, and pollution dispersion and turbulence intensity with ANSYS Fluent version 16.2 are presented here [30]. The simulations are conducted in three scenarios that differentiate wind speed and ethane gas discharge rate in the 2D street canyon. In addition to these changes, air temperature distribution is calculated to consider the effects of real environment on wind distribution and pollutant dispersion in the selected domain. In this regard, the air temperature is assumed to be 27ºC as an average of a normal summer day. The ethane discharge temperature is added to the atmosphere temperature and assumed to be 77ºC. The temperature distributions are assumed to be constant for these scenarios. Table 1 summarizes the three scenarios using ANSYS Fluent V16.2.

Table 1
Simulation scenarios using ANSYS Fluent V16.2

Parameters	***Scenario* 1**	***Scenario* 2**	***Scenario* 3**
Wind Speed (m/s)	2	4	2
Ethane Gas Discharge Rate (l/h)	4	4	40
$k-\varepsilon$ Turbulence model	- Standard -RNG -Realizable	-Standard -RNG -Realizable	-Standard -RNG -Realizable
Temperature (k)	Air: 27ºC Pollution: 27ºC	Air: 27ºC Pollution: 27ºC	Air: 27ºC Pollution: 27ºC

3.1. Temperature effects

In a canyon with the aspect ratio of 1, most of the air is well mixed, even though the temperature differences are available between the ground and the ambient temperature. Since the differences are very small and negligible, it has fewer impacts on the distribution of heat to the street canyon. In addition to the heat released from the ground, the heat that emits by vehicles and human activates will create a thermal plume above the street canyon. Figure 2 shows the temperature distribution and heat flux in the domain of interest with various computational models. The heat encircles at the center of the domain and causes maximum concentrations at the leeward roof level and leeward and windward ground corners. The temperature distribution depends not only on the source emission but also on the wind speed that across through the canopy. As the wind speed increases, the temperature plume raises more toward the leeward side of the building. The higher wind speed leads to a more reduction in temperature in street canyon. Meanwhile, if more heat is emitted, the heat flux will increase and thus trap more in the street with AR of 1, and as a result, the temperature in this area will also increase significantly.

It is noteworthy that there are differences between temperature distribution and pollutant concentration to some extent. On the one hand, the sizes of the pollutants' source are various: temperature has an area heat source that emits from the street floor, while the pollutant source is assumed to be a line source in the center of the street. In addition, the temperature is constant at boundaries. Thus its distribution is also constant and independent of the heating intensity, thus any slight variations in the temperature distribution are due to the differences in advection. In contrast, the boundary conditions for the pollutant are assumed to be none, and hence the pollutant dispersion is sensitive to the AR and heating capacity. It should be noted that the role of anthropogenic and natural heating sources is crucial in calculating temperature dispersion and heat flux in the domain of interest, which is disregarded in the current study.

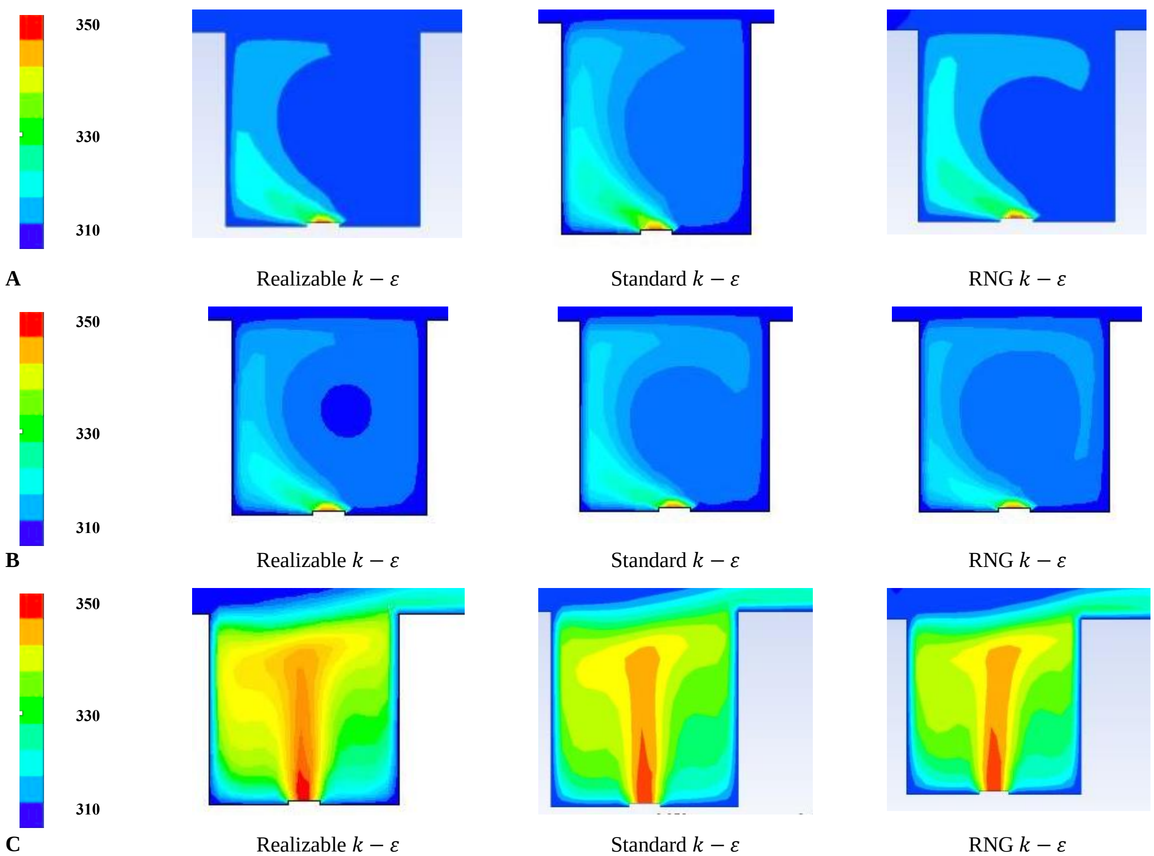

Fig. 2. The temperature distributions within the street canyon (AR=1) under different turbulence models. (A: Qe = 4 l/h and Uw=2 m/s; B: Qe = 4 l/h and Uw=4 m/s; C: Qe = 40 l/h and Uw=2 m/s).

3.2. Wind speed effects

The simulation results indicate that the wind speed and velocity distribution on the building 's leeward side is more significant than the windward one. Thus, the pollutant concentrations reduce more from the floor to the top of the buildings due to the wind speed circulation and the pollutant concentrations (that are nearly steady along with the height of the downstream building on the windward side). The results show that the standard and RNG $k-\varepsilon$ turbulence model represent similar outcomes for pollutant accumulations on both sides of the buildings. But, by comparing with the realizable $k-\varepsilon$ turbulence model, the pollutant accumulations on the building's leeward side are more substantial. The results of these simulations are in good agreement with the results of the experiments by previous studies [6,28–32].

Figure 3 shows the results of these simulations with different $k-\varepsilon$ turbulence model. When the wind speed is assumed to be 2 m/s, the standard $k-\varepsilon$ turbulence model represents the best-calculated results, while the RNG and realizable $k-\varepsilon$ turbulence model under-predicts and over-predicts the pollutant concentrations on the building's leeward side, respectively. Whereas, wind speed raises to 4 m/s, the standard and realizable $k-\varepsilon$ turbulence model over-predicts the pollutant accumulations on the leeward and windward sides of the buildings, while the RNG $k-\varepsilon$ turbulence model provides the best calculated data. The RNG $k-\varepsilon$ turbulence model represents less significant changes by increasing the wind speed. In this regard, the RNG $k-\varepsilon$ turbulence model seems to be the most favorable of the turbulence model to assess the airflow. Figure 3C shows the wind speed vector distribution (with the speed of 2 m/s) and the mass flow rate of ethane. The clockwise vortex distribution is generated as the wind breezes across the street. The center of the circulation is pointed near the middle of geometry. Furthermore, a small vortex produces at the lower corner region on the building's leeward side. Thus, pollutants are carried out by wind circulations from the line source of pollution to the leeward side of the upstream building, and therefore it causes more pollutant concentrations on the leeward side than the windward side of the domain.

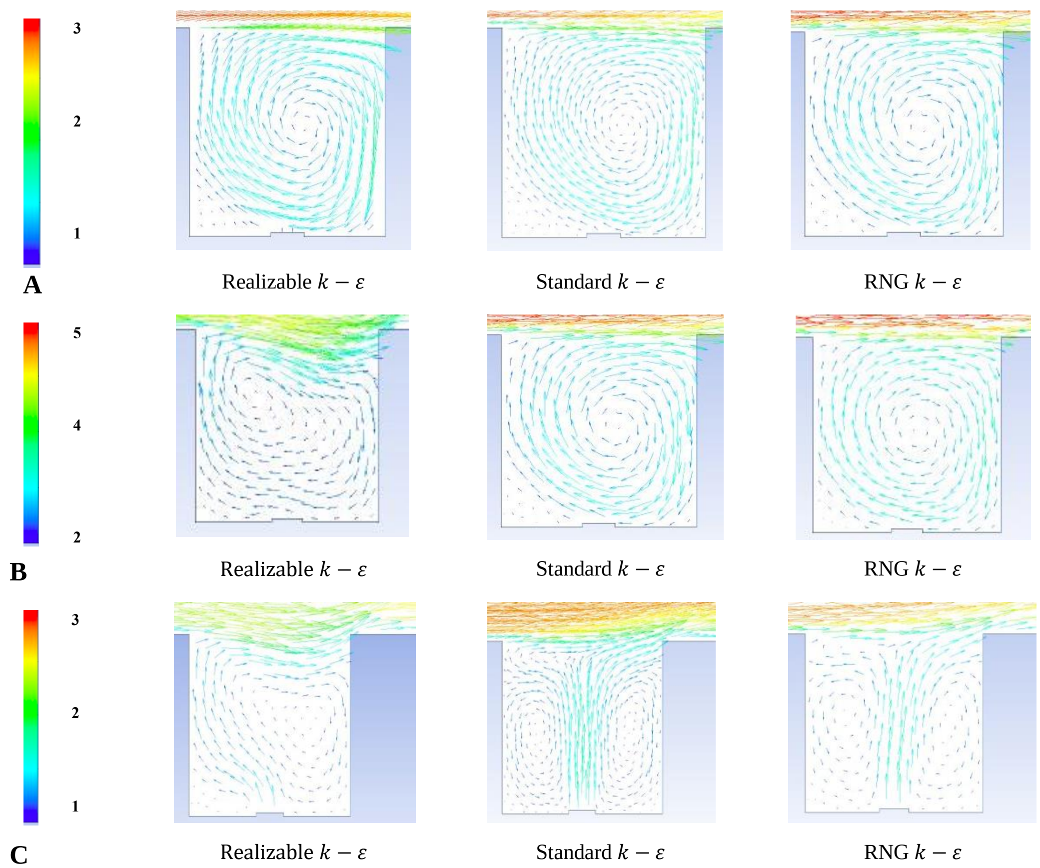

Fig. 3. Wind-speed distribution within a street canyon (AR=1) under different turbulence models. (A: Qe = 4 l/h and Uw=2 m/s; B: Qe = 4 l/h and Uw=4 m/s; C: Qe = 40 l/h and Uw=2 m/s)

3.3. Pollution dispersion effects

The variation of the source of the pollution corresponds to the traffic volumes in the street canyon and urban areas. Here, the two ethane-gas discharge rates are considered regarding the low traffic (Qe = 4 l/h) and high traffic (40 l/h) volume in a street canyon. The aim is to consider the effects of the line source of the pollution and wind speed concerning the pollutant dispersion within the domain of interest. Figure 4 shows the mass fraction of C_2H_6 distribution within a street canyon (AR=1) under different turbulence models. When the wind speed is increased, the pollution dispersion in street canyon is in a more reasonable behavior, so the pollution is decreased in better circumstances comparing to the lower wind speed. The other notable issue is that the pollution concentration is higher in the leeward side of the buildings comparing to the windward side of the buildings.

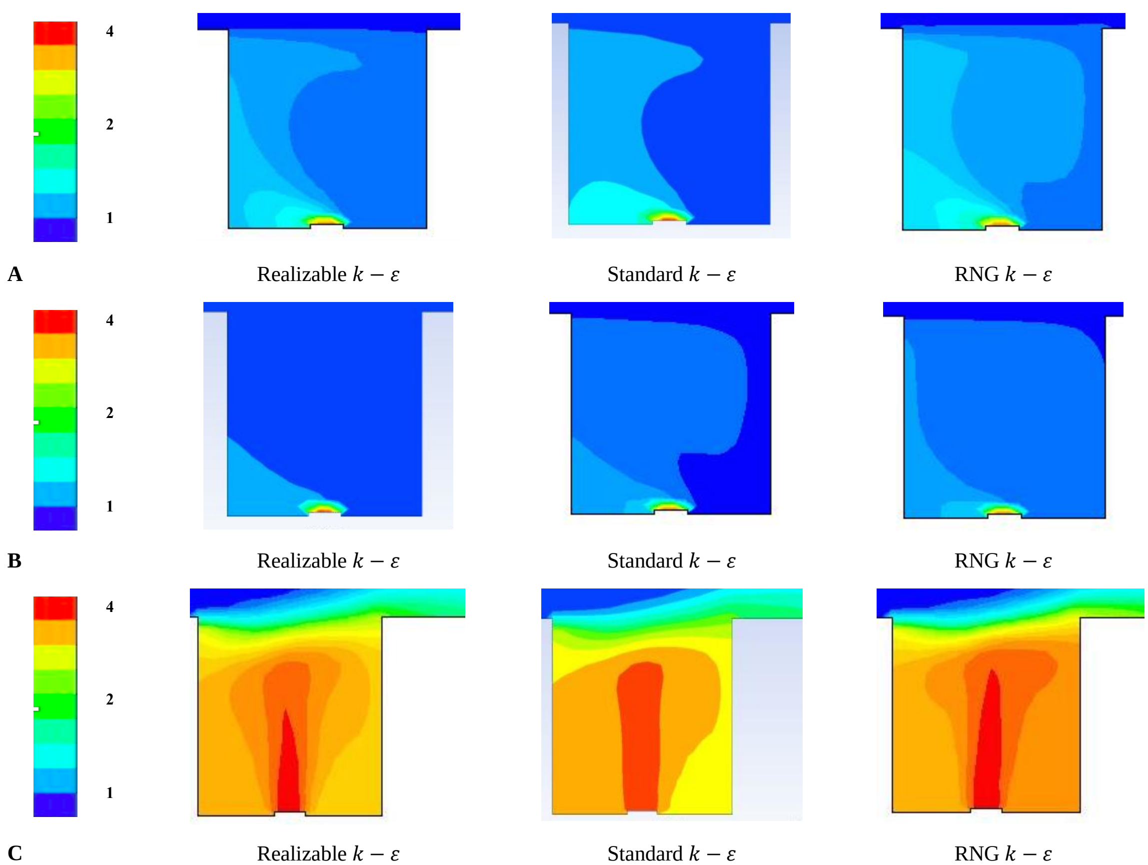

Fig. 4. Mass fraction of pollution C_2H_6 distribution within a street canyon (AR=1) under different turbulence models.
(A: Qe = 4 l/h and Uw=2 m/s; B: Qe = 4 l/h and Uw=4 m/s; C: Qe = 40 l/h and Uw=2 m/s)

The pollutant flux is weakening along the windward wall due to the ground heating and wind speed. However, the pollutant flux is strengthening along the leeward wall due to the pollutant accumulations. The results show that by increasing wind speed, more pollutants are transported from the street, and fewer are trapped inside. Here, the pollutant concentration is calculated to be dimensionless for further considerations (11):

$$P = \frac{CHL}{Q} \tag{11}$$

Whereas P is the dimensionless form of pollutant concentration; C is the volume fraction of ethane; H and L are the height of the building and the length of the line source, respectively, and Q is the volume flow rate of ethane. Figure 5 shows the dimensionless pollutant concentration (P) distributions with two different wind speeds (2 and 4 m/s) and two different ethane concentrations (4 and 40 l/h). It represents the magnitude of pollutant accumulations on leeward and windward sides of the buildings. The solid lines and dashed lines respectively represent the pollutant concentration on the leeward and windward sides of the buildings. The pair of red and purple, blue and green, gray and yellow represent the RNG, standard, realizable $k-\varepsilon$ turbulence models respectively. The results showed that the P is much more notable on the leeward side than the windward side of the buildings in a 2D canyon and is almost constant on the windward sides.

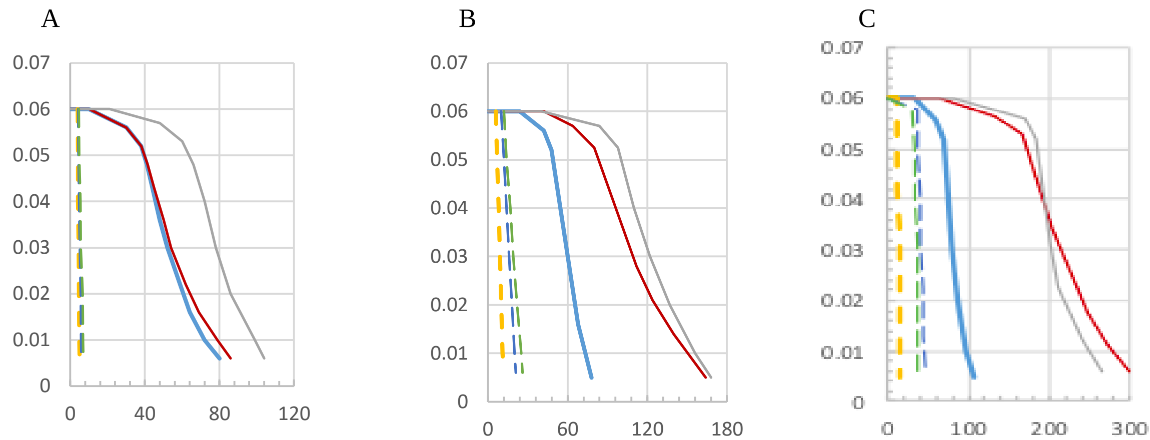

Fig. 5. Pollution Concentration on leeward and windward sides of the buildings.
(A: Qe = 4 l/h and Uw=2 m/s; B: Qe = 4 l/h and Uw=4 m/s; C: Qe = 40 l/h and Uw=2 m/s)

4. Summary and conclusions

The pollutant dispersion is simulated in a 2D numerical model that consists of two buildings in the street. The computational domain is defined to have an AR (the ratio of buildings height to street width) of 1. The numerical calculations are based on the RANS equations coupled with a series of standard, RNG and realizable $k-\varepsilon$ turbulence models using the SIMPLE algorithm in ANSYS Fluent version 16.2. The results indicate that the RNG $k-\varepsilon$ turbulence model is the most favorable one. The improvement of turbulent viscosity term of the RNG $k-\varepsilon$ turbulence model equips the researchers with a more accurate and reliable numerical solution regarding the pollution dispersion in a canyon. The simulation results also indicate that the dimensionless pollutant concentrations, P, is larger on the leeward side of the buildings and decrease exponentially from floor to top of the buildings, while on the windward side are nearly the same and constant along the height of buildings. Furthermore, the pollutant accumulations on the leeward side are more significant comparing to the windward side due to the vortex circulation of pollutant. The calculated results indicate that a rotative vortex circulation in a street with aspect ratio 1 can transport the pollutant from the line source to other nearby areas. This study is a beginning of an endless road to develop an innovative method and improve the existing ones to extend the concept of this field. Other aspects ratio of 2D street canyon need to be considered as well. The building configuration and characteristics also need to be addressed in further studies. These analyses are of the interest to urban planners and policy makers in the field of air quality. The current study is carried out in a 2D canyon and so a 3-dimesional street canyon need to be investigated for further consideration. The results are based on the ANSYS Fluent simulations and thus it is suggested to be carried out by other simulation platforms in future.

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