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INFLUENCE OF STREET CANYON GEOMETRY ON WIND FLOW PATTERNS AND FIRE PLUME DISPERSION: A NUMERICAL STUDY

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Abstract. *Computational Fluid Dynamics techniques are widely applied to predict pollutant transport within urban areas. In this study, the Large Eddy Simulation (LES) method of the Fire Dynamic Simulator (FDS) software package has been used to investigate the effects of building geometries on fire plume dispersion generated by a car fire and atmospheric pollution under wind conditions. The simulations have been carried out for four separate cases of different street canyon configurations (one case of uniform canyons and three cases of non-uniform canyons as the combinations of step-up and step-down notches), commonly found in many urban areas. The results show that the street geometry is crucial for airflow and pollutant dispersion inside and over the canyons. Due to different building heights, there is a strong interaction between the wind flow at the street rooftops and the in-canyon fire plume flow. The flow field patterns in the canyons are changed depending on the building geometries. These geometries also affect the wind inflow into canyons, and consequently, the generation, transport and dispersion of fire pollutants. The results of this study show that the air pollution level in complex structures can be effectively investigated by using the FDS LES model. Moreover, these results can be used not only to assess the air pollution level under extreme conditions such as fire accidents, but also to support urban planning and air quality control strategies aimed at reducing air pollution levels in urban areas.*

Key words: *Large eddy simulation, Street canyon geometry, Fire accident, Wind flow, Air pollution*

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1. INTRODUCTION

Outdoor air quality has attracted great attention in recent decades, due to an increase in pollutant emissions in the atmosphere and air pollution within urban areas. The large pollution levels occur within dense urban areas, especially inside the street canyons where the buildings flanking the streets act as obstacles to wind flow and reduce natural ventilation. This is one of the serious health hazards in many cities worldwide due to the fact that air pollution is associated with a broad spectrum of acute and chronic health effects. Therefore, the strategies to reduce air pollution require an understanding of both pollution sources and pollutant transport and dispersion.

During the last decades, air quality management has required the use of advanced modeling tools, able to predict and evaluate the pollution level under different conditions. Numerical air quality models simulate the spatial and temporal distributions of numerous chemically complex air pollutants [1]. The main objective of air quality modeling is to predict ambient air pollutant concentrations of one or more species in space and time, as related to independent variables such as emissions and meteorological parameters. Computational Fluid Dynamics (CFD) techniques are widely applied for the prediction of pollutant flow and dispersion in urban areas. Many numerical studies have been conducted to investigate the air pollution level using steady-state Reynolds-averaged Naviere-Stokes (RANS) equations [2, 3, 4]. Large Eddy Simulation (LES) method is nowadays applied to simulate the unsteady and intermittent fluctuations of the flow field such as pollutant dispersion inside street canyons [5, 6].

Pollutant flow field inside a canyon depends on the wind at the street top and the interaction between atmospheric flow and flow around and near buildings. Many researchers have concentrated on the simulations of airflow inside the canyons in order to investigate turbulent flow phenomena, such as separation, vortex shedding and recirculation [7]. The vortex structure determines the pollutants' flow pattern and their accumulation inside a canyon. The air pollution level inside a uniform street canyon depends on the street aspect ratio, roof height and shape, and wind inflow into the street [1, 8].

The studies mentioned above focused on the pollutant dispersion with no buoyancy or weak buoyancy effect as a consequence of vehicle exhaust gases circulating inside poorly ventilated urban structures. A few researchers have taken into account the possibility that the fire accident as a strong buoyancy source may pollute the air inside a uniform street canyon. They investigated the dispersion of fire-induced buoyancy-driven plume generated by a burning car [9, 10, 11] or by a gasoline tanker truck fire [12, 13].

However, the street canyon geometry is crucial for airflow and pollutant dispersion inside a canyon. In uniform street canyon models, the buildings are assumed to be of the same height. Nevertheless, in an actual street canyon, the surrounding buildings usually have different heights and they may be asymmetric. The flow patterns, and consequently, the spatial distribution of pollutants inside an actual canyon are different from those in a uniform canyon. Therefore, it is necessary to investigate the flow pattern and the air pollution level in case of a fire inside non-uniform street canyon models. Since the fire plume under circumstances induced by wind flow can also pollute the air inside the neighboring streets, it is of general interest to examine the plume dispersion and air pollution level within complex urban geometry.

In this study, the LES method has been used to investigate the effects of building geometries on fire plume dispersion in two street canyons. In order to examine the flow patterns and ventilation inside these street models, the approaching wind is set to be perpendicular to the street axes. The simulations have been carried out for four cases, i.e., one case of uniform street canyons and three cases of non-uniform canyons, which are the combination of step-up and step-down notches. The main aim of this study is to investigate the air pollution levels inside and over the canyons. The results would not only be useful for assessing the air pollution level under extreme conditions such as a fire accident, but also for assessing the risk to occupants' health in the building compartments with openings oriented towards the streets and on the canyon ground levels.

2. Methodology

2.1. Numerical method

This investigation was carried out using the open-source Fire Dynamics Simulator (FDS) code, developed by the National Institute of Standards and Technology [14]. The origin pollutant concentrations generated by fire have been obtained from a two-step mixture fraction combustion model. Smoke plume dispersion was simulated by Lagrangian particles. Since the LES method was used for solving the turbulence of the air and fire-induced flows, large-scale fluid motions are calculated by solving numerically the Navier-Stokes equations. Only the small eddies in the flow fields are modeled by the Sub-grid-scale turbulence model.

2.2. Model configuration

It is known that air pollution studies in urban areas can be performed very well by LES simulations. However, LES has the disadvantage of demanding significantly high computational resources [15]. To reduce computational time and resources, in this study the three-dimensional computational domain (24 m wide, 18 m long and 10 m high) represented by 1:6 full-scale was designed for LES simulations. The ground level of the domain was designed as a solid boundary, while the other exterior boundaries were designed without solid boundaries and were all set to be naturally opened in order to allow gases to flow freely in and out.

Table 1 Buildings and street dimensions

Case	H_{B1} (m)	H_{B2} (m)	H_{B3} (m)	H_{B1}/H_{B2}	H_{B2}/H_{B3}	$W_{B1}=W_{B2}=W_{B3}$ (m)	$W_{S1}=W_{S2}$ (m)	$L_{S1}=L_{S2}$ (m)
1	3 (18)	3 (18)	3 (18)	1	1	3 (18)	3 (18)	12 (72)
2	1.5 (9)	3 (18)	3 (18)	0.5	1	3 (18)	3 (18)	12 (72)
3	3 (18)	1.5 (9)	3 (18)	2	0.5	3 (18)	3 (18)	12 (72)
4	3 (18)	6 (36)	3 (18)	0.5	2	3 (18)	3 (18)	12 (72)

NB: Values represent the model dimensions (1:6). Full-scale dimensions are those in parentheses.

Since the nearby buildings may distort streamlines and modify the local flow field in a street canyon, in order to investigate the flow patterns inside and over the canyons, the three rows of buildings were designed to form two street canyons. The four different urban street canyon configurations were considered to estimate the effects of the street geometry on the airflow and fire plume dispersion. The square canyons were defined with identical building heights and street widths. Due to the fact that buildings differ in height, step-up and step-down configurations were defined with the taller or shorter downwind buildings than the upwind buildings. The street widths as well as the building widths and lengths remained unchanged in all simulations. The building dimensions and their ratios, as well as the street dimensions, are given in Table 1.

A pool fire (i.e. car fire), as a pollutant source, was set at the center of the first-street canyon. The fire source was provided by the burning of gasoline. The reaction of the "OCTANE" type, according to the data stored in the FDS reaction database, was specified for the generation of combustion products from the fire source. The evolution of a fire scenario is often represented in terms of Heat Release Rate (HRR). The HRR of burning passenger cars was 5 MW [16]. T-square fire was used for the fire growth phase [17]. In this investigation, the HRR curve was assumed to be in fast mode, and thus it reached 0.8 MW in 120 seconds and then remained constant.

The accuracy of LES simulation is largely dependent on the grid size, which should be fine enough to include the turbulence scales associated with the largest eddy motions. Since the cell size depends on the HRR and the air properties, these factors are combined to give a characteristic fire diameter $D*$, as follows [14]

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}} \tag{1}$$

where, $\dot{Q}$ - HRR, c_p - specific heat of smoke, ρ_∞ - air density, T_∞ - ambient air temperature, g - acceleration due to gravity.

The grid size is determined by the expression $D*/\delta x$ where δx is the nominal cell size. It must be no larger than $0.1D*$ to obtain viable simulation results [18]. For the HRR of fire used in the simulations, $D*$ was computed to be approximately 2.0 m, and then $0.1D*$ would be 0.2 m, which can be taken as a reasonable grid size. However, it is very important to determine the optimal grid size near the fire. Therefore, the finer grid size of 0.1 m was chosen within the first street canyon because of the fire source and the vorticities near the building walls. The total number of grid cells was 1,026,000 (30x180x100 in the first canyon and 108x90x50 in other parts of the computational domain).

The simulations were carried out for different conditions of the recirculating flow into and over the street canyons. In the first case, the impacts of building geometries and wind on the airflow patterns were taken into account, while the second one focused on their impact on the dispersion of the fire plume inside and outside the canyons, as well as at the pedestrian level. The simulations lasted for 600 s since after this period the flow field was shown to be already quasi-steady.

3. Results and Discussion

The air pollution investigations require the examination of the interaction of the air in the street canyons with the air-flow above the canyons, [19]. Due to the fact that the particularly unfavorable ventilation conditions exist in the street canyons when the wind is oriented perpendicular to the canyon axis, this study investigated the flow patterns in street canyons, both in the absence of and during a car fire within the first street canyon.

3.1. Airflow patterns

The simulation results show that the building geometries strongly affect the airflow dynamics. Namely, the approaching wind interacts with the building which disturbs the wind flow, changing its direction along the wall of the building. The impact of the first building geometries on the wind flow regimes is shown in Fig. 1.

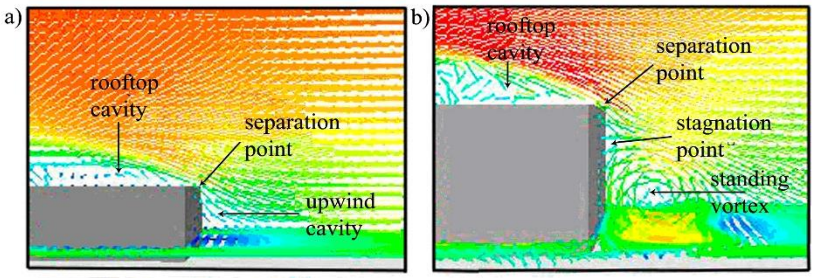

Fig. 1 Wind flow near first building: (a) step-up canyon, (b) step-down and square canyons

When the approaching wind interacts with the building's front wall, it disturbs the wind flow structure by generating different flow zones. In case of the low building, the increase of the pressure caused by the wall provokes the wind flow upwards towards the building roof level (Fig. 1a). Two prominent flow zones near the upwind building wall are identified here: the upwind cavity zone and the separation zone. In case of a tall building as a barrier to free wind flow, there are three main zones near the front wall (Fig. 1b). The interaction between the wind flow and the building wall develops a reverse flow pattern in the first zone, because the wall forces the wind to come back. As a consequence, the flow is characterized by the formation of a counterclockwise rotating vortex near the ground level. The stagnation zone with very weak velocity is located upwind of the building wall above the developed vortex. The third zone is the separation zone developed on the rooftop of the building.

The roof cavities are formed above the building rooftops in both cases. The separation angle at the upwind wall of a taller building increases and, consequently, its rooftop cavity also increases. The reason for this is the fact that the taller building's rooftop is within the region of higher wind flow velocity. Therefore, this circumstance increases flow acceleration and, thereby, the formation of a larger rooftop cavity. The roof cavities, as well as all other analyzed effects near the upwind wall of the buildings, can be attributed to the increased wind velocity in the vicinity of the building front walls, as a result of a free wind flow blockage.

The recirculating regions that are formed between the first and the second building have different characteristics that are caused by the building geometries. The airflow patterns inside different street canyon configurations are shown in Fig. 2.

In case of a step-up street canyon, a step-up notch is formed due to the fact that the upwind building is lower compared to the downwind building (Fig. 2a). A clockwise rotating vortex is formed within the step-up canyon. The vortex is approximately the same height as the upwind building and it is distorted and dislocated, with the center shifted towards the downwind building wall facing the street. It should be noted that an increased height of the downwind building strengthens the vortex within this canyon. This building also increases the strength of the downdraft flow near its wall. Consequently, the lower part of the canyon is also occupied by strong downdraft flow.

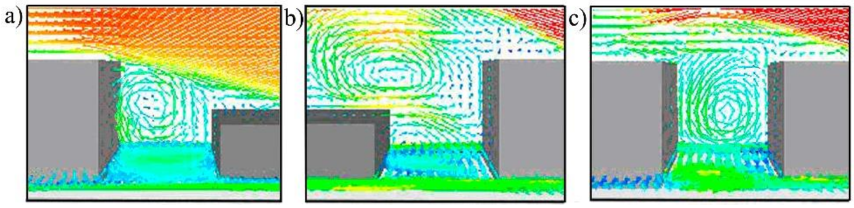

Fig. 2 Airflow pattern in: (a) step-up canyon, (b) step-down canyon, (c) square canyon

In case when the downwind building is lower than the upwind building, the flow structure in the vicinity of the buildings is modified and the step-down notch is being formed. The airflow pattern in the step-down canyon suggests the simultaneous formation of two separating co-rotating vortices with different directions: the large recirculating clockwise primary vortex and the counterclockwise rotating secondary vortex (Fig. 2b). The primary vortex extends from the rooftop of the upwind building to the downwind building rooftop covering approximately the two-thirds of its width. The vortex center is shifted above the downwind building top. The part of this vortex extends towards the canyon. The weak secondary vortex is formed in the corner cavity of the downwind building near the street ground level. Its direction is opposite to the primary vortex, i.e., there is a counterclockwise rotating vortex in the canyon part. It is obvious that the secondary vortex is much smaller than the primary vortex.

The simulation results show that in case of two buildings with heights identical to the street width (i.e. square canyon), a single large clockwise rotating vortex is formed inside the canyon (Fig. 2c). The vortex primarily extends towards the downwind side of the canyon; afterwards, it has horizontal direction near the ground level and then extends along the upwind canyon side. It stretches from the wall of one building to the wall of another building, thus covering most of the canyon.

The obtained results indicate that the building geometries significantly affect the dynamics of canyon vortices and the airflow patterns inside and over the street canyons. The airflow patterns inside the canyons are a result of the interaction between the rooftop cavity, the downdraft induced by the downwind buildings, and the flow along the upwind buildings.

3.2. Fire plume flow patterns

The fire in the street canyon causes a complex interaction between the wind flow and the buoyancy-driven fire plume. The simulation results of the flow patterns in case of the car fire at the center of the first street canyon are shown in Fig. 3.

In case of a car fire, a freely standing plume is formed inside the street canyon. The velocity of the fire plume flow is 3.5 m/s, which is the same as the wind flow velocity at the street rooftop. The plume carried by strong buoyancy flows directly upward and encounters the wind at the rooftop of the street. The turbulent mixing of smoke and fresh air induces fluctuations in the plume and the air flows inside and over the canyons. Due to the interaction of wind inertial and fire buoyancy forces, a weak clockwise rotating vortex is formed above the rooftop of the upwind building. This flow pattern differs from the airflow pattern without the fire when the roof cavity at the upwind building top is formed. Because the wind pushes the fire plume in its direction towards the downstream building, their flows become disturbed above the streets and, as a consequence, the vortices inside the street canyons are formed.

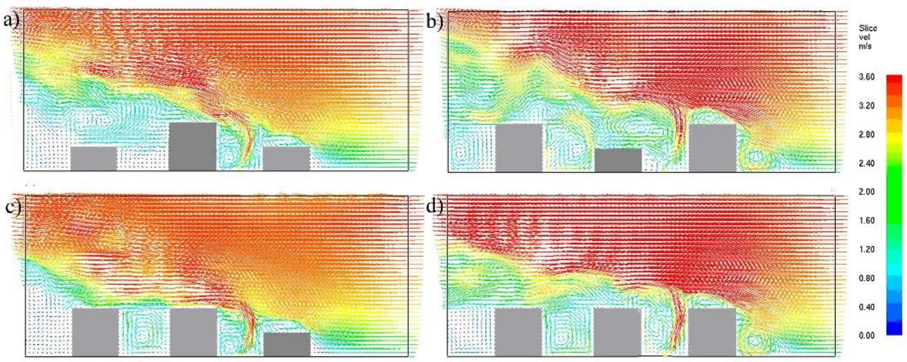

Fig. 3 Vectors of the mean vertical velocity of the fire plume under different street configurations

As it can be seen in Fig. 3, in all analyzed scenarios, the centers of the vortices formed inside the first canyon are shifted towards its downstream side because the fire plume flows near the upstream side of the canyon. In case of the square street canyon, the clockwise rotating vortex is formed in the middle of the canyon height (Fig. 3d), while in the step-up canyon case, the clockwise rotating vortex is formed in the lower part of the canyon (Figs. 3a and 3c). It should be noted that, due to the increased height of the downstream building, the fire plume gets attached to the building's front. The vortex formed in the step-up canyon is stronger than the one in the square canyon. In the step-down canyon case, the flow pattern is characterized by the pair of vortices with different directions of rotation (Fig. 3b). The large clockwise rotating vortex is located near the downstream building rooftop, while the small counterclockwise rotating vortex is formed in the corner cavity of the downstream building near the street ground level.

The simulation results indicate that there is a strong interaction between the wind flow at the first upwind building rooftop and the in-canyon fire plume flow. Namely, the buoyancy force forces the upward-moving fire plume to leave the street top. On the other hand, the wind inertial force opposes the buoyancy force and tends to push the plume to touch the walls of the downstream building, forcing it to return back into the canyon.

The results of the flow patterns in the second street canyons show that, between the twin buildings, the vortex center is shifted towards the downstream building wall facing the street (Figs. 3c and 3d). The flow direction is from the downstream to the upstream building, i.e. the vortex is clockwise inside this recirculating zone. In the second step-up canyon case, the clockwise rotating vortex is formed with the center shifted towards its upstream side (Fig. 3b). The vortex location is influenced by the higher downstream building. Due to the lower upstream building, there is a large recirculating zone between the two street canyons. Finally, in the second step-down canyon case, the main higher vortex is shifted upwards above the rooftop of the third building. The weaker lower vortex inside the second canyon has a flow direction opposite to the main vortex (Fig. 3a).

It is obvious that the flow field patterns in the canyons are changed depending on the building geometries. The appearance of the clockwise or counterclockwise rotating vortices in the street canyons depends on the flow characteristics.

3.3. Fire plume dispersion

The formed vortices restrict the airflow and cause the fire plume dispersion. The fire plume dispersion under analyzed circumstances is shown in Fig. 4.

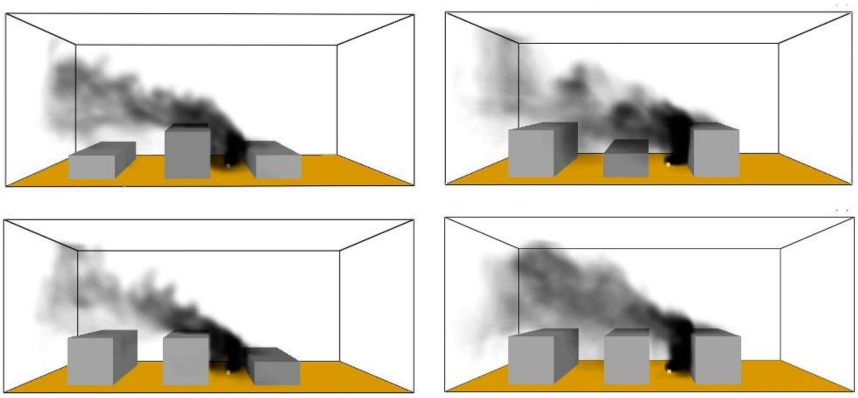

Fig. 4 Fire plume dispersion inside and over street canyons

Fig. 4 allows a quantitative analysis of the fire plume behavior above the fire source, around the buildings and inside and outside the street canyons. In all scenarios, due to the formed vortices in the first canyon, the fire plume flows upward along the wall of the upstream building inside the canyon. When the plume encounters the wind at the rooftop, it bends in the wind direction.

Depending on the geometry of the downstream building, the fire plume goes over its rooftop or re-enters along its wall facing the canyon, thus reaching the street ground level. In the square canyon case, the part of the plume re-enters the canyon while its greater part goes over the downstream building top. In case of the step-up canyon, because of the higher downstream building, the greatest part of the plume comes back into the street and reaches the street surface. Contrary to this, in the step-down canyon case, due to the lower downstream building, the greatest part of the plume goes over its top.

The geometries of the second street canyon also influence the plume dispersion regime. In the case of the second square canyon, the small part of the plume enters the canyon while its greater part flows over the canyon top. On the other hand, the greater part of the plume enters the second step-up canyon. The reason for this is the higher downstream building which serves as a blockage for the fire plume flow. Finally, due to the lower downstream building in the second step-down canyon, the plume flows over the canyon top.

4. CONCLUSIONS

The FDS LES method was employed to study the effects of street canyon geometry on the dispersion and accumulation of fire pollutants in and above the street canyon. Numerical simulations have been carried out for different street canyons and surrounding building configurations. The main conclusions can be summarized as follows:

- The building geometries significantly influence the airflow patterns around the buildings, as well as inside and over the street canyons. Depending on the height of the buildings, which act as a blockage for free wind flow, different vortices are formed. Clockwise rotating vortices are formed inside the square and step-up canyons, as well as in the higher parts of the step-down canyons. Counterclockwise vortices are formed in the downwind building corners of the step-down canyons.
- Due to different building heights, there is a strong interaction between the wind flow and the in-canyon fire plume flow. The flow field patterns in the canyons are changed depending on the building geometries. The formed vortices restrict the air inflow and cause the fire plume dispersion inside and over the canyons.
- The street geometries affect the wind inflow into the canyons, and consequently, the generation, transport and dispersion of the fire pollutants.

This study shows that the air pollution level in complex urban areas can be effectively modelled by implementing the FDS LES model. The obtained results are appealing to both air quality management in the design of effective control strategies to reduce the emissions of harmful air pollutants, and urban planning strategies aimed at reducing the air pollution within urban areas.

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