Outdoor Commercial buildings: A CFD study of the impact of streets layout on airflow.

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ORIGINAL STUDY

Outdoor Commercial Buildings: A CFD Study of the Impact of Streets Layout on Airflow

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Abstract

The impact of the general layout of commercial streets and their orientation relative to prevailing wind direction on urban comfort due to natural ventilation is unknown. To study the natural airflow pattern in the commercial street mall, this research investigates the impact of different building layouts on airflow characteristics. To do this we conduct a parametric CFD simulation for 12 simulation cases, in which the commercial street layout changes to include secondary streets in four different cases. All cases are also subjected to three different wind directions. The study highlights that different wind orientations can significantly impact pedestrian comfort in shopping centres. Also, the presence of side streets can cause severe discomfort in cold climates while they could be utilized for comfort in temperate climates. The study is important for the purpose of architectural design where architects need to understand the implications of the different design layouts and wind angles on pedestrian comfort in commercial streets.

Keywords: CFD simulation, Natural ventilation, Open-air commercial streets, Thermal comfort, Urban design

1. Introduction

Urban open spaces play a critical role in the cities' structure, they bring vibrancy, and livability to the city, and enhance the quality of life for their inhabitants (Ng et al., 2011; Nikolopoulou, 2010). Also outdoor activities provide a chance for people to integrate with the natural environment which promotes people's health. Recent studies showed that open-air commercial streets are emerging as a preferable solution for commercial activities especially in moderate climate (Coleman, 2007; Rao, 2019; Li and Zhao, 2013; Zhu et al., 2020; Yuan and Xiao, 2014). Nonetheless even in moderate climate regions, designers of open commercial streets face the challenge of providing a reasonable microclimate for the users especially in the summer. According to (Nikolopoulou, 2010; Coleman, 2007), thermally comfortable outdoor spaces attract more users and encourage them to spend more time using them. According to ASHREA (ASHRAE, 2001) there are six factors that influence human outdoor thermal comfort; environmental factors (i.e., air temperature, air velocity, radiant temperature and relative humidity), and personal factors (i.e., metabolic rate and clothing insulation). Airflow is an important factor which not only affects the pedestrian thermal comfort but also has a great influence on human health and the energy efficiency of buildings (Ahmed, 2003; Al-Sallal and Al-Rais, 2012; Anselm Akubue, 2019; Niachou et al., 2008; Yousefian et al., 2021). Recent studies indicate many benefits to fast air movement in, which users have no control over. Such benefits include the cooling effect of the fast air movement, and the extension of thermal comfort range. Also studies have shown that fast air movement has led to an increase in the number of people expressing thermal satisfied (when ambient temperature is below 34 °C) (Ahmed, 2003; Al-Sallal and Al-Rais, 2012).

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The wind behavior in the urban canyon is affected by its physical structure (Yousefian et al., 2021). The canyon aspect ratio, its orientation, and profile are the main physical structures of the shopping canyon that influence the air movement in it (Li and Zhao, 2013; Yuan and Xiao, 2014; Chatzidimitriou and Yannas, 2017; Cui et al., 2021; Oke et al., 2017; Mills, 2008). The pattern of the airflow takes place inside the urban canyon is determined based on its aspect ratio, where two regions are formed; the recirculation region and the ventilated region. Airflow patterns can be classified into isolated flow (H/W < 1/3), skimming flow (H/W > 2/3), and finally, wake interface flow for the intermediate ratio (Anselm Akubue, 2019; Oke et al., 2017). Fig. 1.

Canyons H/W ratio has a significant impact on the permeability of the airflow inside (Shishegar, 2013; Ali-Toudert and Mayer, 2006).

A study in fez morocco, examined the wind speed of two urban canyon with an aspect ratio 9.7 and 0.6, it showed that the wind speed is slower in the deep canyon in both summer and winter (Johansson, 2006). Another study found that the wind velocity is much slower in narrow streets whose aspect ratio 2.8 compared to the wider street of aspect ratio 1.75 (Al-Sallal and Al-Rais, 2012).

Architects and city planner should choose the orientation of the shopping corridor in a way that maximize the summer ventilation.

Another equally important factor of the canyon design is the orientation (Yuan and Xiao, 2014). When the wind is parallel to the canyon axis, the flow streams and no vortices are formed; the canyon architecture cannot block the wind, and in case of a high aspect ratio the airflow velocity increases as a result of the canyon effect (Li and Zhao, 2013; Chatzidimitriou and Yannas, 2017; Cui et al., 2021). On the contrary, when the wind is perpendicular to the canyon axis, recirculation vortices are formed at the cavity of the windward building, and the canyon aspect ratio determines the number of the formed vortices. When the flow is inclined to the canyon axis, the result is a helical flow, which is the vector sum of the transverse and longitudinal flow components (Oke et al., 2017; Erell, 2012). Another factor that plays an important role in shaping the canyon wind environment is the canyon profile. Shopping canyon buildings may have symmetric or asymmetric heights; they may also have some physical features, such as arcades, balconies or canopies. The simplest shape of the shopping canyon profile is where the shop unit is single or multi-story, and the vertical circulation takes place in it (Coleman, 2007). A study carried out to investigate the wind behavior in urban canyons with symmetric and asymmetric profile showed that canyons with height symmetrically buildings have relatively higher wind speed that canyon with asymmetric buildings height when the wind blows normal to the canyon axis (Cui et al., 2021). The excessive height difference between buildings on both sides of the canyon should be avoided to prevent wind blockage or wind chill (Li and Zhao, 2013). Another factors that influence the airflow in the urban canyon in general are the buildings topology, terrain roughness, and buildings density (Ng et al., 2011; Oke et al., 2017; Erell, 2012; Oke, 2002).

It is then important to study the impact of the presence of side malls intersecting with the main commercial street under different orientation (wind angles) scenarios. This is expected to provide an understanding of the impact of the plan layout of the building on natural airflow inside the malls, thus providing a tool for targeting pedestrian comfort in different climates.

To achieve this, we conduct a set of parametric studies using computational fluid dynamics software (CFD) to study the behavior of airflow and air speed inside the outdoor commercial streets under a few wind angles.

Section two discusses the methodology used in this research, section three highlights the details of the computational study, section three presents the results of the different parametric scenarios, and section four discusses the finding of the research. Finally, section five is the conclusion and future research.

1.1. Research aim

The main aim of this study is to improve the thermal comfort of the outdoor shopping environments by enhancing their wind environment.

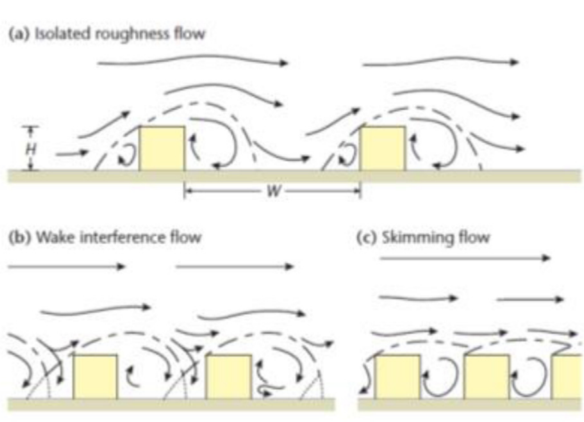


Fig. 1. Airflow patterns over buildings arrays of different H/W Source: (Oke et al., 2017)

1.2. Research objectives

(1) Study the design factors affects the airflow movement in the outdoor shopping environments.
(2) Show the wind behavior in different scenarios of linear shopping corridors.
(3) Investigate the effect of the corridor orientation on the wind behavior.

1.3. Research significance

Keeping the outdoor shopping environments vibrant and livable, mainly on hot summer days by using the passive cooling potentials, and enhance the thermal comfort of their users by improving their natural ventilation.

2. Methodology

This research is a parametric study into the impact of the design layout of open urban commercial streets on the airflow speed between buildings. To do this we use Computational fluid dynamics (CFD) to test twelve design cases and evaluate their results. The study begins with a brief investigation into current design practices of open-air commercial streets. Six different design proposals are analyzed to identify the general sizing and design criteria that guide outdoor commercial streets' urban layout.

2.1. Current design practices of open-air shopping malls

While commercial malls can be either indoor or outdoor facilities, we chose all chosen examples are popular outdoor commercial centers found in mild climatic regions with moderate precipitation across the year. This choice facilitates the possibility of outdoor use, thus brings about the importance of thermal comfort between buildings. Table 1 shows the plan layout and a schematic plan for six popular outdoor shopping malls from different parts of the world. Examples have shown that in all cases, outdoor shopping centers have had a main linear mall with a few secondary malls. Based on this we conduct a CFD study to investigate what effect a main mall with secondary perpendicular malls can have on airflow patterns.

2.2. CFD simulations

Based on previously discussed examples, we conduct a full-scale CFD investigation into the role of the open-air shopping mall design layout and orientation into pedestrian comfort requirements.

The CFD study is a systematic investigation where four different design layouts are studied under three different wind angles. Fig. 2 For each design case, the building layout, including street organization, width-to-height (W/H) ratio, and street length, as well as wind speed, remain constant while wind direction is varied between 0° (parallel to mall main corridor) and 45°. Table 2 shows all scenarios of the simulation cases.

The aim is to identify the effect of the different layouts and wind angles on comfort in the malls. For this, the normalized U/U_{ref} indicator is used to measure the efficiency of natural ventilation in the mall. U is the air speed along the centerline of all design cases at height $H = 1.5$ m, while U_{ref} is the reference wind speed at the building height (2 m/s).

All four shopping mall scenarios have identical dimensions and proportions. The main corridor is 300 m long, and 20 m wide, and they all have a H/W ratio of 0.5, rendering building heights on both sides of the corridor to be 10 m tall. The variety between the different cases is in the presence and design of the transversal streets. Case A has no side streets, while Case B has one side street, splitting the side building block into two equally sized blocks. Case C has a T-shaped layout in which the two side buildings are split into two equally sized blocks. Case D has a staggered layout where two side streets on the sides of the main shopping corridor split both buildings into two blocks of different sizes.

3. CFD study

3.1. Computational domain

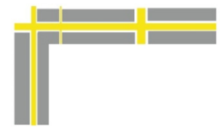
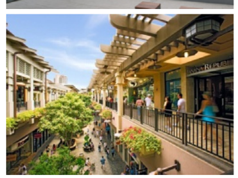
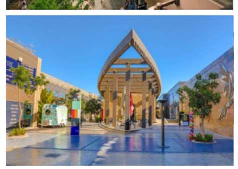
The computational domain for all simulation scenarios was designed to recommend best practice guides (Tominaga et al., 2008; Franke et al., 2004; Baetke et al., 1990).

The designed distance between the domain's inlet and the windward facade of the simulated cases is 7H, while the minimum lateral distance between the sides of the model and the edge of the domain is 7H as well. The leeward distance between the end of the model and the domain edge is 20H.

Also, the domain height was 5H above the top of the models. These settings rendered a domain of width, length, and height of 240 × 570 × 160 m. Fig. 3.

For the oblique wind simulation cases, the domain dimensions had to be readjusted, in which the domain is tilted to match the wind angle while maintaining the minimum required distances. For

Table 1. Examples of the open-air mall.

Mall	Image	Architectural Plan	Layout sketch	Dimensions
Third promenade street - Santa Monica, USA.				Main Canyon Length = 625 m Canyon width = 22 m Buildings height = 5 m–14 m
lijnbaan street - Rotterdam, Netherlands.				Fist Canyon Length = 310 m Second Canyon Length = 127 m Width of canyons = 18 m and 12 m, respectively Building height = 8.2 m
The Grove Mall - California, USA.				Main Canyon = 400 m Canyon width = 18.2 m and 44 m. Buildings height from 10 to 15 m
Asmacati Shopping Center - Izmir, Turkey.				Main Canyon Length = 155 m Width = 35 m–22 m Buildings height = 8.2 m–11.4 m
The Ala Moana Shopping Center - Honulolo, USA.				Main Canyon length = 530 m Canyon width = 14 m Buildings height approximately 12 m
The Walk Of Cairo - Cairo, Egypt.				Main Canyon length = 790 m Canyon width = 16–24 m Buildings height approximately 10–12 m

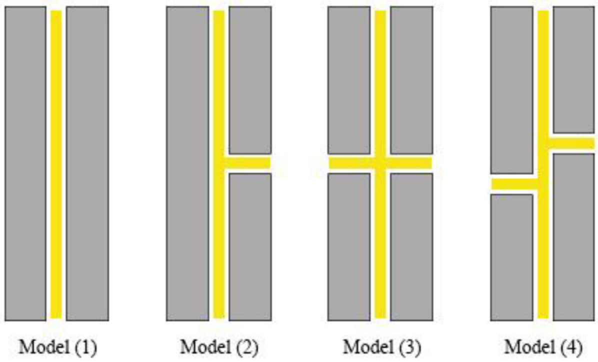


Fig. 2. Layout of all four simulation cases.

the oblique wind angles 22.5° and 45°, the size of the domain is 680 × 550 × 60 and 700 × 700 × 60, respectively.

3.2. Grid design

All simulated cases were meshed using the software GMSH to provide a structured grid (Geuzaine and Remacle, 2009). GMSH facilitated full control over the design of the grid, where we followed a technique described in reference (van Hooff and Blocken, 2010). The technique allows refinement of the grid to capture important flow characteristics near the wall regions and extend to coarse mesh in the perimeter of the domain. Fig. 4.

The near wall mesh has a fine grid cell of dimension 0.1 m, which then extends at a rate of no more than 1.2. Fig. 5 Table 3 shows the total grid cells for each simulated scenario.

3.3. Boundary conditions and solver settings

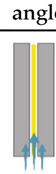
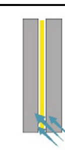
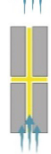
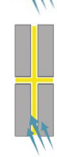
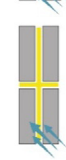
For the same domain design discussed, an inlet, outlet and symmetry boundary conditions were assigned to the windward side, leeward side, and sides and top planes of the domain, respectively (Tominaga et al., 2008; Franke et al., 2004; Reiter, 2008).

All simulations were isothermal using the Reynolds-Average-Navier-Stokes (RANS) model run using the open-source software OpenFoam. (Overview)

RANS turbulence models are some of the most popular in research due to their reasonable computing demands and reliable results (Yousefian et al., 2021; Tabatabaian, 2015; Yusof et al., 2020; Shirzadi et al., 2020).

For this study, we used the sheer stress (SST) turbulence model K- ω. K-ω (SST) is a hybrid model that can switch between the computations of turbulence near-wall (K-ω) and reasonably predicts the flow regime away from the walls (K-ϵ). It is validated extensively in research due to its known compromise between computing resources and reasonably

Table 2. Case studies.

Shopping canyon configuration	Prevailing wind angle = 0°	Prevailing wind angle = 22.5°	Prevailing wind angle = 45°
Model (1)			
Model (2)			
Model (3)			
Model (4)			
Canyon width	20 m		
Canyon Height	10 m		

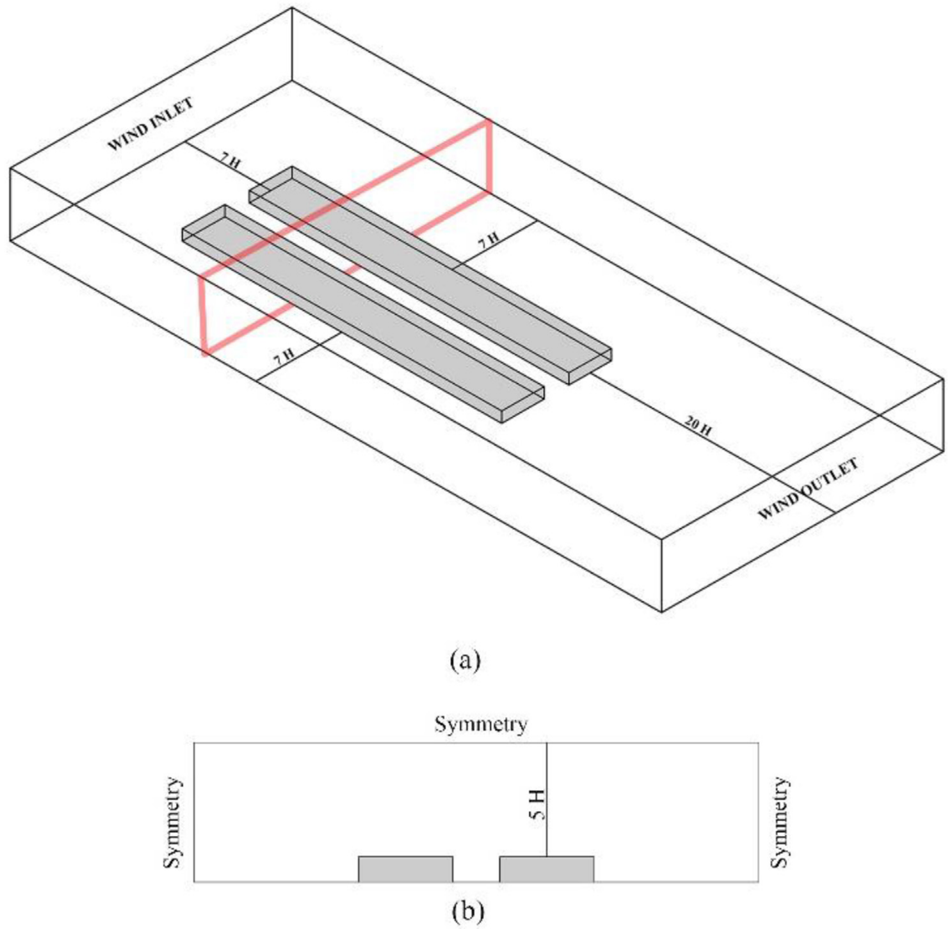


Fig. 3. Top: 3D showing the design of the domain in reference to the model dimensions. Bottom: cross section showing domain height and boundary conditions.

accurate results (Tabatabaian, 2015; Menter, 1994; Lacombe et al., 2019).

4. Results

To assess the ventilation efficiency in all simulation cases, we use the U/U_{ref} value in which the air speed (U) at pedestrian height (1.5 m) is compared to the free stream wind speed ($U_{ref} = 2$ m/s). This indicator highlights the changes in air speed along the mall in response to the mall layout and wind direction. Figs. 6–8 show the velocity contours at plan level height = 1.5 m, along with a set of charts that plot the U/U_{ref} at the same height.

4.1. Wind direction parallel to the main mall

All cases show an increase in air velocity immediately after the inlet of the mall. This is due to the separation taking place at the corners of the windward face of the mall buildings. In Case A, the peak zone records U/U_{ref} of 1.08, which then eases down and stabilizes to an average of 0.8. Cases B, C and D maintain the peak U/U_{ref} zone, yet the rest of the mall shows different behaviour. Case B has a peak U/U_{ref} of 1.55, then the average U/U_{ref} is 0.8. Maintaining a similar behaviour, Air speed, however, shows a sudden increase reaching the value $U/U_{ref} = 1.17$ coinciding with the location of the side street followed by a U/U_{ref} drop to 0.07 which gradually rises to an average of 0.8 again until the end of the mall.

Cases C and D have peak and average U/U_{ref} values of 1.3 and 1.38, and 0.731677 and 0.799781, respectively. Both cases show the sudden rise and fall in speed that coincide with the side streets.

Cases B and D have higher average U/U_{ref} in the side street compared to the main mall. This is attributed to turbulent flow in the narrow side streets. Cases B and D have respective U/U_{ref} values of 1.05 and 0.97, while Case C has an average U/U_{ref} of 0.66 Fig. 6.

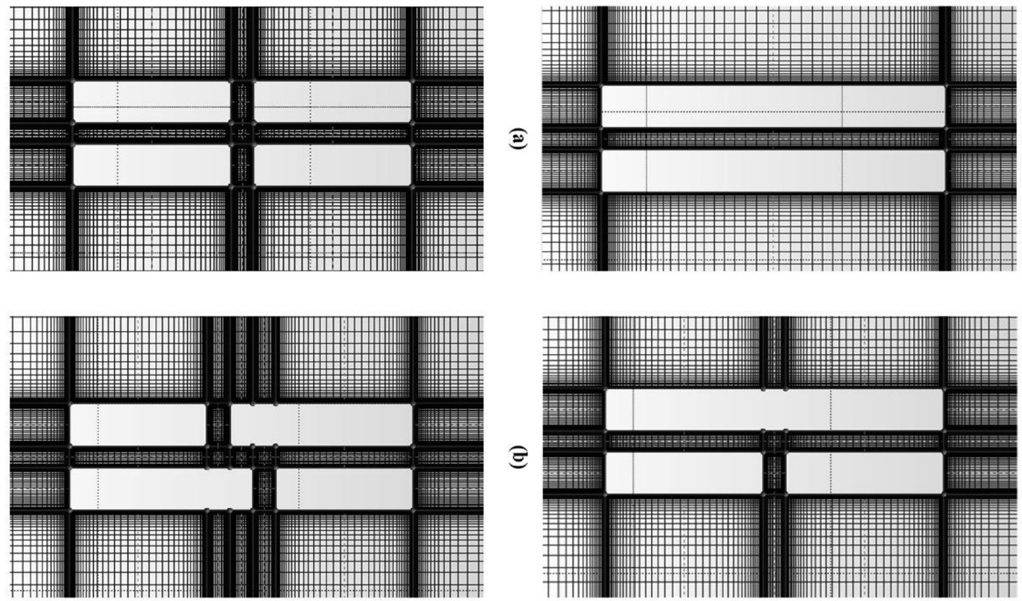


Fig. 4. A plan layout showing the grid design for the parallel to main mall wind on (a) Case A, (b) Case B, (c) Case C, and (d) Case D.

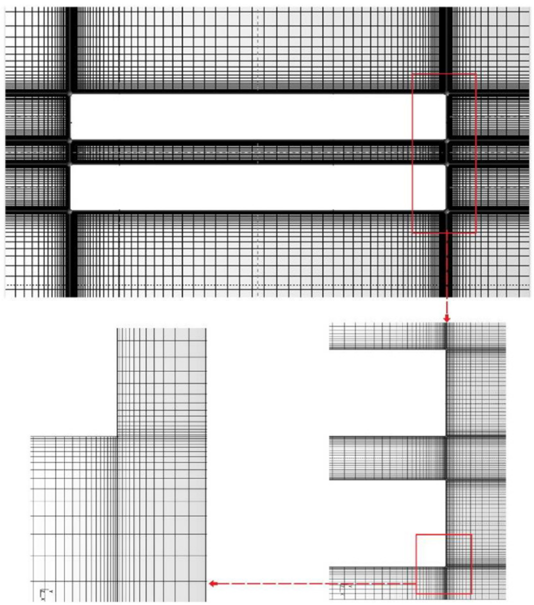


Fig. 5. Zoom in showing the very fine near-wall cells.

Table 3. Number of grid cells in each simulation case for all scenarios.

Wind Angle	Case A	Case B	Case C	Case D
the wind is inclined to the canyon axis by 0°	805,188	1,146,796	1,204,340	1,726,848
wind is inclined to the canyon axis by 22.5°	1,148,590	1,552,581	1,584,501	1,956,831
wind is inclined to the canyon axis by 45°	1,126,272	1,610,812	1,715,832	2,040,676

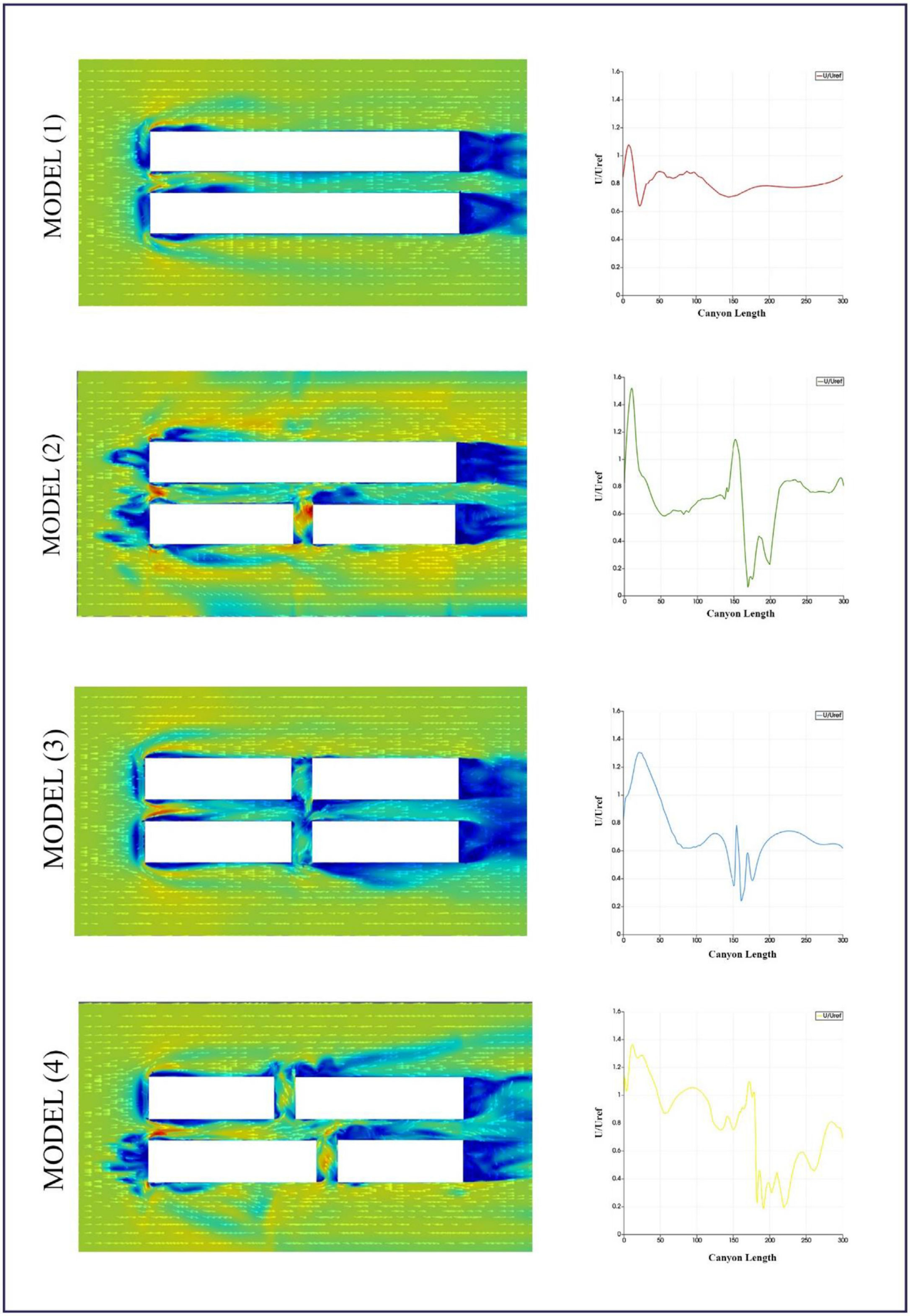


Fig. 6. Simulation results when the wind direction parallel to the main mall.

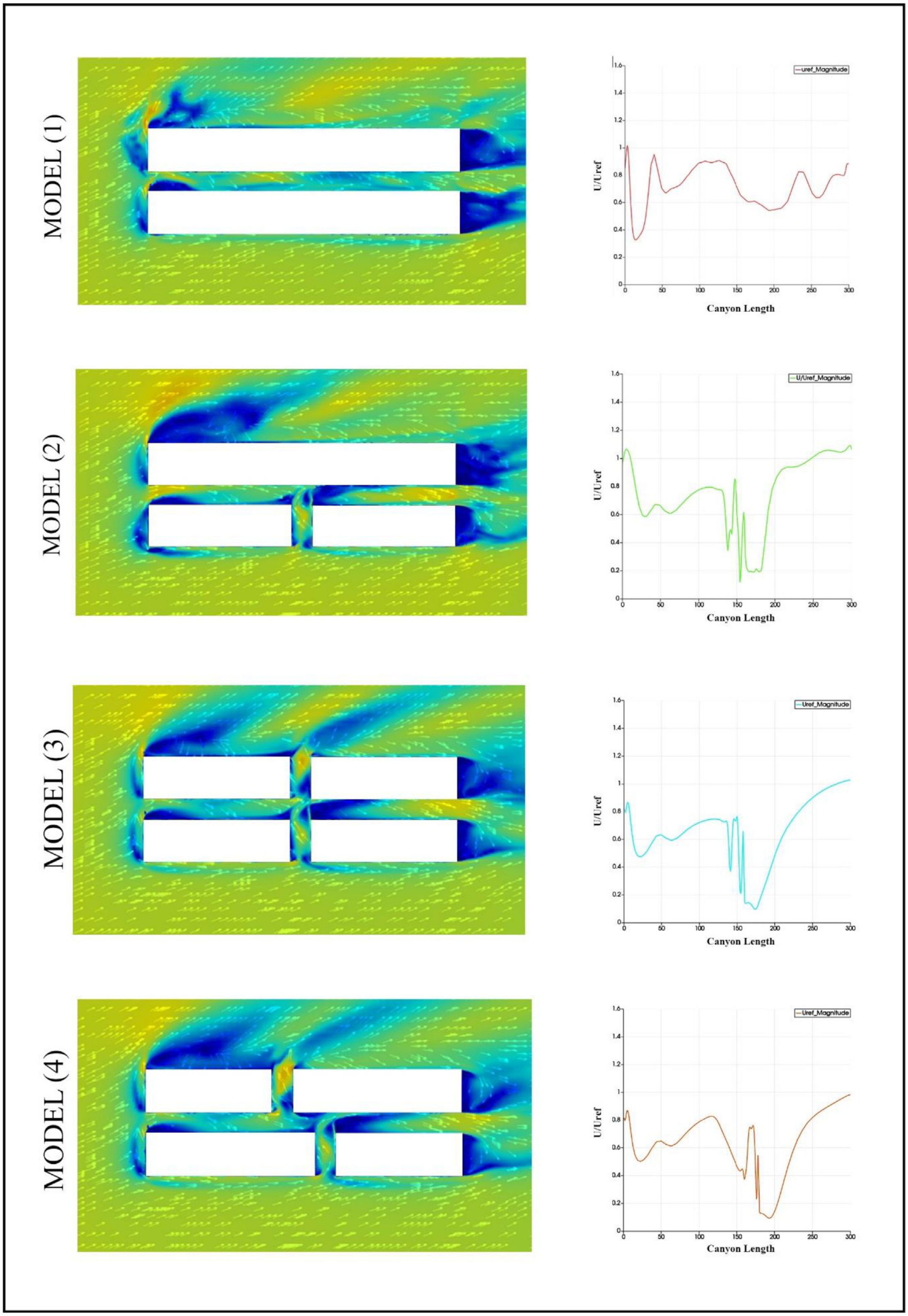


Fig. 7. Simulation results at prevailing wind angle = 22.5°.

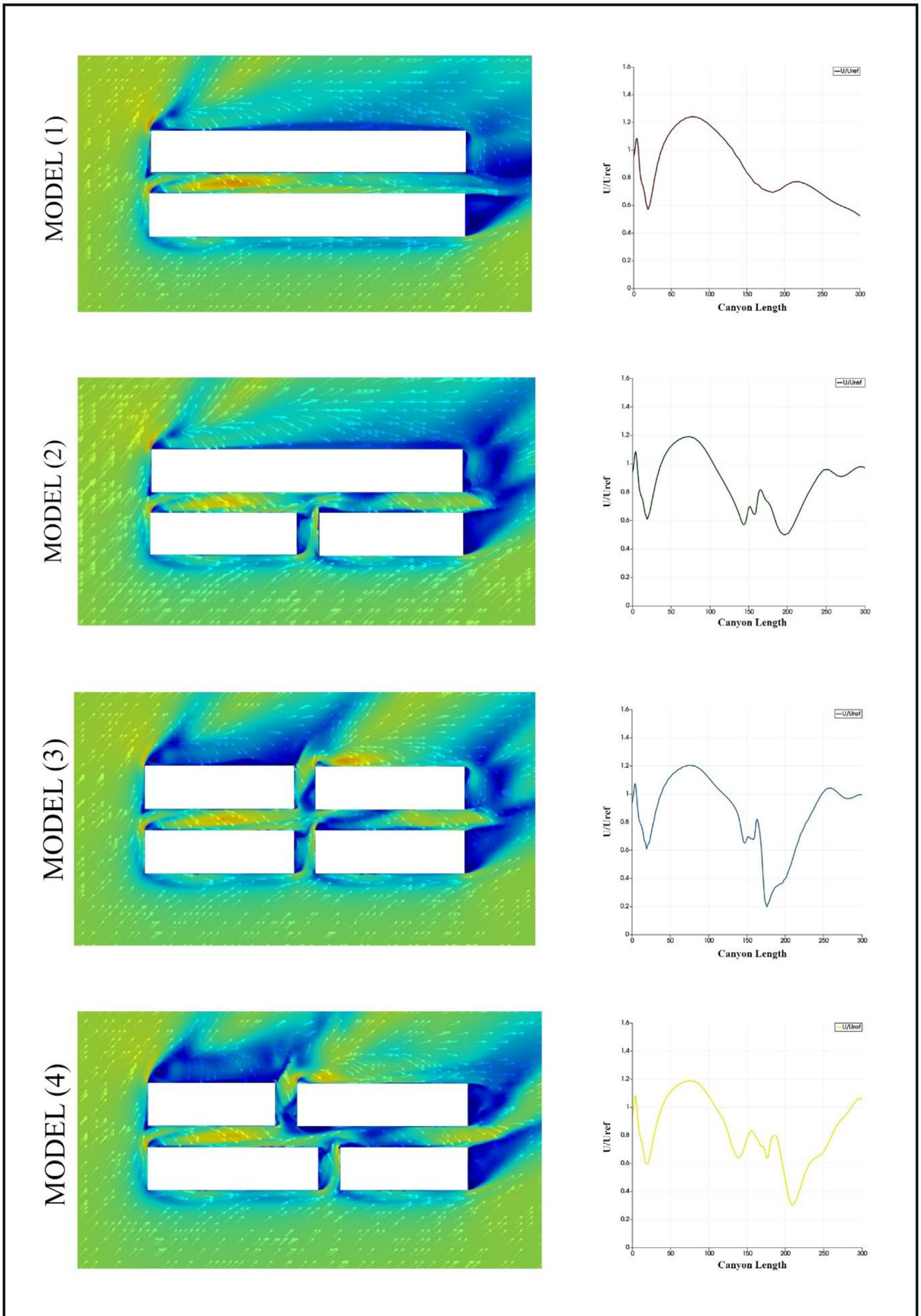


Fig. 8. Simulation results when wind direction 45° to the main mal.

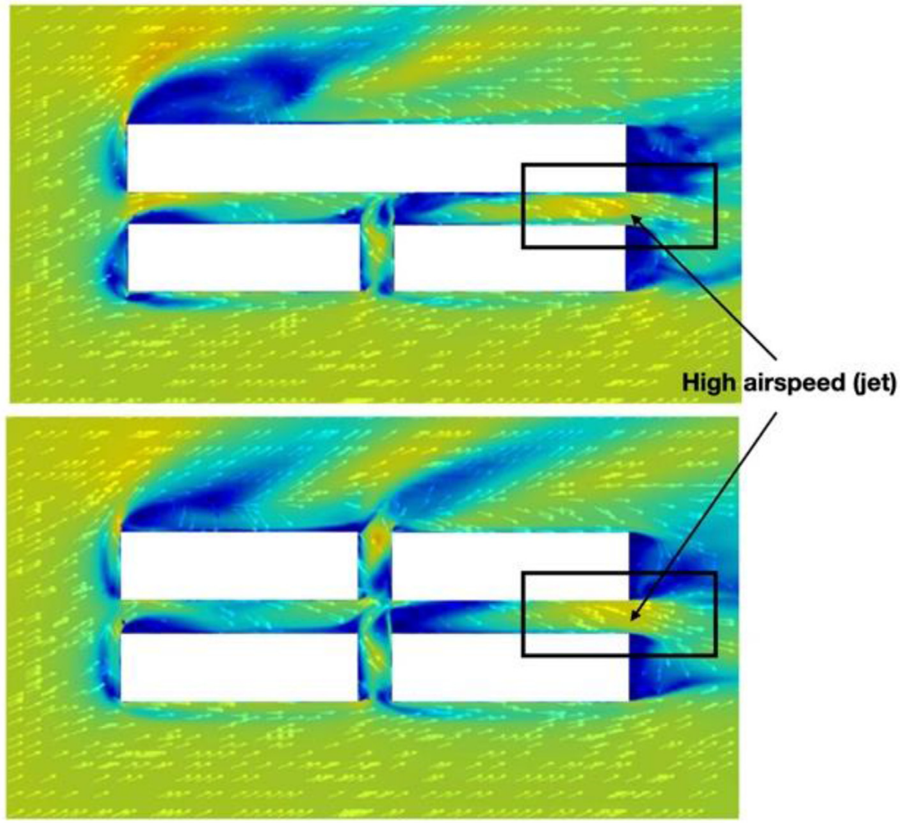


Fig. 9. Velocity contours at plan level show a jet effect at the leeward side of the main shopping mall (sample for the cases B and C).

4.2. Wind direction 22.5° to the main mall

The introduction of the side streets in Cases B, C and D has a major impact on the air speed inside the main mall. The inclined wind angle means that the side streets are also an entry to the airflow into the main mall from the outside. This has an impact on the air behavior at the intersection between the secondary and main malls. In all three cases with the secondary mall, the flow from the secondary mall separates at the intersection with the main mall and creates a suction zone at the corner of the secondary mall and until about the point 200 m downwind of the main mall. The flow speed then rises to form a jet at the leeward exit of the main mall. The U/U_{ref} value at the leeward exit of the mall for Cases B, C and D are 1.1, 1.06, and 0.98, respectively. Figs. 7 and 9.

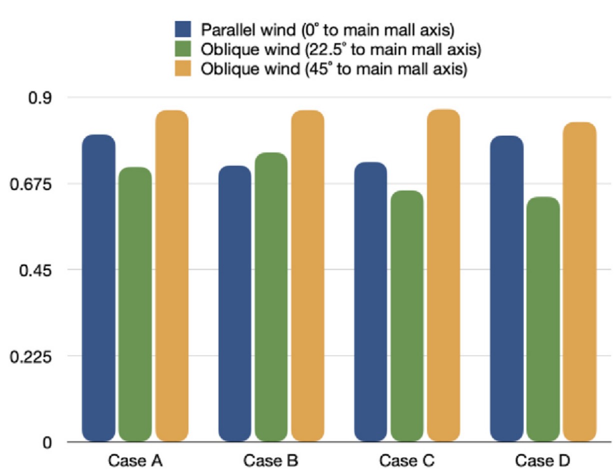


Fig. 10. Chart showing the average U/U_{ref} for all four scenarios under the different wind angles.

4.3. Wind direction 45° to the main mall

The U/U_{ref} pattern in the 45° scenario is lightly different than previous cases. Primarily, the wind angle is eliminating the jet effect at the inlet of the main mall. Instead, the wind is separating from the inner windward corner of the building, causing a drop in velocity (suction) followed by a rise in the speed along the main mall that peaks between the distance 50 and 100 m downwind the main mall. After the 100 m point the U/U_{ref} is different in Case A compared to cases B, C and D. in Case A, the hike in the air speed at the 100 m point is followed by a gradual drop in the U/U_{ref} until the leeward edge of the mall.

For Cases B, C and D the central side street is causing another suction region at the separation corner of side street, however, U/U_{ref} then quickly rises causing an exit jet at the leeward side of the main mall.

The average U/U_{ref} for Cases A, B, and C is 0.86, while Case D has an average U/U_{ref} value of 0.835. Fig. 8.

5. Discussion

Generally, the oblique wind has the highest average U/U_{ref} among all other scenarios. Followed by the parallel-to-wind layouts, while the least average U/U_{ref} of all scenarios was the 22.5° wind angle scenario Fig. 10.

The simulation results indicate that the high velocity at the inlet of the main mall gradually drops after about 50 m to reach the average speed along the mall. It is noted that the highest peak velocity at the inlet is for the parallel to wind followed by the 45° wind angle scenario then the lowest U/U_{ref} was for the 22.5° wind angle. Fig. 11.

For the oblique wind scenarios (22.5° and 45° angle wind), side streets are creating a secondary air inlet into the main mall which leads to high air speed immediately at the intersection between the main mall and the secondary street followed by a steep suction zone extending until the leeward end of the main mall.

Similarly, the area along the main mall that coincides with the side streets in all wind angle scenarios has a sharp rise in air speed. The side streets act as a secondary air inlet causing an air jet at the intersection followed by a turbulent zone (suction area) due to separation at the corner of the side street.

For the oblique wind scenario of 22.5° alone, the presence of an air inlet through the secondary streets has led to a monitored increase in the air speed (forming a jet effect) at the exit of the main mall. The $(U/U_{ref\text{-}exit})/(U/U_{ref\text{-}inlet})$ for this scenario's Cases A, B, C and D are 0.846, 1.04, 1.30, and 1.166, respectively. This indicates that the introduction of the side malls under this wind scenario caused a jet effect at the leeward exit that surpasses the inlet jet at the windward side of the main mall. Fig. 9.

This highlights the importance of the intersection between the main and secondary malls in outdoor commercial street design. Such intersections (under all scenarios) must be treated differently according to the climatic regions.

Temperate climates may dictate a short main mall to utilize the fast flow at the inlet for comfort. Alternatively, multiple side streets intersection can achieve a similar outcome. On the other hand in the

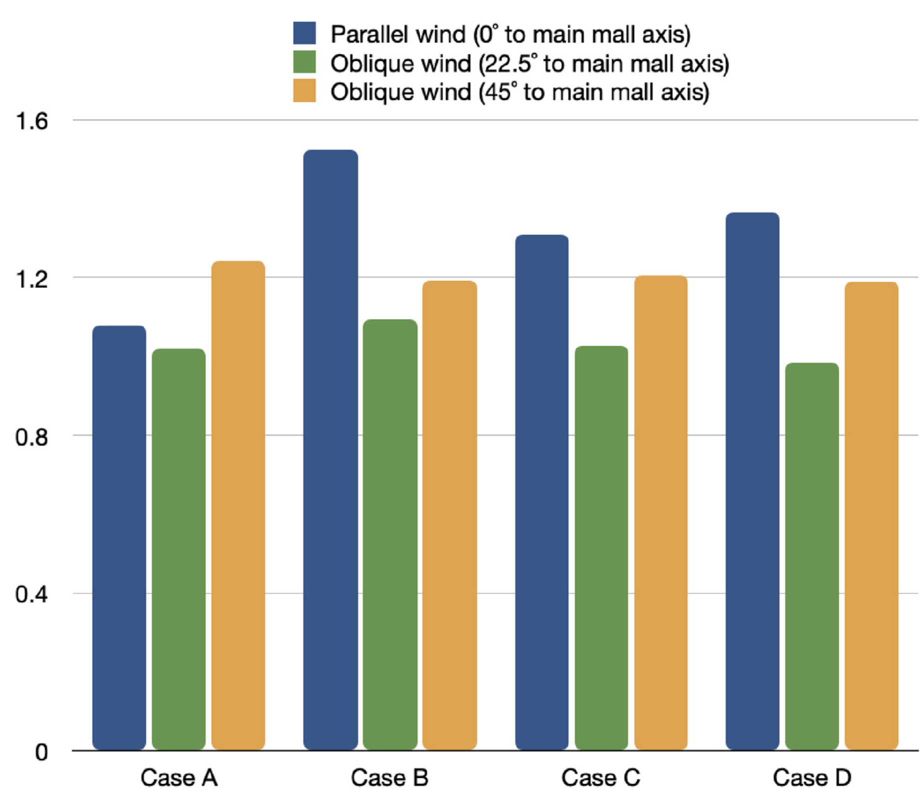


Fig. 11. Chart showing the U/U_{ref} values at the inlet for all four scenarios under the different wind angles.

cold regions, the different jet zones and regions of turbulent flow should be treated with care to avoid extremely uncomfortable gusty conditions, while visitors enter or exit the mall. Fig. 12.

Fig. 12 shows the impact of the different layout Cases B, C and D on the flow characteristics. It is noticed that the limited distance between the two opposite side streets either in the staggered or the straight layout causes the flow separation and thus the suction zone and the jet flow.

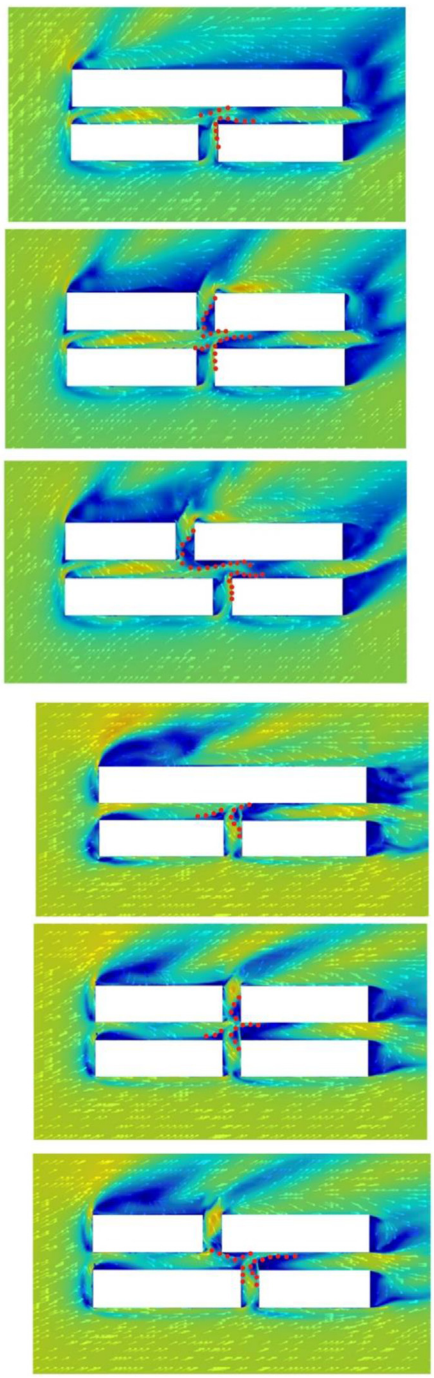


Fig. 12. Fast airflow and separation at intersections highlighted with red dots.

6. Conclusion and future research

This research is a parametric CFD study into the impact of the organizational layout of outdoor commercial streets on airflow characteristics and speed of wind for pedestrian comfort. Twelve CFD simulations were conducted in which four design alternatives were studied under different wind angles. The design variations included only the introduction of side streets intersecting with the main commercial mall through a number of layouts including T-shaped and X-shaped layouts. Results indicate that the intersections play a critical role in the airflow characteristics inside the main mall as they cause fluctuation between high and low airspeeds at the intersection.

Wind angles also have an impact on the 'jet' effect either at the inlet or the outlet of the main mall. Both points affect user experience in the main and secondary malls and thus must be considered carefully by the designers in the different climatic regions. In cold climates, for example, secondary streets should be used sparingly and should be oriented away from the angled wind to avoid adverse consequences on user comfort.

While this research sheds the light on important results that affect the architectural design of outdoor commercial streets, more questions should be studied in the future. This includes variations in the H/W ratio of main and secondary streets and more variations in the wind angles. Another important factor that should be investigated in the future is the impact of the surrounding buildings on the found results of this research.

Authors contribution

BASMA MAGED IBRAHIM: 1- Conception the work. 2- Data collection and tools. 3- Data analysis. 4- Methodology. 5- Drafting the article. *Bakr Mohamed Gomaa:* 1- Conception of the work. 2- Data analysis and interpretation. 3- Methodology. 4- Critical revision of the article. 5- Writing the final version of the article. *Alaa Eldin Sarhan:* 1- Data analysis and interpretation. 2- Supervision. 3- Critical revision of the article.

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Conflicts of interest

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