International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

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ARTICLE TITLE	THE IMPACT OF URBAN MORPHOLOGY ON WIND FLOW IN A SEMI-ARID CLIMATE. CASE STUDY: THE OLD CITY OF CONSTANTINE, ALGERIA
ARTICLE INFO	Bouhidel Mohamed Abdelkrim Khaled, Mahimoud Aissa. (2024) The Impact of Urban Morphology on Wind Flow in a Semi-Arid Climate. Case Study: The Old City of Constantine, Algeria. *International Journal of Innovative Technologies in Social Science*. 4(44). doi: 10.31435/ijitss.4(44).2024.2951
DOI	https://doi.org/10.31435/ijitss.4(44).2024.2951
RECEIVED	30 September 2024
ACCEPTED	22 November 2024
PUBLISHED	06 December 2024
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THE IMPACT OF URBAN MORPHOLOGY ON WIND FLOW IN A SEMI-ARID CLIMATE. CASE STUDY: THE OLD CITY OF CONSTANTINE, ALGERIA

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ABSTRACT

Wind flow studies using wind tunnels can be very costly due to their nature and implementation. An alternative method involves using numerical methods, specifically CFD (Computational Fluid Dynamics), which offers significant time and cost savings, along with quicker and more flexible results for meaningful research outcomes. To conduct this research effectively, two software tools were required: Sketch Up for modeling the various urban morphologies, and the Fluent module of Ansys for simulations, which is recognized by the scientific community.
The objective of this study was to provide an evaluation of airflow behavior in three samples of different morphologies within the old city of Constantine, namely: the traditional vernacular fabric (Zone A), the hybrid fabric (Zone B), and the colonial fabric (Zone C), based on a series of CFD simulations. The study aimed to assess the various effects of wind flow and velocity through the different typologies of the old city and identify the resulting aerodynamic effects that impact pedestrian comfort.

KEYWORDS

Wind Flow, CFD, Buildings, CAD, Modeling, Urban Morphology, Porosity, Wind Velocity, Urban Typologies

CITATION

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1. Introduction.

The ancient city of Constantine, with its over 2,500-year history, stands as a monumental representation of evolving architectural and urban heritage. Over centuries, diverse civilizations have shaped its urban morphology, influencing its microclimatic conditions and aerodynamic comfort. These historical interventions have produced a mosaic of urban typologies, each contributing uniquely to the city's airflow dynamics.

In Constantine's semi-arid climate characterized by hot summers, cold winters, and significant temperature variations urban configurations can significantly affect pedestrian comfort. Properly designed urban layouts have the potential to optimize wind flow, reduce thermal discomfort, and enhance energy efficiency. Consequently, understanding the aerodynamic implications of the city's urban fabric is essential for architects and urban planners.

This study explores the airflow behavior within three distinct urban morphologies in Constantine's old city: the traditional vernacular fabric (Zone A), the hybrid fabric (Zone B), and the colonial fabric (Zone C).

Utilizing Computational Fluid Dynamics (CFD) simulations through the Fluent module of Ansys, the research evaluates wind velocity and aerodynamic effects across these typologies. Complemented by SketchUp for precise urban modeling, the methodology provides a detailed assessment of how these zones interact with wind flow, emphasizing the implications for pedestrian comfort.

Zone A features a dense network of narrow, irregular streets and interconnected squares typical of vernacular design. Zone B reflects colonial interventions, with wider streets and mixed-use areas bridging vernacular and colonial elements. Zone C, representing the colonial legacy, is characterized by its open avenues and systematically arranged buildings. By examining these configurations, the research identifies patterns in wind behavior and their impact on urban livability.

This analysis not only underscores the importance of integrating aerodynamic principles into urban design but also demonstrates the efficacy of CFD as a cost-effective, precise tool for simulating urban microclimates. The findings aim to contribute to a deeper understanding of urban aerodynamics, fostering more sustainable and pedestrian-friendly environments in Constantine and similar urban contexts.

2. Materials and Methods.

The traditional approach to wind flow studies involves testing different urban configurations in a wind tunnel, considering the orientation of prevailing winds, their averages, and the terrain's roughness to closely approximate urban microclimate conditions depending on the study’s nature.

CFD (Computational Fluid Dynamics) offers a much faster, less expensive, and more scientifically refined and precise means for designing the urban environment. Knowledge and proper use of these tools allow space designers to have a more comprehensive vision of the impact of their designs on the local microclimate and to visualize, correct, optimize, and even preemptively address potential issues in new designs.

The use of the Fluent module in Ansys software, widely used in scientific research and industries requiring aerodynamic studies—such as electronic component overheating, aerodynamic flow in buildings, or optimization studies of vehicles (cars, airplanes, etc.)—proved very useful in this study to demonstrate the various aerodynamic effects observed during the simulations.

To meet the study’s objectives, the work was divided into two major parts: the creation of a computer model in a synthetic image reproducing a large portion of the old city of Constantine, and the subsequent simulation of wind flows from the Southwest of the city at an average initial speed of 7 m/s, chosen based on the most unfavorable case (see Figure 1).

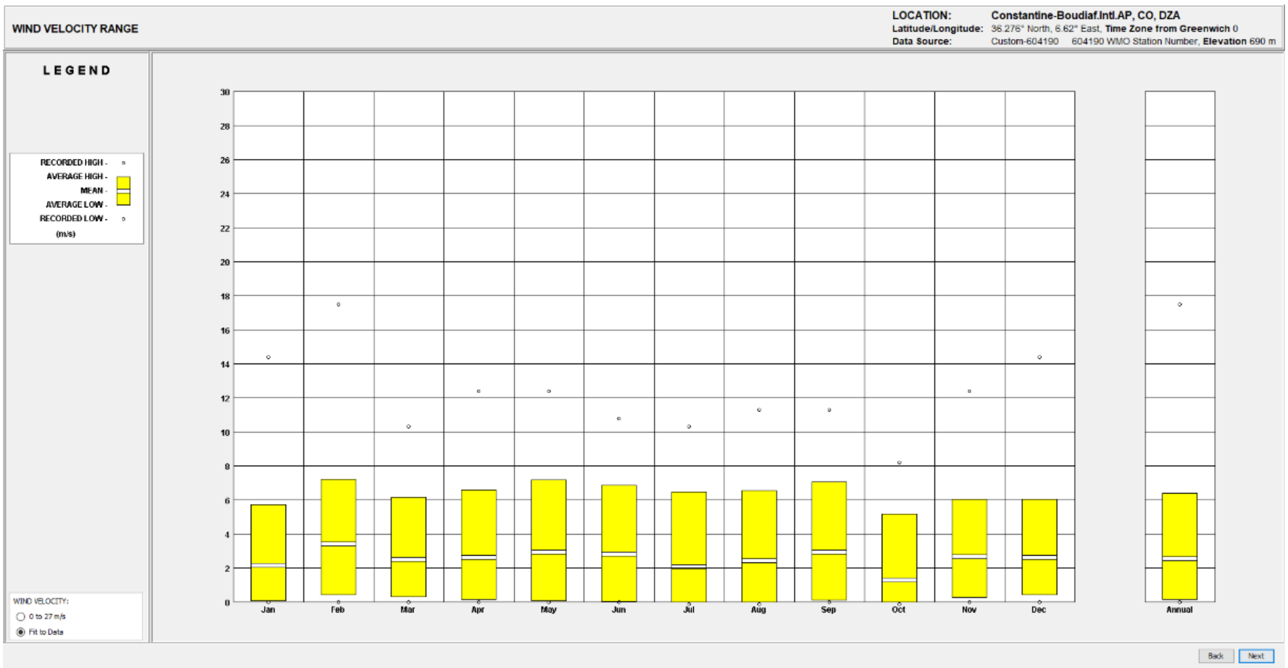

Fig. 1. Average Monthly Wind Gusts for the City of Constantine, Source: Climate Consultant 6 (2020)

2.1 Case Study Selection (Sampling).

Constantine is one of the most important cities in eastern Algeria, located at 36°22'00 N and 6°36'40 E. It occupies a central position in the region, serving as a hub city in northeastern Algeria at the crossroads of the main North-South (Skikda-Biskra) and East-West (Sétif-Annaba) routes. It is also the main metropolis in the east and the largest inland city, with significant cultural and industrial importance (see Figure 2).

According to the climate classification, the city is characterized by:

- A hot and humid summer, with significant temperature differences between day and night.
- A cold and dry winter, with substantial temperature variations between day and night.

Fig. 2. Map of the Old City of ConstantineSource: PDAU - Urban Planning Directorate of Constantine

2.2 Contextual Presentation of the Study.

According to the wind rose diagram in Figure 3, the average annual wind comes mainly from the Southwest and West of the city, with an average wind speed of 7 m/s. The strongest wind comes from the north, with a maximum speed of 8 m/s. This study focuses only on the southern portion of the old city of Constantine, where the various urban fabrics are very distinct (see Figure 4). We will take an average wind gust of 7 m/s from the Southwest, which seems to be the median point between the lowest and highest speeds. These real data allow us to better evaluate pedestrian comfort in our research.

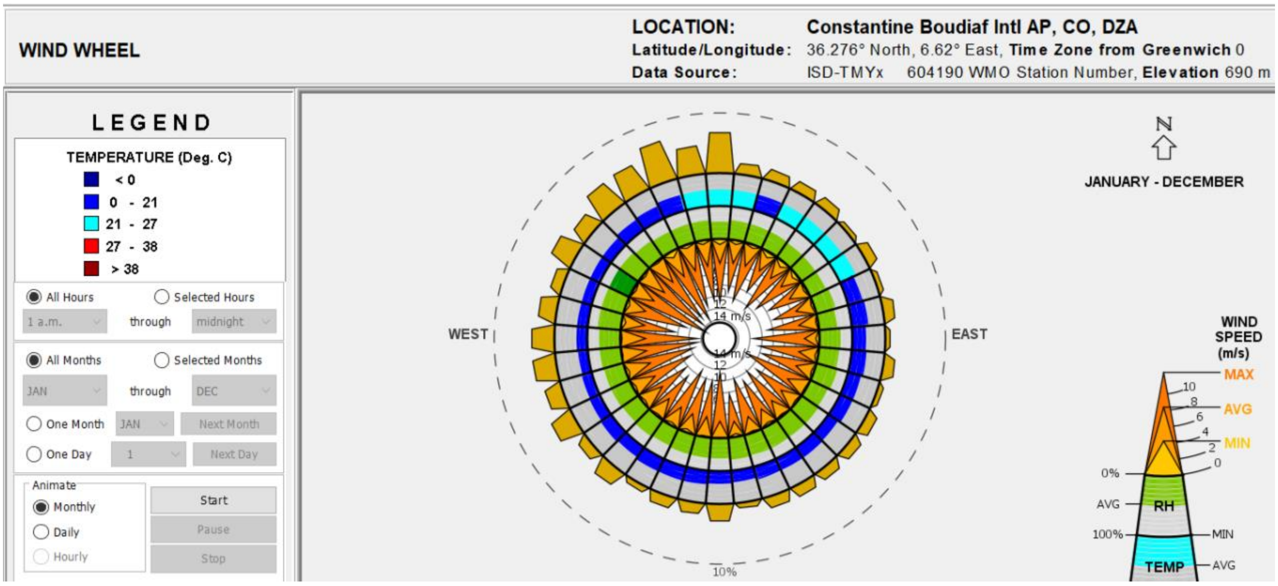

Fig. 3. Annual Wind Rose of the City of Constantine
Source: Climate Consultant 6 (2020)

In this study, we will divide the study area of the city according to its typology. Indeed, after the colonial intervention in the urban structure of the city of Constantine, we can distinguish three fundamental components: a vernacular fabric (see Figure 4, blue zone), a colonial fabric (see Figure 4, red zone), and a mixed fabric, where colonial architecture surrounds vernacular architecture (see Figure 4, green zone).

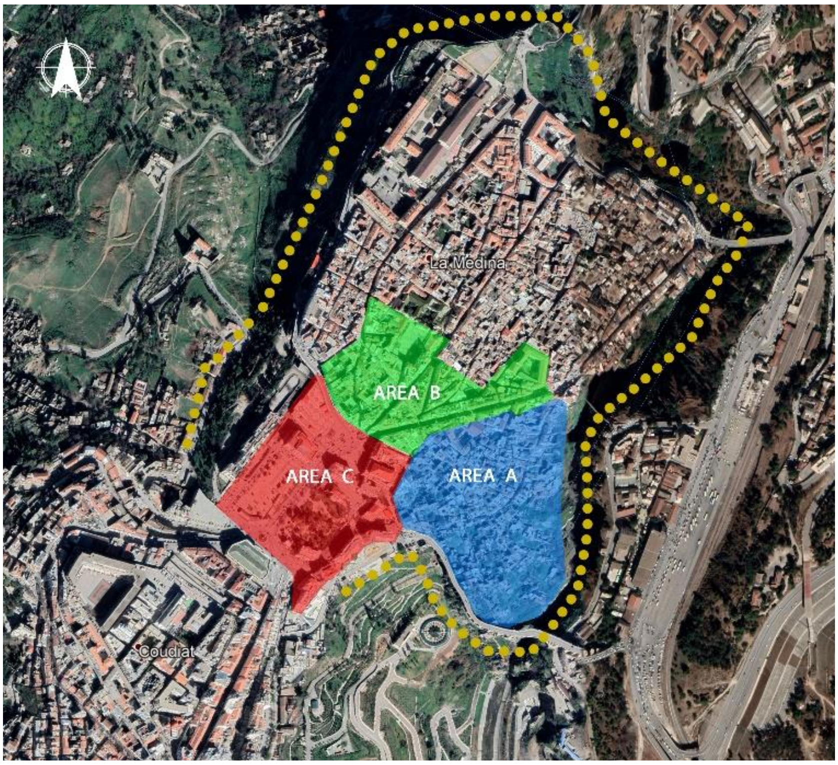

Fig. 4. Division of the 3 study zones corresponding to the 3 different urban fabrics: vernacular, hybrid, and colonial. (Source: Google earth Pro, Author 2024)

2.3 Typologies of the Old City of Constantine.

Throughout history, the city of Constantine (formerly known as Cirta) has undergone changes from various civilizations. This history is reflected in the intertwining of different urban typologies specific to each historical period. These typologies include a "vernacular fabric," a hybrid fabric (vernacular/colonial), and a purely colonial fabric that emerged after the occupation of the city in 1837. In the following table (see Table 1), the different urban characteristics of each typology of the old city within the portion chosen for this study are distinguished.

Table 1.
Characteristics of the Three Urban Fabrics in the Study Area (Source: Author 2024)

Zone	Designation of Urban Elements	Dimensions	Obesrvations
Zone A Vernacular	Avenue	/	It is characterized by high urban density, narrow streets that are often irregular and change direction, irregularly shaped squares that are primarily commercial and interconnected, as well as alleys with dead ends that often lead to residences.
	Street	3.1 à 6m	
	Alley	1.2 à 3 m	
	Number of floors in a building	2 à 3	
	Square	/	
	Plaza	7x 7m 10 x 4.5m 10 x 7 .5 m	
Zone B Mixed (vernacular/colonial)	Avenue	/	There are buildings that extend along the Haussmannian thoroughfares that cut through the old vernacular city. These buildings are aligned along these new, wider streets, ranging from 4.5 meters on "Souidani Boudjemaa" Street in the north of the old city to 10 meters on "Larbi Ben M'Hidi" Street, which crosses the center of the old city on the West-East axis. These new buildings also encircle the old vernacular houses. Additionally, a large square was created in front of the entrance to the Bey's palace. The presence of alleys provides access to the vernacular houses that are surrounded by the new colonial buildings. There is also a large square and more defined small plazas.
	Street	4.5 à 10m	
	Alley	1.5 à 4.9m	
	Number of floors in a building	3 à 5	
	Square	45 x 64.5 m	
	Plaza	15 x 13m 20 x 16 m	
Zone C Colonial	Avenue	17.2 à 22.2 m	It is characterized by a much lower density, with the presence of avenues, and a more open layout. This extension is located toward the southern and southwestern parts of the old city. Several buildings are aligned with spacing ranging from approximately 6 meters to 16 meters between them. There are green spaces, large squares, and public facilities.
	Street	6 à 16m	
	Alley	4.7 à 5 m	
	Number of floors in a building	3 à 6	
	Square	65 x 50 m 92 x 57 m 70 x 140m	
	Plaza	/	

3. Analysis and Discussion.

In this research, numerical simulation using CFD methods is more appropriate for our case study due to the rapid implementation of the model, the significantly lower cost compared to a wind tunnel, as well as the precision of the results and the ability to retrieve different data at any point in the simulation domain at any time. For this study, the Fluent module of Ansys software was chosen; however, it seems that the calculation time increases significantly with complex geometries (by increasing the number of polygons of the object to be simulated). (see Figure 5).

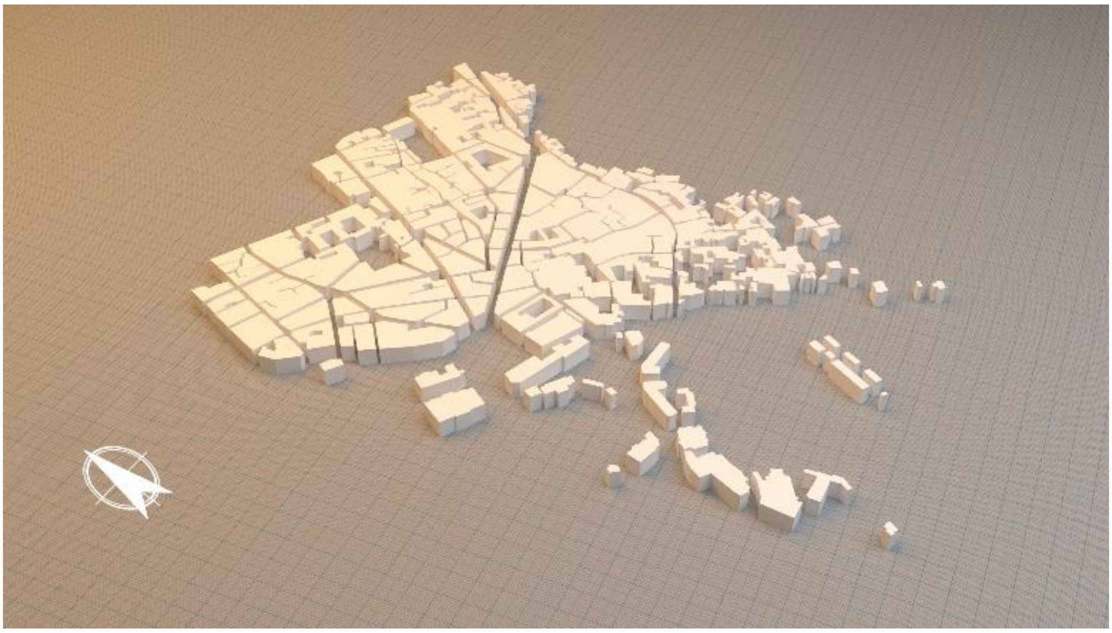

Fig. 5. 3D Study Area of the City of Constantine (Source: Author 2024)

3.1 Simulation Conditions.

3.1.1 Boundary Conditions of the Computational Domain.

Given the size of the chosen portion of the city, it seemed more appropriate to select an unstructured grid with a fineness of 0.5m. This level of detail improves computer performance during simulation and avoids crashes and calculation errors mainly due to the quantity of polygons generated by the mesh.

A grid resolution of 0.5 meters allows for observing the various effects of wind flow friction at building geometry corners and also enables relatively quick aerodynamic solution calculations relative to the amount of generated mesh.

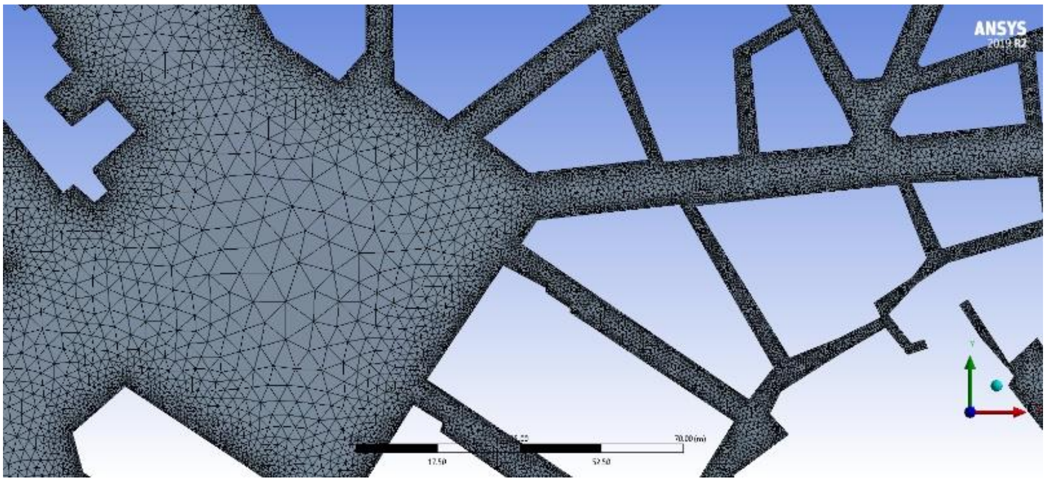

Fig. 6. Mesh Precision with a Resolution of 0.5m (Source: Author 2024)

The wind inlet was applied to the SOUTH-WEST of the city (see Figure 7). The initial wind speed chosen is 7 m/s based on the wind rose of Constantine. Additionally, the direction of the wind flows was chosen by considering the most unfavorable case, directing the wind flows of the simulation towards the part of the city that connects terrestrially to its extension. The air outlet in the simulation was placed to the North-East of the city. The dimensions of the simulation domain are 951.47 m x 917.15 m.

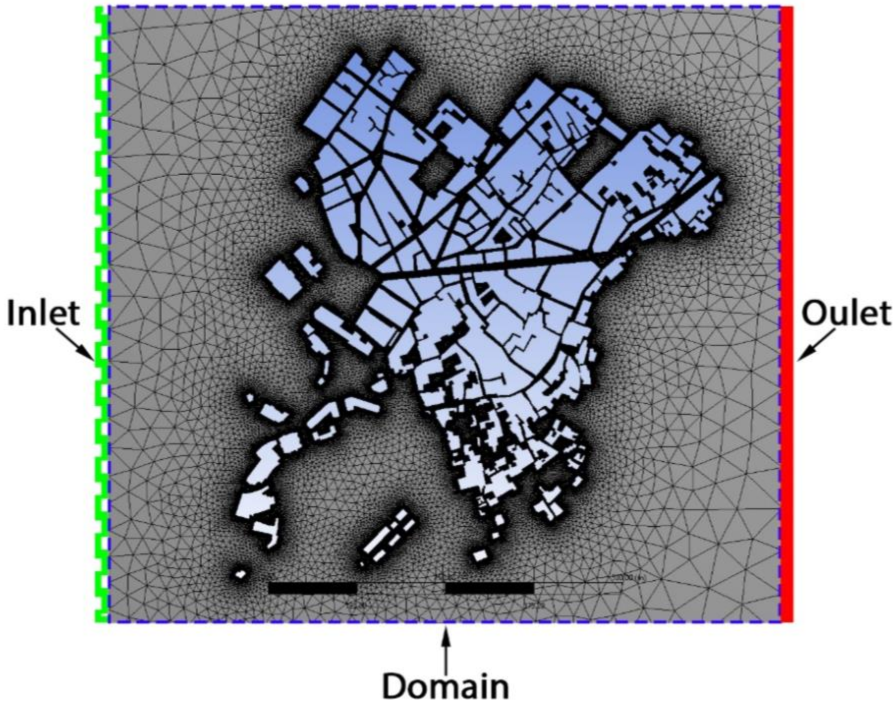

Fig. 7. 2D Mesh of the Study Area (Source: Author 2024)

3.2 Simulation Results.

From the overall view, it is clear that Zone A (vernacular) located in the Southeast of the old city of Constantine shows low wind flow speeds ranging from 0 m/s (stationary zone) to moderate speeds reaching 2 m/s (see Figure 8).

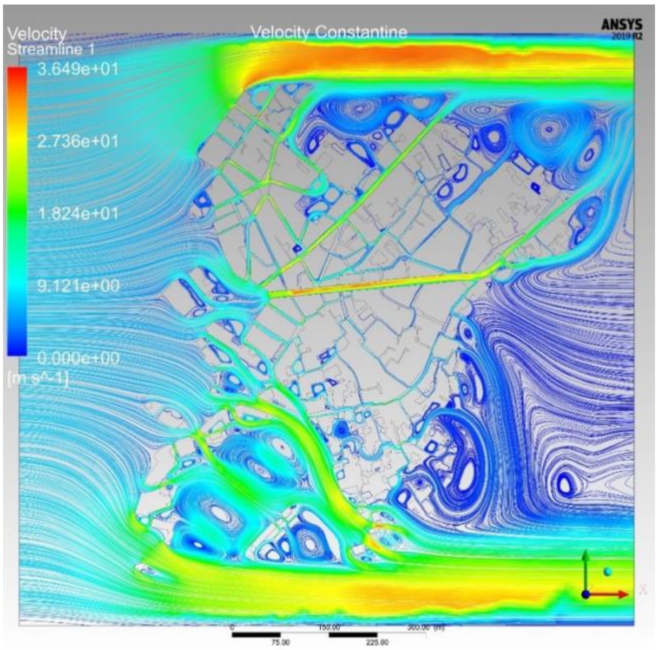

Fig. 8: Velocity Streamlines in Winter Coming from S-SW across the Entire Old City of Constantine (Source: Author 2024)

Zone B, representing a hybrid area in the North of the old city of Constantine, shows higher wind speeds in streets and alleys with larger dimensions than those of the vernacular city. The creation of small squares and "Palais du Bey Square" seems to play a role as speed regulators for wind flows (see Figure 9).

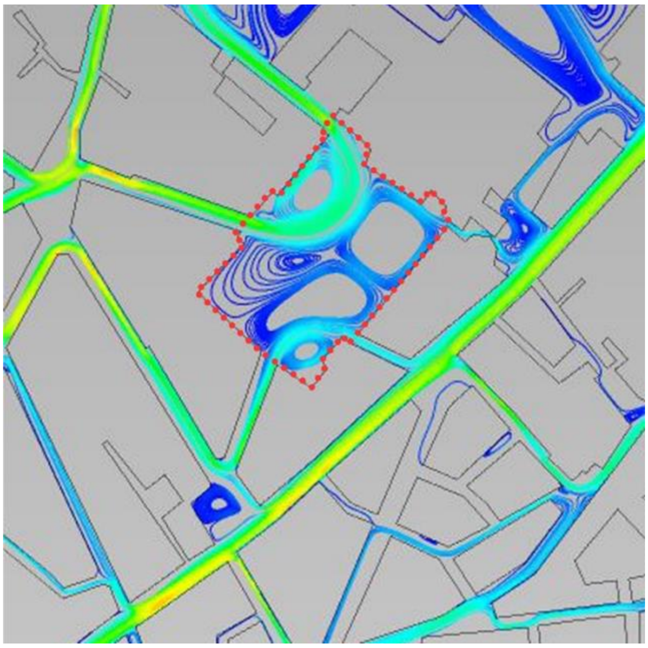

Fig. 9. Zoom of the "Palais du Bey" Square (Source: Author 2024)

Zone C, located in the Southwest of the old city of Constantine, where purely colonial buildings form a kind of wind barrier, shows more significant aerodynamic anomalies. High wind flow speeds are observed, along with the appearance of wake effects and more pronounced corner effects than in the rest of the study area (see Figure 10).

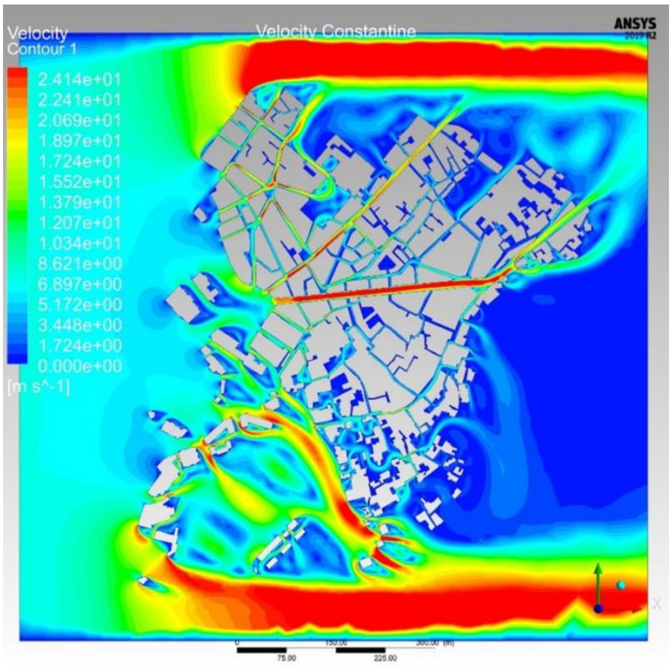

Fig. 10: Velocity contours in winter coming from S-SW across the entire old city of Constantine (Source: Author 2024)

Zone A - Vernacular Architecture:

The change in street direction and constrictions help accelerate wind flow in the main streets compared to the surrounding alleys, where wind speeds are relatively low, reaching up to 2 m/s. The compact configuration of the vernacular area significantly reduces the starting wind speed of 7 m/s. Overall, this remains within the pedestrian comfort threshold according to the Beaufort scale (see Figures 11 and 12).

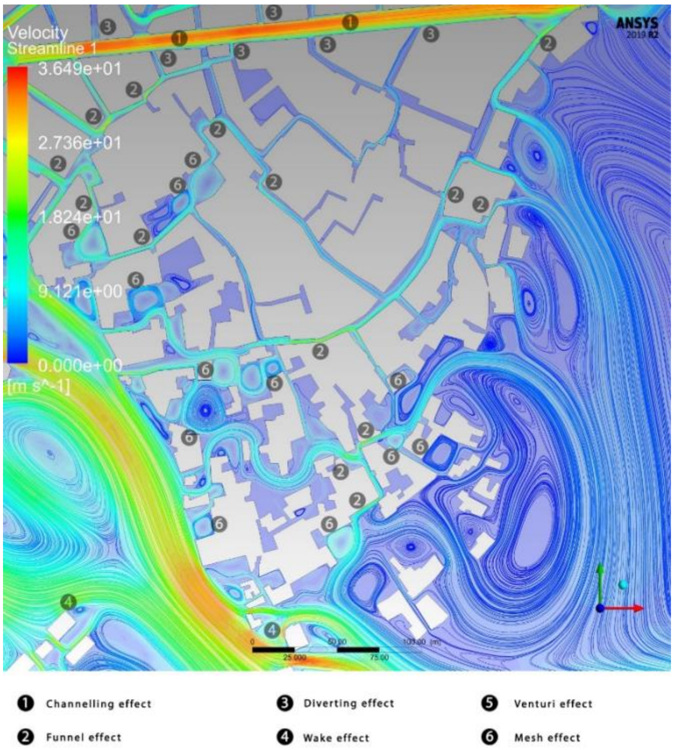

Fig. 11. Velocity streamlines in winter coming from S-SW in Area A "vernacular area", (Source: Author 2024)

When buildings are not directly exposed to wind flow impacts and when the geometry is compact, significant corner effects and wake phenomena are absent (see Figure 11). The presence of squares of various sizes in the vernacular city creates a mesh effect with wind speeds less than 1 m/s in dead-ends, alleys, and unconnected squares. On the other hand, wind flow accelerates to about 9 m/s between interconnected squares and streets along the WEST-EAST axis (see Figure 12).

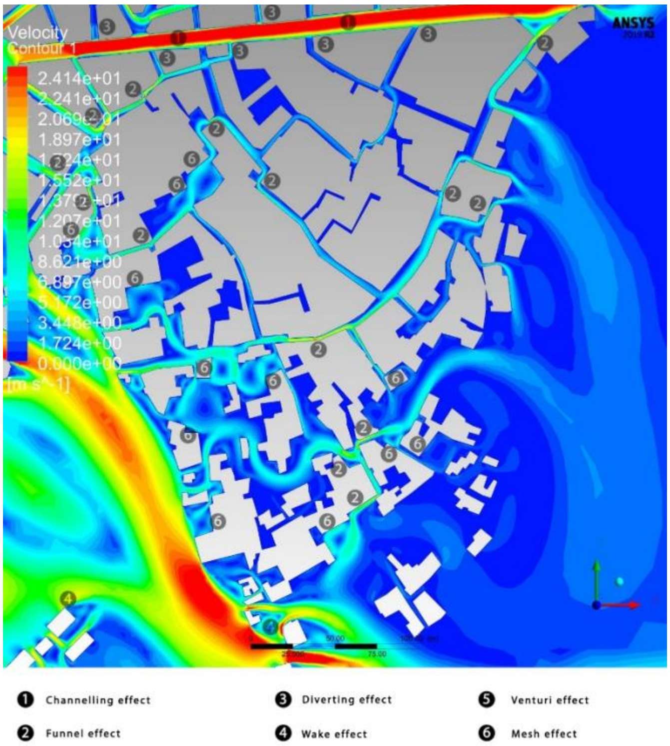

Fig. 12. Velocity contours in winter coming from S-SW in Area A "vernacular area", (Source: Author 2024)

Zone B – Hybrid Architecture:

The creation of colonial breakthroughs along the WEST-EAST and WEST-NORTH EAST axes throughout the city, with streets of significant dimensions ranging from 4.5 m to 10 m, promotes substantial acceleration of wind flow, reaching speeds more than three times the initial speed of 7 m/s (see Figure 14). The Bey's palace square acts as a funnel and speed regulator for various wind flows coming from different directions, channeling air from the South-West towards streets located in the North-East (see Figure 13).

The creation of the Bey's palace square during the colonial era, with dimensions of approximately 45 x 64.5 m at the center, generates a space for the accumulation of solid particles (dust, debris) in the air, favored by the significant mesh effect and corner effects (see Figure 13).

Areas with squares about 1/8 the size of the central Bey's palace square or smaller represent calm zones where wind speeds are relatively low, not exceeding 1 m/s (see Figure 14).

The direct exposure of the streets from the colonial breakthroughs in a compact vernacular fabric causes a Venturi effect at the entrance of each avenue (see Figure 14).

The clear impact of colonial intervention is evident, as these breakthroughs in the vernacular fabric through long, wide streets have altered aerodynamic flow behavior. This intervention promotes wind acceleration along the streets, enhances city ventilation with the advent of cars, but also has a negative impact on pedestrian comfort, as wind speeds can exceed three times the initial speed of 7 m/s (see Figure 14).

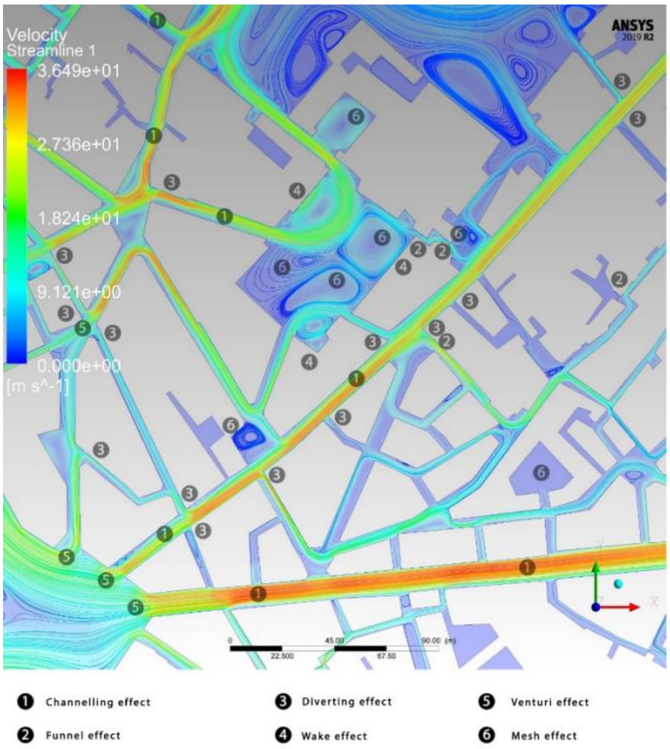

Fig. 13. Velocity streamlines in winter coming from S-SW in Area B "mixed area", (Source: Author 2024)

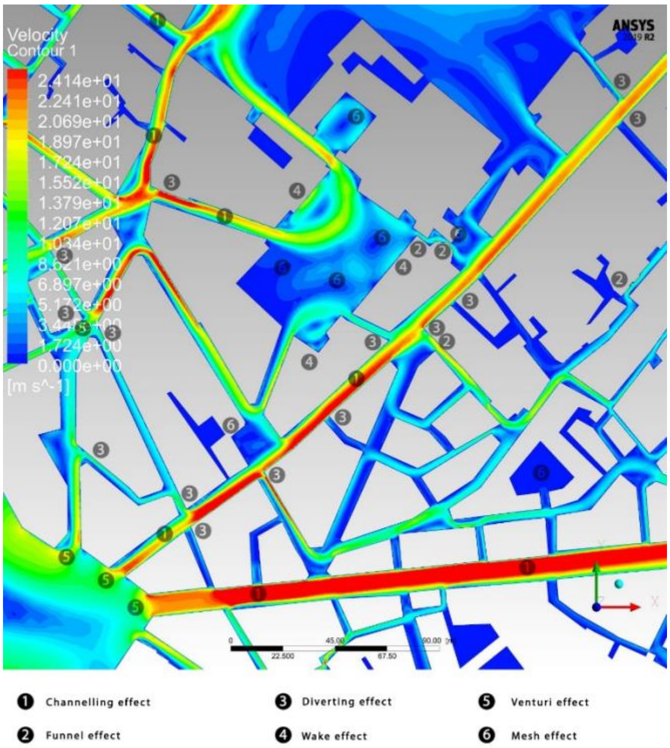

Fig. 14. Velocity contours in winter coming from S-SW in Area B "mixed area", (Source: Author 2024)

<u>Zone C – Colonial Architecture:</u>

Colonial buildings directly exposed to wind flow and acting as obstacles create significant corner and wake effects in the South-West of the city (see Figure 15).

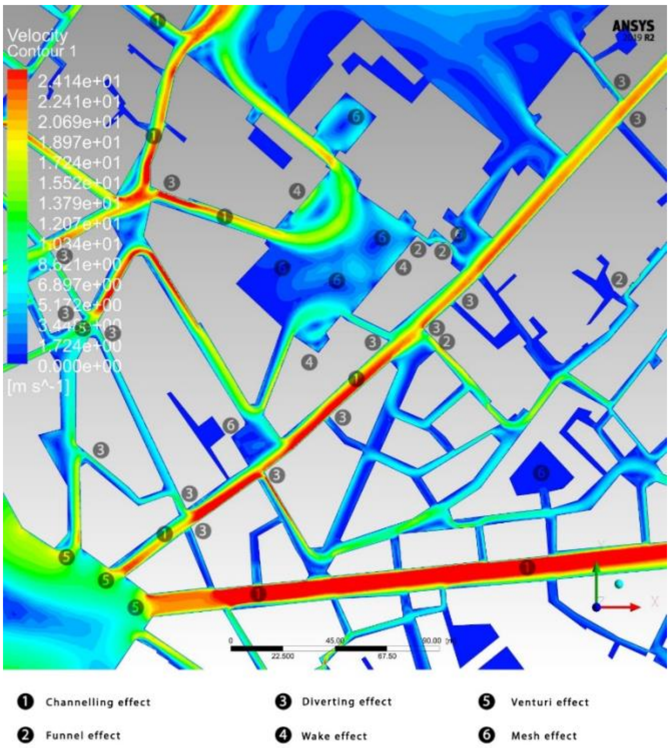

Fig. 15. Velocity streamlines in winter coming from S-SW in Area C "colonial area", (Source: Author 2024)

The presence of colonial buildings acting as obstacles to wind in the South-West part of the city generates substantial corner and wake effects. Small openings between buildings contribute to the creation of Venturi effects and significant wind acceleration (see Figure 16).

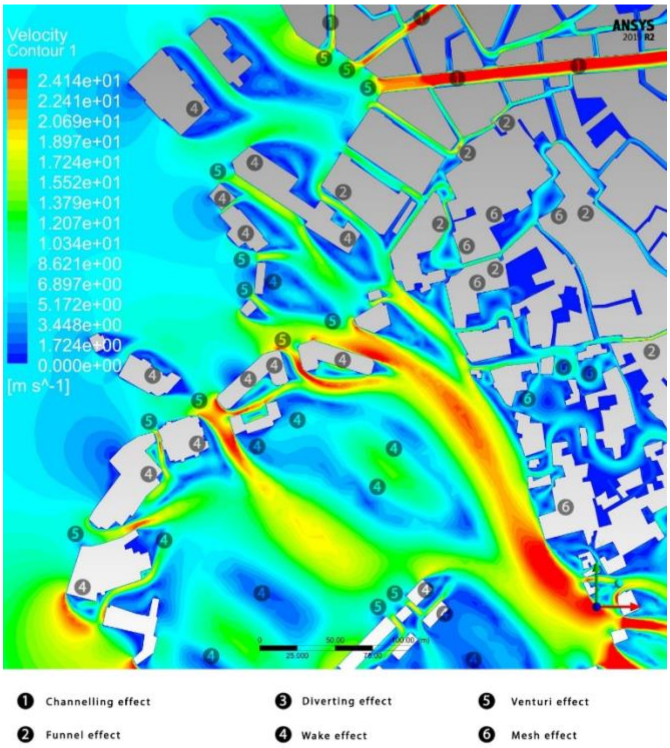

Fig. 16. Velocity contours in winter coming from S-SW in Area C "colonial area", (Source: Author 2024)

4. Discussion of The Results.

Through this study of the three different typologies that make up the old city of Constantine, several levels of comfort are observed according to the Beaufort scale. Zone A: Vernacular, presents very comfortable areas from an aerodynamic perspective, with wind flow speeds often less than 4 m/s and, in the most unfavorable case, a maximum of 9 m/s between the connected squares in commercial areas. This results in maximum comfort in less frequented alleys and squares as well as in streets and squares with higher pedestrian traffic.

Zone B, a mixed typology, features larger streets and displays more significant aerodynamic flows throughout the Haussmannian breakthroughs, which can reach speeds up to three times the initial 7 m/s. This is due to the formation of tunnel effects combined with canyon and Venturi effects that channel the wind and significantly increase wind flow speed. While this improves city ventilation, it considerably reduces aerodynamic comfort for users. The presence of squares helps to reduce wind speeds, creating comfortable stationary zones for pedestrians. However, the resulting wake effects lead to the stagnation of solid particles like dust. The Bey's palace square clearly demonstrates wake effects and stationary zones, but it also acts as a funnel due to the width of the streets leading into it, which is about 5 m. This allows wind flows to spill into the large square and then redistribute into the surrounding streets, with wind speeds in these streets not exceeding 10 m/s, which is comfortable for pedestrians during brisk walking.

Zone C, characterized by colonial typologies, has a more open and less dense fabric with the presence of avenues. This spacing generates Venturi effects, significant wake effects in the SOUTHEAST of the buildings, and corner effects with speeds more than four times the initial speed. This creates areas of aerodynamic discomfort for pedestrians visible on buildings in the SOUTHWEST. However, large squares between buildings in the northern part of Zone C create aerodynamic comfort zones for pedestrians with stationary areas and wind speeds ranging between 1 and 14 m/s.

5. Conclusions.

CFD analysis today allows for simulations that are very close to reality due to advancements in computing. This type of analysis effectively addresses aerodynamic issues in architecture and urban planning, optimizing them for pedestrian comfort and improving city permeability, thereby reducing wind friction on buildings. Such improvements lead to energy savings in heating and cooling at the city scale.

The objective of this study was to highlight the impact of wind flows and their resulting effects on different urban typologies visible within the same urban fabric. The old city of Constantine is a particularly interesting case due to the presence of multiple urban configurations within the same old city fabric.

This study was structured around CFD (Computational Fluid Dynamics) simulation, which provides a cost-effective analysis close to reality and does not require the extensive implementation and logistics associated with wind tunnel tests or in-situ measurements. In this context, ANSYS with its "Fluent" module was chosen for its excellent analytical methods, capability to interpret complex geometries, and reduction in error margins, especially at building corners.

The simulation results indicate that the three urban typologies each present advantages and disadvantages regarding pedestrian comfort. The ratio of street and square dimensions in a compact city fabric can radically change wind flows, thus improving city ventilation, reducing aerodynamic flow speeds, and positively affecting pedestrian comfort. Specifically, Zone A, with its moderately sized streets that change direction and are punctuated by squares, appears to be the most aerodynamically comfortable for pedestrians. However, it is not designed for the presence of cars in the city.

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