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Parametric CFD-Based Assessment of Urban Geometry for Bioclimatic Design: Wind Flow Analysis in Bahria Town, Lahore

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ABSTRACT

The rapid growth of Pakistan's urban areas, especially large cities such as Lahore, poses many challenges for their infrastructure and natural resources. With the increased construction of buildings and the crowding of the urban areas, the urban environment becomes hotter and less pleasant, and air quality worsens. For cities located in hot semi-arid regions, their form plays a crucial role in wind and urban outdoor temperatures. That is why it is critical to apply bio-climatic principles when considering climate parameters in urban development. This research investigates the influence of urban geometry on wind flow and aims to develop ***simulation-supported guidelines for bio-climatic urban design in hot, semi-arid climates****. The study critically reviews the existing research on bio-climatic urban design, categorized into geometric structures, vegetation and construction with different coating materials with computer modeling. First, it looks at relevant literature to understand how city structure, wind, and climate comfort are connected. According to the outcomes, it identifies Main Avenue in LDA-approved housing society of Lahore as case studies. These existing street layouts are modeled digitally and evaluated using* ***Computational Fluid Dynamics (CFD) simulations in CFD software, Sim-scale****. The simulations check air movement and the wind velocity distribution. Alternative urban geometric configurations are subsequently tested to examine their influence on wind movement and natural ventilation. The results are compared to find city layouts that allow for better airflow and natural ventilation in these urban areas. These findings are then combined with the literature review for* ***wind-responsive bio-climatic urban design guidelines in hot, semi arid climates****. The CFD simulations evaluate the* ***spatial distribution of wind velocity and airflow patterns around the selected urban geometries****. The simulation-supported guidelines could help create sustainable cities that are aligned with the environment and have better natural ventilation, and offer more thermal comfort to the people.*

Introduction

Pakistan's cities are changing rapidly because more and more people are moving there. Every year, people leave rural areas and smaller towns to find better jobs in the cities. In the previous decades 10% population was living in urban areas, whereas now it is estimated that by 2030 it will be 75%. (Abbasi et al., 2022). This population movement is making it hard to develop cities in a way that can last. Sustainability has become a popular topic of conversation worldwide. In places with hot climates, about half that is 40%-50% of all energy is used just to keep things cool. (Amer, Bouffant, and Ibrahim 2015) as some state it to be 60% (Saeed, Ahmed, and Butt 2013).In order to develop a framework for thermal comfort, we first need to understand how a person’s body mitigate energy. It is about balancing between the energy we take in and the energy we use. Energy input is what our bodies absorb, and energy output is what our bodies release into the surroundings.The internal thermal state of a human body should range from **36 C to 38 C** (Geneva et al. 2019).The upper and lower state of thermal ranges are known as hypothermia and hyperthermi (Doshi and Giudici 2015).The seven main parameters that influence how much energy a person uses are air temperature, wind, solar radiation, terrestrial radiation, metabolic heat, the body's own heat production, and how warm their clothes keep them. The first five parameters are impacted by the city environment. The last two depend on what individuals decide to do. Factors like air temperature are pretty stable at ground level (1.5 meters up) and don't change much over short distances. The main things that really affect how we feel heat are wind, direct sunlight, and heat radiating from the ground. Considering how much energy humans need to exchange with their environment, city planning should naturally focus on climate, making sure crowded areas are safe from the bad effects of heat waves.(Mazhar et al. 2015).

This paper investigates , wind flow and how it connects to the urban geometry of the cities. Wind is a key factor for how human bodies feel heat and how comfortable the outer environment makes us feel. Using **computer simulations (CFD)**, the study examines where the speed of winds are highest and how air moves around various urban geometrical structures .It also checks how changes in the city design affect wind movement.

Pakistan’s Climatic Context

Pakistan's climate is mostly dry or semi-dry, but it changes a lot depending on the season and the area. Many parts of the country have hot summers with not much humidity. Winters are mild in the south but very cold in the northern mountains. The climate is greatly affected by the South Asian monsoon, western weather patterns, how high up the land is, how far inland it is, and how close it is to the Arabian Sea. The monsoon usually brings most of the yearly rain in the summer.

In the winter, rain and snow in the north and west often comes from those western weather systems. Pakistan typically has four seasons: winter, spring, summer, and autumn. The length and strength of these seasons change depending on the location. Summer is especially significant for studying urban environments in Pakistan because many areas get very hot for long stretches and have strong sunlight(Khan 2010) .In cities during the summer, things like lots of buildings, paved roads, not much greenery, heat from human activities, and lack of wind can make the area even hotter. This can make the Urban Heat Island effect worse and mean buildings need more energy to stay cool. The integration of climatic analysis into urban design is crucial for enhancing the sustainability and climate-responsive cities in Pakistan.

Climatic Performance Analysis of Lahore:

Lahore is the second largest city in population and it lies in the semi-arid zone. Semi-arid zones are the one which encounter precipitation rate below the potential evaporation but these areas are not as low as a desert .

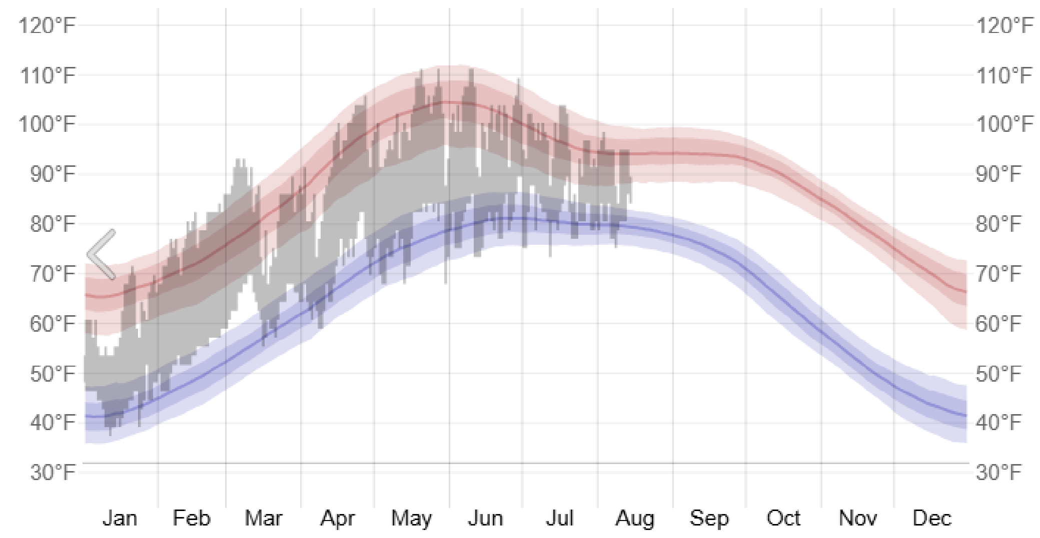

Figure 1 Lahore Temperature History 2026, https://weatherspark.com/h/y/108021/2026/Historical-Weather-during-2026-in-Lahore-Pakistan#Figures-Temperature

From the above data monthly approximately high and approximately low temperature of all months of Lahore are taken , in order to calculate the mean temperature.

Month	Approx. High Temperature	Approx. Low Temperature	Mean Temperature	Mean Humidity	Climatic Character
January	65°F	43°F	54°F	66%	Cool winter
February	72°F	48°F	60°F	58%	Cool to mild
March	85°F	60°F	73°F	53%	Mild and warming
April	96°F	70°F	83°F	42%	Warm to hot
May	106°F	80°F	93°F	36%	Very hot
June	108°F	84°F	96°F	42%	Extremely hot
July	100°F	82°F	91°F	66%	Hot and humid
August	97°F	80°F	89°F	70%	Hot and humid
September	97°F	77°F	87°F	63%	Hot
October	88°F	68°F	78°F	58%	Warm
November	78°F	55°F	67°F	53%	Mild to cool
December	70°F	45°F	58°F	67%	Cool winter

Table 1 Monthly temperature table of Lahore City

The temperature of Lahore, shows a consistent pattern throughout the year. Winters are the coldest times in Lahore, during which the average temperature is 54°F in January and 60°F in February month. As spring emerges, there comes a rise in temperature to 73°F in March and 83°F in April. The summer months record even higher temperatures in the form of 93°F in May and 96°F in June. After that, the gradual decline begins in the temperature till 91°F in July, 89°F in August, and 87°F in September. The drop of temperature is much more apparent in the season of autumn , when the average temperatures are 78°F in October, 67°F in November, and 58°F in December. The blue column in table 1 shows the mean temperature, the green column shows the mean humidity whereas the climatic character in table 1 with yellow rows shows the months that are warm and need cooling.

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Thermal Comfort and Bio-Climatic Chart of Lahore City

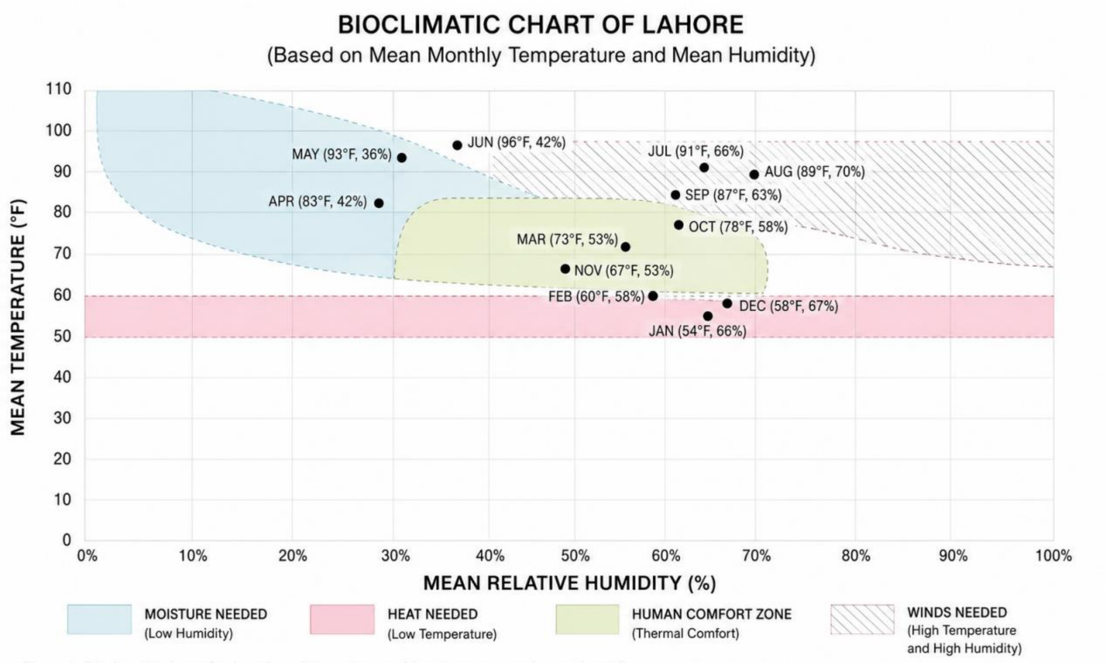

Figure 2 Bio-Climatic Chart of Lahore City,

The above chart for detecting the comfortable climate conditions for living a comfortable life was generated by the **Olgyay's Brother in 1950's**. This graph represented the association among the climatic factors. The comfortable thermal zone of humans that does not require any artificial heating or cooling is described in the center of this graph. The process involves documenting mean temperature data throughout the year and then plotting it against the mean humidity of Lahore in 2026 in the whole year.

The thermal comfort zone diagram of Lahore for 2026 (figure 2), depicts the climate conditions in all 12 months including temperature and humidity in Lahore. The months of January (54F, 66%), February (60F, 58%) and December (58F, 67%) needs heating. The month of March (73F, 53%) and November (67F, 53%) are comfortable months which do not need any heating or cooling. The months of May (93F, 36%) and June (96F, 42%) needs humidity. The months of April (83F, 42%) and October (78F, 58%) needs humidity and wind whereas the months of July (91F, 66%), August (89F, 70%) and September (87F, 63%) needs winds only. This depicts the overall number of hot months that require active cooling are seven and out of it five require climate-responsive integration of airflow. This shows the significance of wind integration for generating microclimate and controlling the human energy budgeting.

Methodological Framework

The formulated research methodological framework is based on the use of simulations and incorporates both qualitative and quantitative analysis using literature based critical analysis and computational modeling of Computational Fluid Dynamics (CFD). Pertinent literature on the topic of bio-climatic urban design was reviewed in order to detect the relation between urban geometry, climate, wind behavior and natural ventilation in terms of geometric structure, vegetation and construction materials and surfaces. The literature data will be in form of secondary data and the simulation results will be in the form of primary data.

The urban geometry factors that influence the airflow behavior in accordance with literature review and climatic features of Lahore including the factors, street orientation, street width, building height, building spacing and building layout. Main Avenue of the **LDA approved residential society in Lahore such as Bahria Town** have been selected for the research and their existing urban geometries have been modeled accurately by using a modelling **software sketch-up** .Evaluation of the model was carried out using computational fluid dynamics simulations performed using the **Sim-Scale simulation** platform in the cloud. The simulation focused mainly on the wind velocity magnitude (m/s), wind direction, and wind velocity distribution, with investigation centered on the high and low wind velocities and possible areas of airflow obstruction. Alternative urban layouts of urban geometry were then modeled and simulated to determine the effects of these urban geometries on wind flow and natural ventilation. The CFD conclusions were interpreted in relation to findings from the current available literature. These findings will help in developing the guidelines for CFD based wind-responsive bio-climatic urban design guidelines **for hot, semi-arid climates.**

Wind-Sensitive Urban Morphology in Hot, Semi-Arid Climates

The urban geometry of cities is a basic building block of urban-ism and is important for influencing the local climatic conditions and human thermal environment. In contrast to an Emphasis on the thermal response of an individual building, this paper will consider the scale of the entire urban environment in which factors such as the urban circulation network , pattern, block, voids and urban spaces, edge conditions, height-to-width ratio of existing buildings, distance between buildings, and orientation of the building impacts the airflow and environmental conditions in the urban spaces. These geometric structures can impact the way winds circulates, solar radiation, heat accumulation, and natural ventilation in urban environments.

On the bases of the climatic conditions of Lahore city as a predominant example of a hot semi-arid urban environment, the research is about to investigate the geometric urban structures of the urban environment that can appropriately responds to the climatic conditions. The focus is on the factor of wind movement since it is very important for convective and evaporative heat exchanges and contributes to outdoor comfort and natural ventilation in urban settings. This research will be done by adopting Computational Fluid Dynamics (CFD) simulations for investigating the relation between wind movement and urban geometry.

Street Patterns, Urban Canyons, and Aspect Ratio

The road network works as a significant **airflow corridors within the urban fabric**, contributing to the movement and distribution of wind through the urban geometry and consequently contributing to the development of the urban microclimate. The configuration, orientation, width, and continuity of streets can either enhance or constrain air circulation. Unplanned or excessively enclosed street patterns may obstruct wind movement and restrict natural ventilation, thereby affecting outdoor microclimate.

Narrow and elongated streets enclosed by buildings form **urban canyons**, in which the surrounding building heights and street width determine the geometry and airflow characteristics of the space. The ratio between building height and street width, commonly referred to as the **urban canyon aspect ratio (H/W)**, is an important geometric parameter for assessing airflow conditions within urban streets. Changes in this ratio can influence wind penetration, air circulation, heat accumulation, and ventilation potential.

At urban scale, the volume of air influenced by the built environment extends above the building roofs and forms part of the **urban boundary layer**, within which urban morphology modifies atmospheric flow (Givoni 1998)**.**The relationship between urban form and environmental factors, focuses on the role of urban geometry in transforming the micro-climate. The evaluation of street geometry and urban canyon aspect ratio provides an important basis for understanding how urban form influences wind circulation and for establishing the **climate-responsive urban design strategies**.

Aspect ratio = Height of the building/ Width of the streets (Oke 1988)

Aspect Ratio = Average Length / Average height of Building

As highlighted in the previous studies and also mentioned in the authors previous publication that the aspect ratio greater than 1 is identified as the most suitable , as it provides extensive pedestrian shading . If the canyon is uniform, its aspect ratio will be equal to 1. Shallow canyon will have aspect ratio below 0.5 and deep canyon will be equal to 2.in the second formula the factors used will be considered as a short canyon when the value of the aspect ratio is 3. It will be a medium canyon when its value is 5 and long when its value is 7.(Naeem et al. 2025)

Wind Orientation Within Urban Canyons

The interaction of wind direction with respect to the longitudinal axis of the urban canyon may take one of three geometrical configurations: **normal, oblique, and parallel.** For a normal or perpendicular wind, the wind hits the urban canyon approximately 90° from the canyon axis; this makes it possible for the wind to interact directly with the building surfaces, which in turn results in formation of recirculating flows and pressure differences in the urban canyon. When the wind interacts with the urban canyon in an oblique manner, the angle between the direction of the wind and the canyon axis allows for the generation of complicated airflow patterns such as helical or spiraling vertices throughout the length of the urban canyon. With the parallel wind, the wind direction is approximately parallel to the canyon axis, which means that the flow can penetrate the canyon through the street corridor with relatively minimal obstruction by the geometric forms of the canyon.(Santamouris, Georgakis, and Niachou 2008)

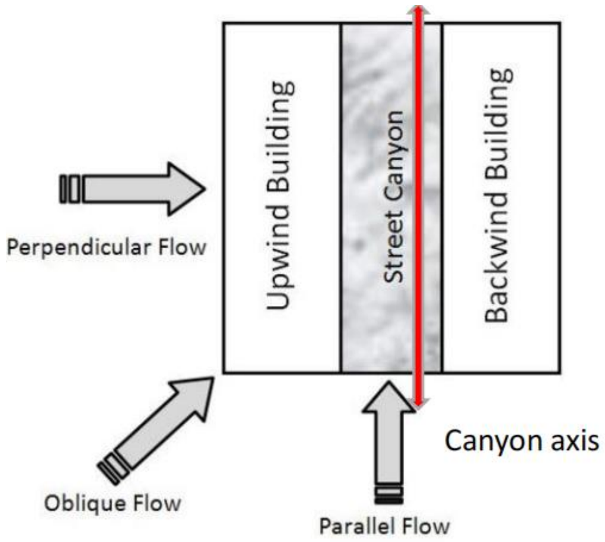

Figure 3 Wind direction angles to the canyon axis

Instead of doing mathematical calculations for aspect ratio to determine the wind impact on the urban geometry in detail , like it was done in the authors previous article (Naeem et al. 2025) . This article will focus more on simulations with just calculating the current situation of the aspect ratio using formula's taken from literature.

Selected Urban Site for CFD Analysis

Bahria Town is a gated ,private society with most of its sectors approved by Lahore Development Authority (LDA).

Figure 4 Map of Bahria Town Lahore

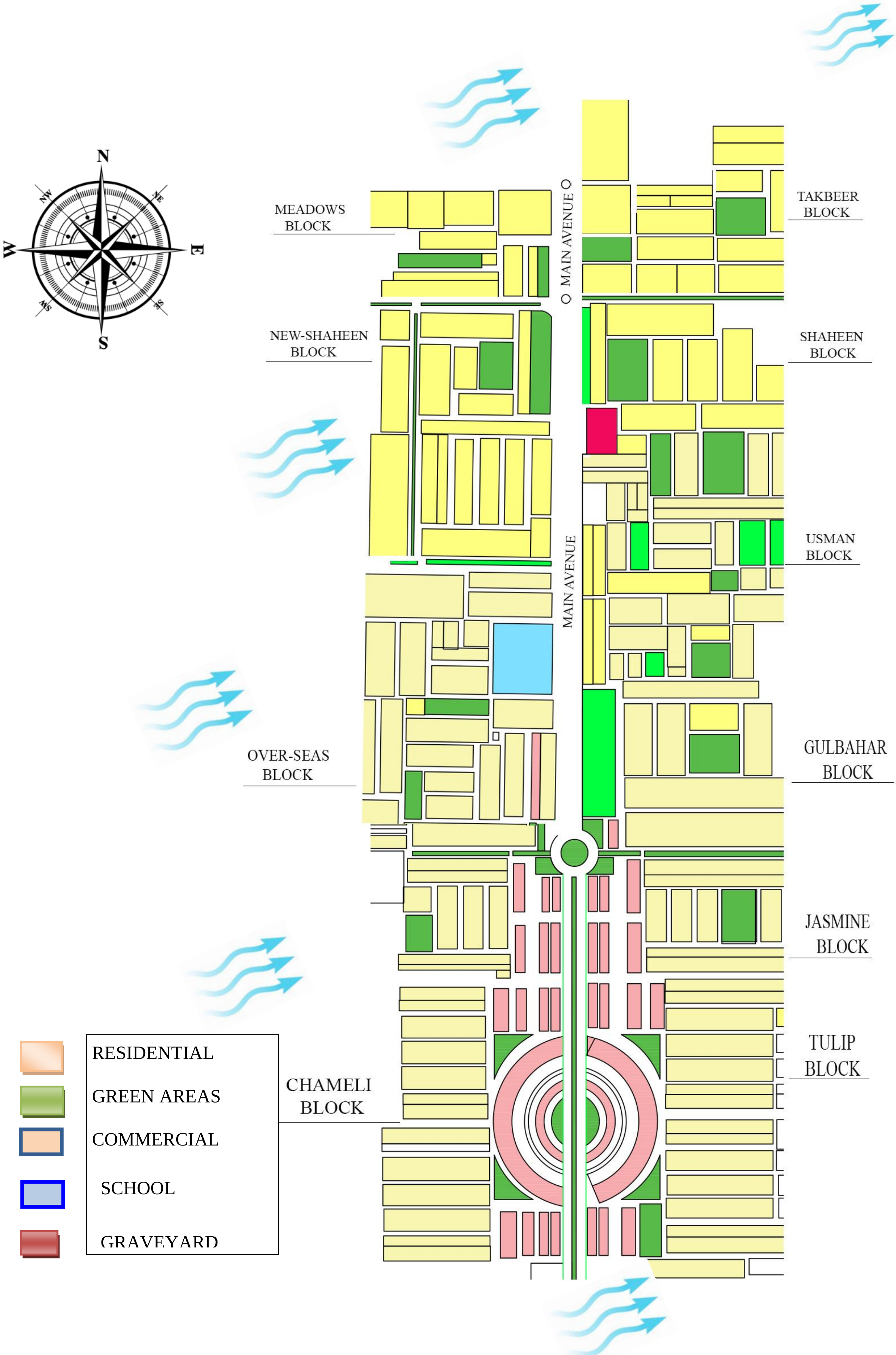

Figure 5 Illustration of the main Avenue of Bahria Town Lahore

The above figure 5 shows the urban morphology , land distribution, road network, open green spaces and wind flow direction of Lahore , specifically for the main avenue of bahria starting from the commercial zone D to the meadows gate. The plan highlights the inclusion of residential zones such as Meadows, Takbeer, New-Shahreen, Shaheen, Usman, Gulbahar, Overseas, Jasmine, Tulip, and Chameli Blocks along the main avenue .The major land use is occupied by residential use however, green lands, commercial lands, educational institutions, and graveyards are also part of the plan. The blue arrows show the wind direction that is **South-West to North-East**.The residential are two floors with mumty , where as the commercial's are mostly six floors.

Bahria Town Current Layout

Analysis with the help of literature review data.

Aspect Ratio

The aspect ratio of the part 1 and 2 will be different because of the height of residential that will be 22 feet with two floors and commercial buildings that will be 66 feet with six floors. The width of street remains constant that is 40 meter or 130 feet.

Aspect ratio = Height of the building/ Width of the streets

Aspect ratio of A = 22 feet / 130 feet
= 0.169

Aspect ratio of B = 66 feet / 130 feet
= 0.507

In **both the cases the aspect ratio is 0.5 and below**, so it will be **shallow canyon**. To avoid that, we have to increase the width of road or heights of the buildings so that the aspect ratio becomes 1 or greater than 1.

Orientation

The orientation of wind is **oblique**. It means it is at diagonal angles with the canyon axis, which means that spiral vertices of wind are formed along the canyon's length. To avoid that the main avenues should be designed in a way to form a parallel relation of wind flow to the canyon axis to enhance the affect of wind in the urban area.

CFD Simulation Of Bahria Town Current Layout

The simulation generated in the research paper will be of June month as it is the hottest month of Pakistan and wind integration is the most significant factor of this month.The Velocity-magnitude CFD simulation is generated with the help of Sim Scale Simulation Generating Software.

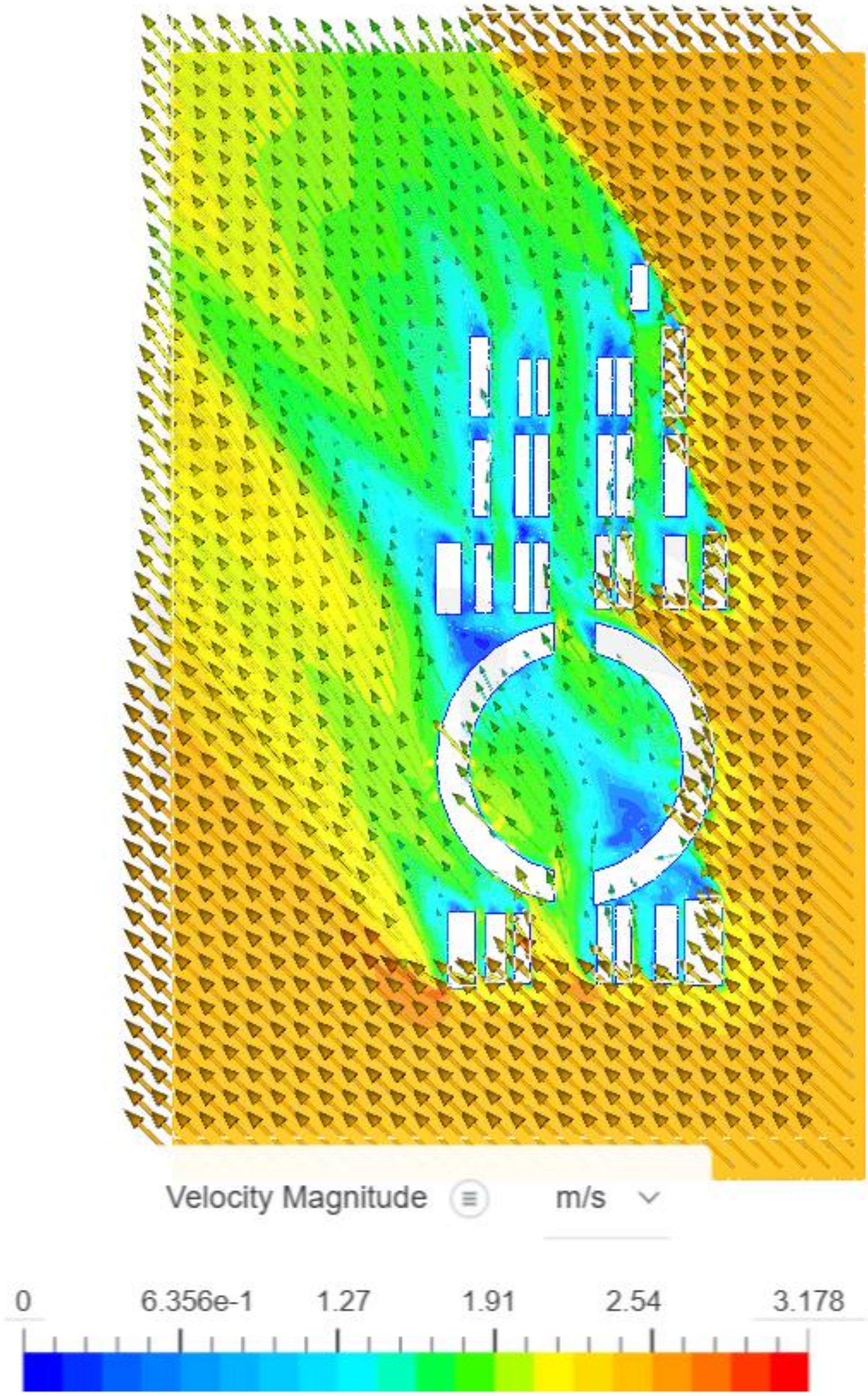

Figure 6 Bahria Town if Wind Flow is Oblique to the Urban Canyon

Results of the Analysis

The Analysis shows the following results visually through the simulation.

1. Velocity Magnitude
2. Wind Direction
3. Wind Velocity Areas

Velocity Magnitude

The color scale in the analysis illustrates the wind velocity in the modeled area. The scale starts from **0 to 3.18 m/s.** The velocity of June is approximately **2.62m/s.** The setting used in the simulation software are **wind velocity at x-axis= -1.85m/s , y-axis=+1.85m/s and z-axis= 0 .**

Wind Direction

The arrows in the analysis shows the wind flow direction. As the wind is flowing diagonally across the chosen site it shows that it is **oblique.** The wind direction is **South-East to North-West.**

Wind Velocity Areas

Different colored arrows show different wind velocity areas. The Yellow region shows the highest and strongest airflow. The green areas are also strong but the blue zones are the lowest wind velocity areas in the simulation. The value of all these colors is mentioned in the scale below the CFD analysis.

This shows that the urban geometrical structures influence the distribution of the wind velocity in the selected site.The site experiences the velocity mostly at green and blue . it means that the specially around the circular commercial zone the wind velocity it at lowest.

CFD Simulation Of Bahria Town if Wind Flow is Parallel to the Urban Canyon

Velocity Magnitude

The scale starts from **0 to 3.18 m/s.** The velocity of June is approximately 2.62m/s. The setting used in the simulation software are **wind velocity at x-axis= 0 , of y-axis=+2.64m/s and z-axis= 0.**

Wind Direction

The arrows in the analysis shows the wind flow direction. As the wind is flowing parallel across the chosen site , It is the best option for the wind flow**.** The wind direction is **South to North.**

Wind Velocity Areas

The CFD analysis shows that most of the wind velocity lies in yellow and green. It mean that the wind parallel to the urban canyon is the best option as it has the highest wind velocity.

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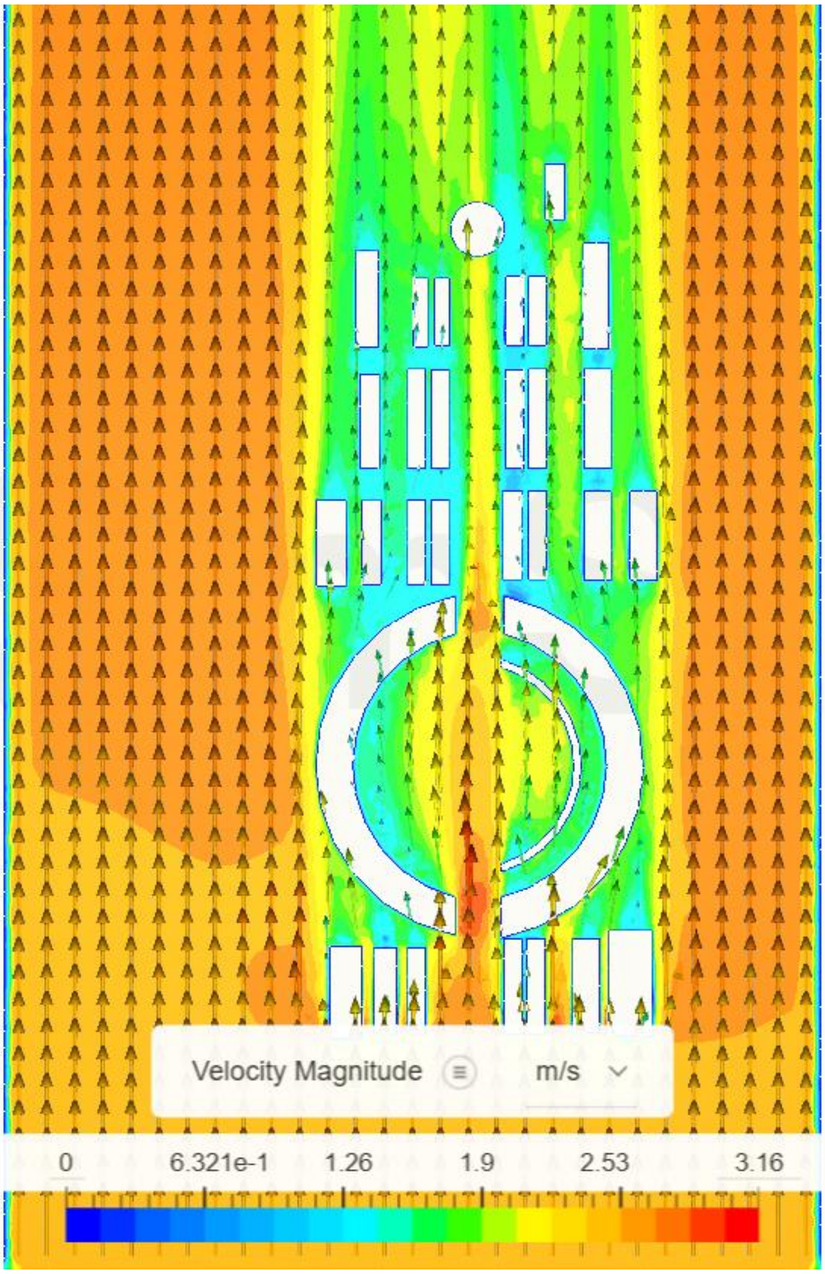

Figure 7 Bahria Town if Wind Flow is Parallel to the Urban Canyon

CFD Simulation Of Bahria Town if Wind Flow is Perpendicular to the Urban Canyon
Velocity Magnitude

The scale starts from **0 to 3.18 m/s.** The velocity of June is approximately 2.62m/s. The setting used in the simulation software are **wind velocity at x-axis= +2.64m/s , of y-axis=0 and z-axis= 0.**

Wind Direction

The arrows in the analysis shows the wind flow direction. As the wind is flowing perpendicular across the chosen site **.** The wind direction is **West to East.**

Wind Velocity Areas

The CFD analysis shows that most of the wind velocity lies in blue after it crosses perpendicularly to the urban geometry. It mean that the wind perpendicular to the urban canyon is the worst option as it has the lowest wind velocity.

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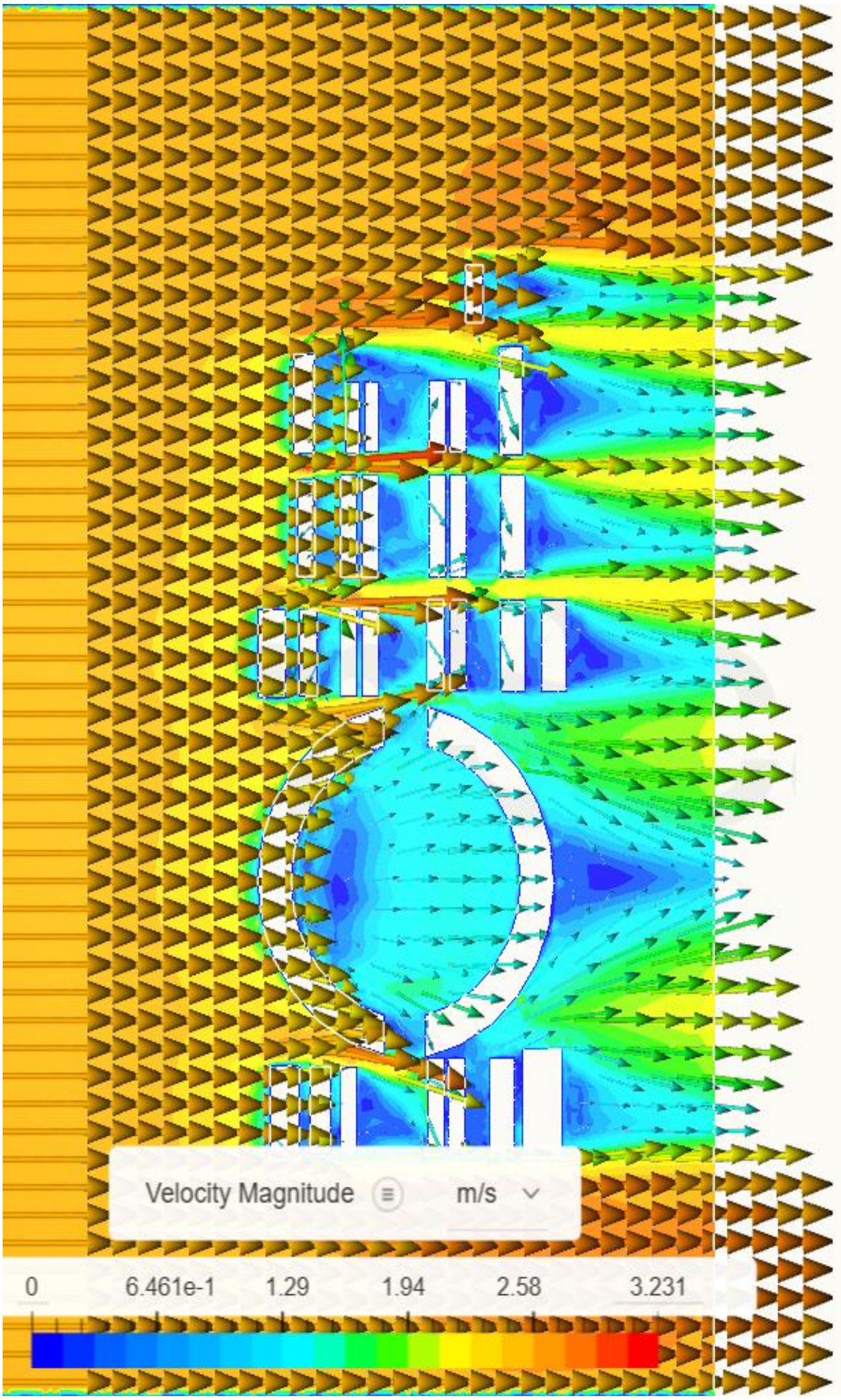

Figure 8 CFD Simulation Of Bahria Town if Wind Flow is Perpendicular to the Urban Canyon

Analysis

The table below shows the comparative analysis of all the three options of wind velocity direction affecting the urban morphology.

Assessing Parameters	Oblique wind direction	Parallel wind direction	Perpendicular wind direction
Link between wind and urban canyon	Wind approaches the urban canyon at an oblique angle	Wind flows parallel to the urban canyon/street axis	Wind approaches the urban canyon perpendicular to its axis
Approx. velocity range shown	0 – 3.18 m/s	0 – 3.16 m/s	0 – 3.23 m/s
Wind integration	Moderate; airflow enters but is progressively deflected	High, airflow integrates deeply along the street network	building masses obstruct direct penetration into urban blocks
Airflow continuity	Moderate; airflow follows a combination of direct and deflected paths	High, relatively continuous airflow corridors are visible	Low to moderate, airflow is interrupted by building masses
Flow pattern in the urban geometry	Deflected	linear and continuous along the canyon	Strong cross-flow and obstruction around building masses
Low-velocity zones	Several low-velocity zones occur around building clusters and open spaces	limited and localized	More prominent sheltered/low-velocity zones behind buildings
High-velocity zones	Higher velocities occur where oblique flow is channelled between buildings	Concentrated along the principal wind corridor	Higher velocities occur mainly around exposed building edges and open areas
Central circular/open space	Circular geometry causes noticeable flow redirection and mixing	Airflow passes through and around the space with relatively good continuity	Flow is more strongly disrupted around the circular space
Overall airflow performance	Moderately favourable	Best Option	Least Recommended
Design implication	Can be used where site constraints prevent direct alignment	Recommended for wind-responsive urban planning	Use cautiously where natural ventilation is a priority
Performance assessment	2nd – Relatively effective	1st – Most effective	3rd – Least favourable
Results	**2nd– Least favourable**	**1st – Most favourable**	**3rd – Least favourable**

Figure 9 comparative analysis, oblique, parallel and perpendicular wind direction

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Research Implications

The CFD analysis conducted by using Sim Scale Software demonstrates that **urban morphology has a significant impact on the distribution and continuation flow of wind pattern within the urban fabric of Lahore city** . The analysis above shows the comparison of parallel, perpendicular, and oblique urban canyon indicates that the orientation of road network and building masses relative to the prevailing wind direction affects wind integration, airflow continuation , and the formation of low and high velocity zones.

Among the three configurations assessed, the **parallel configuration indicates the most favourable overall airflow assessment .** The perpendicular configuration showed greater obstruction of air integration and the formation of more low velocity zones , while the oblique configuration shows a moderate response, with airflow being redirected around urban geometry.

In addition to this, the maximum wind speed alone cannot help in evaluating the effectiveness of an urban planning what matters instead is the distribution, continuity, and penetration of air flow in the urban geometry. As the direction of wind movement is a natural climatic phenomenon which cannot be regulated by urban layout of the site, it can be inferred that the urban layout should be planned in such a way that it respects to the wind direction. The CFD results show **simulation-supported bio-climatic urban design guidelines**, particularly concerning street orientation of the design , urban canyon configuration, building arrangement, and the provision of continuous airflow pathways. The proposed approach shows climatic analysis and CFD simulation can be integrated into the urban design process to support more environmentally responsive development in hot semi-arid cities.

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