

Original Article

Urban Morphology and Micro-Wind Potential: A CFD-based Assessment of Built Form in Pune, India

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Abstract - Urban growth in cities such as Pune is transforming urban morphology and influencing micro-climatic wind behaviour, necessitating wind-responsive approaches in sustainable design. This study investigates the impact of built form and inter-building spacing on ventilation performance and micro-wind potential using Computational Fluid Dynamics. Twenty-six twin-adjacency configurations across four spacing categories are analysed under steady-state conditions using average wind data of Pune. The RANS *k*-epsilon model is employed, with results evaluated at four building heights, generating 416 observations. Gap wind velocity is used to quantify wind amplification within inter-block spaces. Results indicate significant wind acceleration, with gap velocities reaching 2-3 times the incident wind speed under favourable configurations. Increased spacing and vertical exposure enhance ventilation potential and indicate zones suitable for micro-wind applications. The study highlights the role of CFD-based urban wind assessment in supporting wind-responsive architectural design for ventilation and energy potential.

Keywords - Building form and spacing, CFD-based assessment, Micro-wind energy potential, Ventilation performance, Urban morphology.

1. Introduction

Wind in cities interacts with structures and in-between spaces resulting in a significant alteration in flow direction and speed due to dense development in cities and its suburbs, compared to that in rural areas [1-3]. Urban wind patterns vary in two ways: the “Urban Heat Island Effect” of strong centripetal winds moving from low-density surroundings towards the warmer urban core particularly at night, and the “Urban Wind Island Effect” of turbulent winds due to man-made obstacles that deflect, redirect and amplify airflow within cities [2-6].

Streets act as wind corridors interspersed with open spaces allowing wind to reach its natural velocity or even higher. Urban winds are therefore influenced by development complexity, urban morphology, voids and porosity, layout configuration, building geometry, and local climatic conditions.

Progression of wind is remarkably enhanced by the unbuilt spaces of the built environment. The open spaces, roads and the building set-backs facilitate the wind traverse through urban layouts. The consistent spacing between the buildings or regular inter-building gaps function as the uninterrupted wind paths to let the wind flow further freely for

ventilation of subsequent structures [7-13]. The gap width affects and controls the velocity of the advancing wind. Narrow gaps constrict and accelerate the wind, while wider gaps facilitate wind penetration and maintain wind flow. Thus, the inter-block spaces exhibit higher gap wind velocities, that can be leveraged to improve ventilation performance and achieve indoor comfort conditions. These spaces also demonstrate potential for harnessing wind energy and provide opportunity for micro-generation [14, 15].

Micro-winds can be accurately simulated via Computational Fluid Dynamics (CFD) modelling for the purpose of architectural planning, wind energy potential and dispersion of air pollution, along with structural load and installation safety [16-18]. The simulation offers wind prediction results that are closer to reality. The research employs CFD simulation method to examine the influence of the morphology-induced gaps on gap wind velocities for evaluating the potential of micro-winds.

The study is conducted through a parametric CFD simulation experiment using simple built-forms representing the typical buildings in Pune city. The concept of harnessing wind can be explored further for implementation within the chosen urban context.



2. Wind Behaviour in the Built Environment

Natural wind is strongly influenced by land-use and land-cover, especially in urban areas where buildings, infrastructure, roads, open spaces, vegetation, water bodies and other structures or temporary installations alter wind flow. Wind is thus influenced by terrain morphology, urban morphology, massing and forms of structures in the urban environment. Wind is disrupted and deflected by buildings, producing varied flow effects as it moves around them and through the gaps between them. Wind accelerating through the building separation gaps results in increased velocity, known as the Venturi effect. Consequently, wind flow patterns vary significantly within urban areas corresponding to the kind of development [19-23].

2.1. Wind in Cities

Wind flow near ground surface is disturbed by trees and structures, causing sudden changes in wind velocity and direction vertically and horizontally, known as wind shear. Urban development increases surface roughness and slows wind flow, while reduced friction at higher altitudes increases wind speed, known as the Height or Speed effect, represented by the vertical wind gradient: the rate of increase in wind speed with height (m/s/km). Wind data of meteorological stations of a location is recorded at 10 m above ground level in open terrain, which is mostly near the airport for cities. Wind speed decreases below 10 m and increases above it, and the corresponding Wind Speed Profile of a location can be determined from the met data average annual wind speed at 10 m using suitable wind speed extrapolation method [23-26] for representing typical urban wind conditions.

Several theories and equations are available for determining the wind speed profile of a place. For general studies, simplified expressions can provide satisfactory results. Average recorded wind speed cannot be used directly without corrections, as urban development significantly affects wind flow. Terrain and height correction factors are applied to estimate wind speed at specific heights based on the prevailing surface roughness.

2.2. Wind and Urban Morphology

A structure influences wind movement through its mass and form, diverting the incident wind upward, downward and sideways. This creates wind shadows, turbulence, eddies, vortices and wakes around the structure [27]. Building form further modifies these effects: taller and wider forms increase deflection and wake zones, concave faces intensify turbulence, while convex faces divert wind sideways. Wind passing through gaps and voids becomes compressed and accelerated, with wind speed and incident angle influencing the intensity of these effects [28, 29]. Wind manoeuvres through building clusters, constricted within gaps driven by the Venturi effect [30]. Linear spaces between buildings act as wind corridors, tunnels or street canyons that further channelize airflow [10]. Wind movement is influenced by

street width, orientation and grid pattern: narrow streets compress and resist wind flow, while wider streets allow faster airflow. Streets parallel to wind direction promote higher wind velocities, whereas perpendicular streets deflect wind over structures, creating low-velocity and turbulent shadow zones. Streets oriented 20-30° to the prevailing wind help maintain wind speed. Breezy, well-oriented street networks combined with dispersed buildings enhance outdoor ventilation [31-33]. Wind can thus be dispersed throughout the urban fabric through wide wind-aligned streets, inter-building passages, loose urban layouts, narrower building faces oriented towards the wind to minimize adverse wind effects, and interconnected open spaces that help direct airflow [13].

2.3. Urban Wind Microclimatic Studies

The urban microclimatic factors studied across macro- to micro-scale built environments include temperature, humidity, wind and radiation, amongst which wind is the only dynamic factor that can be altered suitably through urban morphology and architectural design to some extent [34-36]. Several studies are done to explore wind patterns in cities, campuses and layouts and around the buildings. Urban morphology can effectively contribute in diluting the urban heat island effect using wind paths or corridors and urban canyons. Meso-scale studies are often done to evaluate spatial planning and layout configurations with regard to placement and composition of morphological elements, to facilitate free wind flow and to avoid turbulent conditions [10, 13, 30, 32, 37]. Wind performance of individual buildings and clusters help to optimise building massing, form, orientation and inter-block gaps for improving occupant safety and comfort, reducing wind effects and wakes, and enhancing micro-wind potential for ventilation and energy generation. Favourable and unfavourable effects of wind can be determined and addressed using CFD simulations at architectural design stage.

2.4. CFD Simulation in Architecture

In architectural aerodynamics and wind engineering, under heavy winds, tall buildings and other structures behave as bluff bodies, obstacles whose un-streamlined shape causes wind flow to separate widely from the upwind surface, thus creating a low-pressure wake zone directly behind the object. As a design and assessment tool, these macro- to -micro-climatic wind patterns can be effectively [10, 28, 30, 32, 33, 37-46], accurately and efficiently illustrated to derive the outdoor air flow and speed by using CFD simulation i.e. virtual wind tunnel that has proven to be a convenient and accessible alternative to costly empirical studies on wind, analytical calculations i.e. Analytical Fluid Dynamics (AFD) and wind-tunnel experiments i.e. Experimental Fluid Dynamics (EFD). The purpose of the simulation for building-wind studies determines the appropriate CFD approach or regime to be employed and the turbulence model to be selected within the flow regime [47, 48]. For comparative design evaluation through design iterations and urban layout restructuring, CFD results can be interpreted and generalized

as average responses. The steady Reynolds-Averaged Navier-Stokes (RANS) framework with average wind speed and direction is useful for comparing multiple design derivatives and configurations under the constant atmospheric boundary conditions for deriving wind pattern and morphological assessment [48-55]. The standard k-epsilon ($k-\epsilon$) model is widely adopted for external building aerodynamics and urban wind studies with reasonable prediction of mean wind-speed distribution, flow separation, recirculation and wake behaviour around bluff built forms. Autodesk CFD [56], ANSYS Fluent [57], SimScale [58], RhinoCFD, Flowsquare, ParaView, Altair, OpenFOAM with Swift, Butterfly (Ladybug tool), Eddy3d [59] plugins, etc. can be effectively and efficiently used for urban built environment wind simulation for wind performance evaluation of building layout designs [15, 60].

2.5. Urban Wind Potential

Interaction between wind and architecture is essential for natural ventilation, pollutant dispersion, aerodynamic design, pedestrian comfort and wind energy harvesting. Although high-rise and wind-prone buildings are commonly analysed for structural safety, wind performance evaluation is rarely integrated into the architectural design process, particularly in developing cities like Pune, India. Incorporating CFD simulations as a routine design practice can support wind-responsive architecture through optimized form, proportion, spacing and layout configuration [17, 18, 61]. Voids and porosity are critical elements of urban morphology for effective wind flow and outdoor ventilation. Wind movement around buildings directly influences indoor airflow, as unobstructed inter-block spaces allow wind to reach façades to enter through fenestrations for indoor ventilation. Thus, optimizing voids or gaps between buildings is effective in increasing gap wind velocities to further improve ventilation performance [11]. The research design originates from the CFD simulation of a neighbourhood in Pune and has evolved into a parametric experiment that focuses on investigating the capacity and potential of urban micro-winds. A residential area was selected for simulation as a representative case study depicting the kind of development in Pune city. Urban land is generally constructed with typical, square-rectangular footprint buildings at limited distances from each other as required by the building bye-laws. The case study thus puts forth a real-world scenario for observing the urban wind performance.

The Pune neighbourhood location: 18.5670401N, 73.9113782E [62, 63] is an organic residential development, having progressively constructed contiguous projects with buildings heights ranging from 2-8 storeys and 6-30 m, on 11 hectares (approximate size of average 345 m x 325 m) of squarish land (Figure 1(a)), getting the advantage of roads on four sides and not-so-dense construction on the West. It was simulated at 5 m/s wind profile for front-side westward inlet, the only customization in the steady-state incompressible RANS $k-\epsilon$ turbulence model with all other default settings of

the vanilla set-up, for exploring micro-climatic wind patterns and feasibility of capitalising on wind.

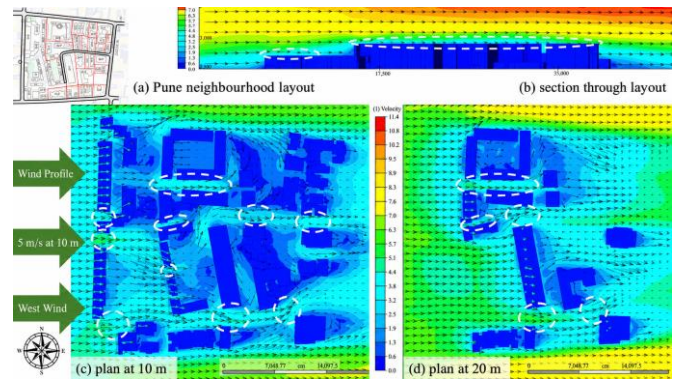


Fig. 1 CFD simulation of Pune neighbourhood layout illustrating micro-wind potential

With respect to the velocity magnitude scale, the results of the simulation illustrated: 0-2.5 m/s low speed or wake zone, 2.5-4.4 m/s moderate or ambient speed zone and 4.4-7 m/s high or potential wind speed zones. The moderate and high velocity spaces around buildings, as marked in plans at 10 m (Figure 1(c)) and 20 m (Figure 1(d)) height, offer good opportunity for ventilation through wall fenestration along the gaps, with wind channelling in between the buildings owing to the funnel effect or venturi effect. Combined with the roof tops of almost all buildings, as marked in the section through the cluster of buildings (Figure 1(b)), the identified points in the layout can be considered as high-potential micro-wind energy zones or wind resource hot-spots, as they are very likely to meet the cut-in speed of micro-wind turbines for number of times in a day.

Thus, beyond considerations of wind loads, air stagnation, pollution and safety, architectural parameters such as built form, building adjacency, inter-block spacing and layout configuration needs to be optimized to assess urban wind potential for natural ventilation and micro-scale wind energy generation.

Urban micro-wind patterns create localized pressure zones and turbulent airflow that may cause discomfort for occupants, but conversely can also enhance ventilation around tall buildings and support wind energy harvesting. Appropriately designed and strategically located small Wind Energy Conversion Systems (WECS) can be the functional energy assets for buildings that utilize the accelerated wind flows [64].

2.6. Urban Wind Micro-Generation Systems

A wind-mill is the Wind Energy Conversion System (WECS) that includes a turbine transforming an amount of kinetic energy of wind into electrical energy making it completely environment-friendly and the best source of clean and green electric energy. Wind-mills are classified by standard power generation capacities (power rating) relevant

to their sizes (rotor diameters) [65, 66]. Big-diameter wind turbines (small to large scale), ranging from standalone units to wind farms, are widely used for energy generation across hills, fields, suburban areas and open terrains. Their large size impacts surroundings through visual intrusion, noise, risks to birds and bats.

Small-diameter wind turbines (micro and mini scale) are more suitable for urban environments, addressing many limitations of larger systems (Table 1). They can generate electricity at relatively low urban wind speeds, are easy to manufacture and install locally, require minimal maintenance, and can cost less than photovoltaic systems of similar capacity. These turbines can support battery charging in remote areas and partially or fully offset energy consumption.

Wind turbines are classified based on the functioning of WECS: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) (Table 2), based on the orientation of the rotor axis (rotating blade-hub assembly) and the aerodynamic forces generating energy from wind [67].

High wind turbulence, wind fluctuations and strong directional variability can cause significant operational challenges for HAWTs. In contrast, VAWTs can operate more effectively under low-speed and turbulent wind conditions commonly found in urban environments.

Hence, VAWTs are considered more suitable and are increasingly being explored as a promising option to harness local urban winds [68-81].

2.7. Intent and Goal of Research Paper

The evolving morphology of cities and the emergence of new urban nodes directly influence natural wind flow and micro-climatic wind patterns. Urban environments comprise both organized and unorganized developments, resulting in significant spatial variation in wind behaviour.

Pune, India, represents an organically growing city with blend of unstructured contiguous development across, with planned development in dispersed urban pockets.

Independent projects and their designs have added to the heterogeneity to the bottom-up city of Pune. Lack of inclusion of wind as a parametric design element and almost no attention to the impact of built-mass and its orientation on surrounding environment has led to wind blockages and wake zones.

Use of CFD as a part of iterative design process is a limitation and hence a rare practice in developing countries like India, compared to simulation studies used in technologically advanced nations [33, 49].

Hence, for understanding of interaction of wind and buildings, architectural designs rely only on the design strategies and rules of thumb stated in past for well-spaced,

low-rise buildings as a part of not-so-dense developments [19-22, 24, 82], which are now not relevant to the dense high-rise development in the city. Wind passage through the urban voids and built-form separations is essential to moderate the urban environment, to maximize wind potential for natural ventilation and energy generation.

The paper focuses on optimising inter-block spaces by evaluating their wind performance that helps in developing planning guidelines for wind-responsive urban layout composition and configuration.

Using average wind conditions of Pune, this study investigates the influence of built form and inter-building spacing on traversing wind velocities through an experiment design. Different building adjacency combinations, orientations and gap configurations are simulated using CFD to evaluate wind flow through inter-block gaps and along building surfaces at different heights. Variations in wind velocity relative to incident wind are analysed to understand the influence of built form parameters on gap wind velocity.

Locations exhibiting favourable wind speeds are identified as potential micro-generation hotspots. The study highlights the importance of CFD-based assessment of urban building clusters for evaluating micro-wind ventilation as well as energy potential and identifying urban wind energy opportunities [42, 47, 49], as the micro-generation technology installations are not conventional yet in urban built environment. However, the findings are limited to the CFD experimental conditions and the average wind data of Pune.

3. Materials and Methods

Since the implementation of new Development Control Regulations in 2020, Pune has been undergoing significant urban transformation, redefining its skyline through an increased permissible building heights over 100 m and accelerated redevelopment [83-86]. The resulting urban morphology influences micro-climatic wind patterns by altering wind direction and velocity. Assessing wind movement through buildings and urban clusters is therefore important for evaluating its potential for natural ventilation and micro-scale wind energy generation.

The interaction of wind with built form can be systematically examined through parametric design models simulated using CFD to evaluate the overall aerodynamic performance of urban morphology. Properly configured CFD models provide accurate, efficient and cost-effective results that closely represent real conditions while offering advantages over conventional wind tunnel testing [87-89].

Through appropriate built-form design and configuration, architecture can integrate wind-responsive strategies to enhance natural ventilation and support local wind energy generation within high-rise urban clusters [37, 39, 51].

Table 1. Classification of windmills as per sizes

Size Class (Purpose)	Installation	Location	Rotor Diameter	Standard Power Rating
Micro (Non-commercial)	on buildings	Rural / Urban	0.5 - 3 m	< 1 kW
Mini (Non-commercial)	on land, farm	Rural / Urban	3 - 10 m	1 - 20 kW
Small (Commercial)	on open land, fields or hills, coastal zones	Country-side	10 - 20 m	20 - 100 kW
Medium (Commercial)		Country-side	20 - 50 m	100 kW - 1 MW
Large (Commercial)		Country-side	> 50 m	> 1 MW

Table 2. Types of wind-mills based on turbine axis and wind direction

Parameter	Horizontal Axis Wind Turbine (HAWT)	Vertical Axis Wind Turbine (VAWT)
Rotor axis	horizontal, parallel to wind	vertical, perpendicular to wind
Wind orientation	requires yaw mechanism	accepts multi-directional wind
Wind dependency	direction dependent	direction independent
Operating wind range	performs at 3-25 m/s, efficient at 10-15 m/s	performs at 2-25 m/s, efficient at 2-5 m/s
Urban wind suitability	steady open-terrain high winds	low and turbulent urban winds
Blade geometry	twisted blades required	constant blade profile
Design & fabrication	complex	simple and easy to fabricate
Installation	mounted on tower	mounted on pedestal or base
Cost & maintenance	higher cost and maintenance	lower cost and maintenance
Impact on birds	higher obstruction risk	lower obstruction risk
Wake recovery length	15-20 × rotor diameter	5-7 × rotor diameter
Noise & vibration	higher noise and vibration	lower noise and vibration
Scale of application	small to large scale, stand-alone to wind farms	micro- to small-scale, stand-alone to multiple
Popularity	conventional, widely established technology	emerging technology for micro-generation

The built environment is recreated by importing Three-Dimensional (3D) “AutoCAD” [90] or “Revit” [91] models into “Autodesk CFD -Ultimate” [56]. The CFD application employs a steady-state, incompressible RANS [51, 52] approach with the standard $k-\epsilon$ turbulence model to simulate steady yet turbulent urban wind behaviour using time-averaged wind data for the Atmospheric Boundary Layer (ABL) wind profile to the inlet. The model provides a practical balance between computational efficiency, numerical stability and accuracy for comparative urban wind assessments.

All simulation cases are solved using identical solver settings, boundary conditions, mesh parameters and turbulence models to maintain consistency across the dataset. Following solver tests, simulation outputs are obtained as velocity contour plots and level maps to analyse wind velocity variations, evaluate natural ventilation potential, and identify suitable locations for micro-wind energy generation.

Detailed turbulence characterization and experimental validation are identified as directions for future research. The present study using the profile-driven custom RANS setup with hydrostatic pressure and heat transfer enabled, allows the simulation to account for vertical pressure variation and thermal effects that may influence airflow behaviour within

built environments, representing the real-world outdoor conditions. The objective of the study is to evaluate wind-flow behaviour around built forms and comparative response of multiple spacing scenarios under representative ambient wind conditions for Pune, for interpretations of design- and spacing-dependent wind acceleration and channelling. The study does not intend to resolve turbulent eddies or transient gusts, but aims to derive generalized insights on the influence of built form and spacing on mean wind-flow behaviour and ventilation performance.

3.1. Research Design

The research is conducted through a CFD simulation modelling experiment in which pairs of blocks of simple built forms and varying orientations (designs), with increasing distances between them (spacing), are tested to determine their effect on the speed of wind flowing through the gaps. The urban environment conditions are simulated using average wind data of Pune to evaluate wind performance and micro-wind potential of all design cases (Figure 2).

3.2. Theory and Calculations

The case-study city of Pune, India experiences a predominant wind direction West for approximately 70% of the year and an annual average wind speed of 5 m/s, based on

observations over the past ten years [92-95]. The simulation analysis is therefore conducted using a wind environment

defined by these parameters, with wind speed increasing with height as described by Wind Profile of Pune.

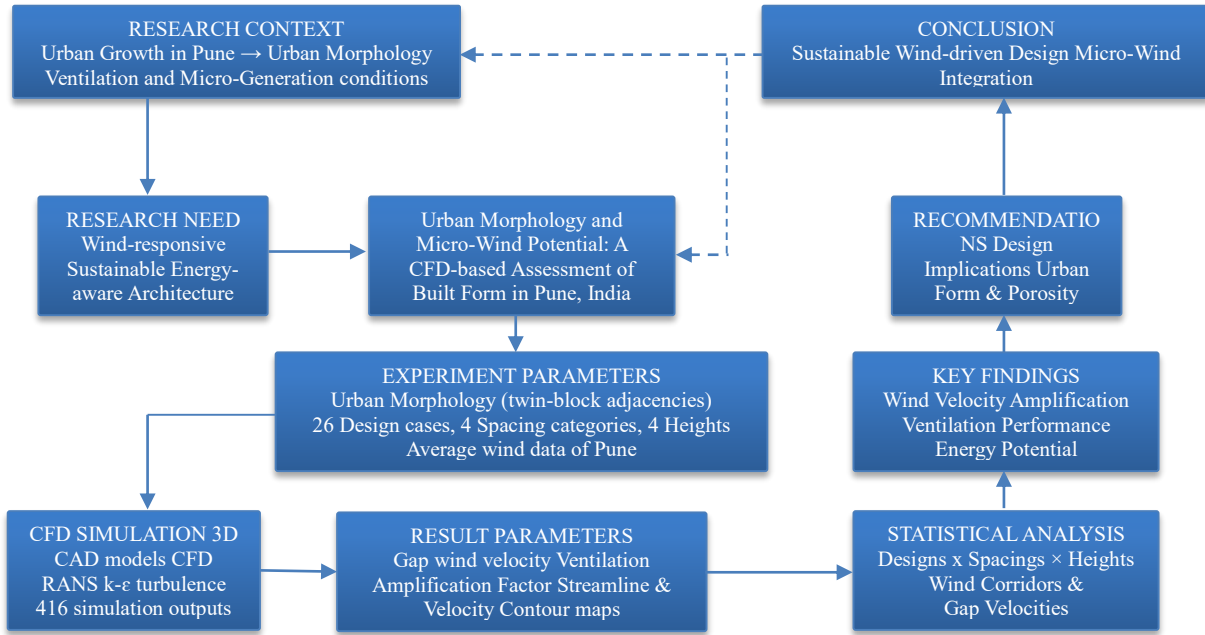


Fig. 2 Research framework for investigating urban wind potential via CFD simulation

3.2.1. Wind Speed Profile of Pune

Basic Exponential Law and Logarithmic Law expressions exhibit good coherence and accuracy for wind speed extrapolation of average wind data to derive Wind Speed Profile [96-104].

Exponential Law or Power Law uses Equation 1:

$$v_2 = v_1 \times \left(\frac{Z_2}{Z_1}\right)^\alpha \quad (1)$$

Where v_2 = desired velocity at desired height Z_2
 Z_2 = desired upper height
 v_1 = reference velocity at height Z_1 at 10m, data from meteorological station
 Z_1 = reference lower height at 10m
 α = Friction coefficient or Hellman Exponent or Wind Shear coefficient

In the context of urban built environment or “City areas with high rise buildings”, Friction Coefficient 0.40 is applicable.

The simplified Logarithmic Wind Profile Law Equation 2 is:

$$v_2 = v_1 \times \frac{\ln(h_2/z_0)}{\ln(h_1/z_0)} \quad (2)$$

Where v_2 = desired velocity at desired height h_2
 h_2 = desired upper height
 v_1 = reference velocity at height h_1 at 10m, data from meteorological station
 h_1 = reference lower height at 10m

z_0 = Roughness coefficient length in meters

For urban built environment or “Large cities dotted with high rise buildings”, Roughness Coefficient Class 3.5 and Length 0.8 is applicable.

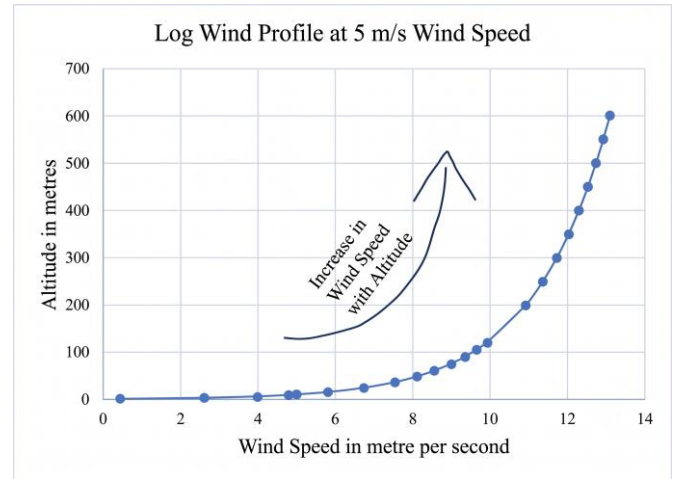


Fig. 3 Log Wind profile of Pune at 5 m/s annual average wind speed

Wind speed profiles can be derived using either method depending on the study context. Power Law Wind Profile is more suitable for locations with fewer windbreaks, whereas the Logarithmic Wind Profile is more appropriate for inland cities with high-density urban development, such as Pune, considering its projected urban growth in the near future. Accordingly, the Logarithmic wind profile of Pune is adopted

as the wind speed input for the urban wind environment in the simulation model (Figure 3) [65].

3.2.2. Wind Power Calculations

When wind moves through the windmill blades, an amount of its kinetic energy is converted into the rotational energy of the rotor. This rotational energy, transmitted as mechanical energy through the gearbox, is converted into electrical energy by the turbine generator, thereby producing wind-generated electrical energy or wind energy. Thus, wind energy is the kinetic energy possessed by moving air and represents its capacity to perform work. Wind power is the rate at which this energy is available to perform work, transferred or harnessed per unit time. Power is expressed in Watts (W) or Kilowatts (kW), while electrical energy consumption is measured in Kilowatt-Hours (kWh), the standard unit used for consumer billing [64, 65, 67]. Available Wind Power in Watts (W) is given by Equation 3:

$$P_w = \frac{1}{2} \times \rho \times S \times V^3 \quad (3)$$

where ρ = air density for the location ($\rho = 1.225 \text{ kg/m}^3$ standard sea-level air density)

S = swept area of wind-mill in m^2 cutting to wind-flow

V = air velocity or reference wind speed in m/s

Longer blades cause more torque and more energy is delivered for the same force in wind.

Swept area is the section of air that encloses the turbine in its movement. Based on the type of turbine, Swept area is given as follows. Area of circle for HAWT, Swept area (where R = rotor radius) is given by Equation 4:

$$S = \pi \times R^2 \quad (4)$$

Area of rectangle for VAWT, Swept area (where R = rotor radius, H = blade height) by Equation 5:

$$S = 2 \times R \times H \quad (5)$$

Thus, Wind Power is dependent on air density, intercepting swept area or wind-mill rotor and wind speed. Wind speed is the determining factor for wind power and wind energy. The actual power generated is significantly lower than the available wind power.

The ratio of actual power output to the available wind power is known as the Power Coefficient. According to the Betz's law, 1926 by the German Physicist Albert Betz, there exists a theoretical limit to the power efficiency of a wind turbine. Lanchester-Betz limit states that no wind turbine can capture more than $16/27$ (59.3%) of the kinetic energy available in wind [71].

The Power Coefficient (C_p) for HAWT is 50% ranging from 40-60%, whereas C_p for VAWT is 20% ranging from 10-30% based on the design, location and installation height of wind-mill [105-110]. In short, at micro-scale, HAWT may

offer upto two-and-a-half to three times higher energy potential than VAWT, considering representative and achievable C_p values, with a conservative upper difference of approximately three times for turbines with identical swept area and when exposed to the same site conditions, meaning approximately three VAWTs are required to match the output of one HAWT.

3.2.3. Ventilation Potential of Local Wind Speed

In residential buildings in Pune, a porosity ratio of about 1.5 is commonly observed between external windows and internal door openings, resulting primarily in indirect cross ventilation. Ventilation performance can be evaluated using the coefficient of ventilation effectiveness.

For direct cross ventilation with a porosity ratio of 1.5, the maximum ventilation effectiveness (K) is 0.70 for wind perpendicular to the building openings (incident angle, $\theta = 0^\circ$), 0.35 for oblique wind ($\theta = 45^\circ$), and 0.15 for wind parallel to the openings ($\theta = 90^\circ$) [24, 111]. Due to indirect cross ventilation involving internal partitions and doors, the effectiveness reduces to approximately 30% lower than these values, resulting in effectiveness values of 0.50, 0.25, and 0.10 respectively [28, 30, 41, 42, 88, 112, 113]. Open house layouts are suitable for improving ventilation effectiveness.

Indoor Air Velocity (IAV) for a porosity ratio of 1.5 under indirect cross-ventilation conditions is estimated from the Outdoor Wind Velocity (OWV) using the corresponding ventilation effectiveness values and associated comfort levels (Table 3).

Comfort levels, expressed as perceived levels of comfort by occupants, are determined based on indoor ventilation requirements for warm climatic conditions of cities, where IAV $< 0.5 \text{ m/s}$ is considered low as $0.5\text{-}1 \text{ m/s}$ is minimum acceptable air movement, $1\text{-}1.5 \text{ m/s}$ is comfortable, $1.5\text{-}2.5 \text{ m/s}$ is desirable and provides enhanced cooling in warm conditions, $2.5\text{-}3.5 \text{ m/s}$ is pleasant in very warm environments or strongly ventilated, and $> 3.5 \text{ m/s}$ leads to excessive draft sensation and occupant discomfort [114-117].

For perpendicular wind incidence, outdoor wind speeds above 2 m/s can provide comfortable indoor conditions. For oblique incidence, speeds above 4 m/s are required, while for wind parallel to openings, speeds above 10 m/s are needed to achieve indoor comfort condition.

3.2.4. Energy Potential of Local Wind Speed

Pune is at a distance of approximately 140-170 km away from the nearest sea coast of the Arabian Sea and at altitude 560m above sea-level. Density of air of Pune is approximately 1.15 kg/m^3 under average conditions [118]. Annual average wind speed over a last 10-year period for Pune has been $4\text{-}6 \text{ m/s}$ i.e. mean wind speed 5 m/s and predominant wind direction has been West.

HAWT is suitable at locations receiving >5 m/s wind speed, cut-in speed at 3 m/s for micro-turbines. VAWT is more appropriate at points receiving low wind speed <10 m/s, cut-in speed at 2 m/s [81]. Hence, selection of type of wind-mill will be based on availability of necessary wind-speed for feasibility of power generation.

While looking at micro-generation wind-mill with small rotor diameter and swept area say 1 sqm (Equation 4, Equation 5), HAWT rotor radius will be 0.56 m with diameter 1.12 m size, while VAWT rotor radius will be 0.35 m with 0.7 m width and 1.4 m height. While assuming 5 m/s wind speed (V) for estimating available Wind Power (Equation 3), P_w at a Pune location ($\rho = 1.15 \text{ kg/m}^3$) for a wind-mill with swept area (S) 1 sqm is 72 Watt.

Table 3. Estimated IAV for OWV with indirect cross-ventilation and 1.5 porosity ratio

OWV (m/s)	Wind normal to Openings $\theta = 0^\circ$			Wind oblique to Openings $\theta = 45^\circ$			Wind parallel to Openings $\theta = 90^\circ$		
	K	IAV (m/s)	Perceived level	K	IAV (m/s)	Perceived level	K	IAV (m/s)	Perceived level
1.25	0.5	0.63	minimum	0.25	0.31	low	0.1	0.13	low
2.5	0.5	1.25	comfortable	0.25	0.63	minimum	0.1	0.25	low
5	0.5	2.5	pleasant	0.25	1.25	comfortable	0.1	0.5	minimum
7.5	0.5	3.75	excessive	0.25	1.88	desirable	0.1	0.75	minimum
10	0.5	5	excessive	0.25	2.5	pleasant	0.1	1	comfortable
15	0.5	7.5	excessive	0.25	3.75	excessive	0.1	1.5	desirable
20	0.5	10	excessive	0.25	5	excessive	0.1	2	desirable

3.4. Twin-Adjacency Parametric Experiment

Building blocks of simple geometry with a height of 100 m, the maximum permissible height in Pune, are considered for simulation testing, as they represent the basic building forms prevalent in urban context of Pune (Figure 4).

Block A1, A2: 30 m width $\times$ 30 m depth $\times$ 100 m height; A2: 45° orientation

Block D: 40 m diameter $\times$ 100 m height

Block B1, B2, B3: 60 m width $\times$ 30 m depth $\times$ 100 m height; B2: 90° and B3: 45° orientation

Block C1, C2, C3: 90 m width $\times$ 30 m depth $\times$ 100 m height; C2: 90° and C3: 45° orientation

Blocks are grouped into clusters as per sizes: (A1, A2, D), (B1, B2, B3) and (C1, C2, C3).

The twin-adjacency configurations are generated through a systematic and strategic examination of permutations and combinations of blocks within each cluster. All relevant block pairings are considered based on their geometric characteristics, relative orientation and potential influence on inter-block gap wind speed.

Configurations exhibiting distinct adjacency relationships and gap-wind behaviour are selected as representative cases, resulting into 6 configurations in cluster (A1, A2, D), 10 in cluster (B1, B2, B3) and 10 in cluster (C1, C2, C3), with a

3.3. Research Process

Urban morphology is represented using building blocks with square, rectangular and circular footprints to reflect the commonly observed built forms in Pune. Urban clusters comprising different combinations of these blocks arranged adjacent to one another (designs) at varying distances (spacing) are simulated in CFD and analysed to understand their impact on incident wind flow and the variation in wind velocity passing through the intermediate gaps. For illustrating the influence of urban morphology on wind velocity beyond the parametric block clusters, a real-world urban cluster is simulated to determine variations in wind velocity within the cluster and the implications for ventilation and energy potential.

total of 26 twin-adjacency configurations or Designs (Figure 4). All possible two-block combinations (twin-adjacencies) within each cluster are tested at various inter-block distances.

Number of Twin-Adjacency combinations in cluster (A1, A2, D): 6 Designs

Number of Twin-Adjacency combinations in cluster (B1, B2, B3): 10 Designs

Number of Twin-Adjacency combinations in cluster (C1, C2, C3): 10 Designs

Twin-Adjacency gaps within blocks: 7.5 m, 15 m, 30 m, 60 m: four Spacing values

Thus, 26 designs $\times$ 4 spacing categories yield 104 twin-adjacency combinations for simulation. Results are extracted at four heights: 10 m, 30 m, 60 m, and 90 m.

Hence, 104 scenarios $\times$ 4 height levels produce 416 observations of maximum gap velocity.

3.5. CFD Simulation of Twin-Adjacencies

CFD tests are performed using 3D-CAD models comprising 26 twin-adjacency configurations within Pune's urban built environment, where buildings are modelled as solid, concrete surfaces. For each simulation, an appropriately sized air domain is created using standard domain extents consisting of an upstream distance equal to five times the building height, lateral clearances of five times the building

height on either side, a downstream distance of fifteen times the building height, and a top clearance of five times the building height [40, 45, 47, 48]. Boundary conditions are assigned such that the inlet is located on the West (front) face of the domain, with incrementally varying steady-state velocity applied using the normal method, spatially linear variation along the z-axis and a piecewise linear function derived using the Logarithmic wind profile at a reference speed of 5 m/s. The outlet is defined on the rear face of the domain with zero Pascal pressure (0 Pa) under steady-state conditions. Default wall functions available in the CFD solver are employed to represent near-wall flow behaviour uniformly across all cases. Based on the precision of the CAD models, mesh settings are configured with auto-refinement length, default mesh generation with automatic size adjustment, and automatic surface and gap refinement. Block combinations are

solved group-wise within each of the three twin-adjacency groups for all spacing categories, using default settings for incompressible flow, hydrostatic pressure, and heat transfer with the k- ϵ turbulence model for 100 steady-state iterations under isothermal conditions. Convergence is assumed when no significant changes are observed in flow patterns or wake extent with additional iterations [54, 55].

The CFD simulation comprises 26 Designs evaluated across four Spacing values and analysed at four Heights, yielding a total of 416 readings of maximum gap wind velocities. The reference input wind speed of 5 m/s is applied at 10 m height, while higher elevations experience increased wind speeds according to the Wind Speed Profile. Levels below 10 m height are considered a limitation of the study due to increased complexities associated with surface friction effects (Figure 5).

Twin-Adjacency Group	Twin-Adjacency between Blocks			Block Height (m) BH	Twin-Adjacency Design Code	Twin-Adjacency between Blocks		Twin-Adjacency DESIGN	No. of DESIGNS	SPACING in-between two Blocks (m)	Input Wind Speed (m/s) at 10 m height	Section HEIGHT (m) for Reading
A1, A2, D				100	TA1	A1	A1		6	7.5, 15, 30, 60	5.0	10, 30, 60, 90
					TA2	A1	A2					
					TA3	A1	D					
					TA4	A2	A2					
					TA5	A2	D					
					TA6	D	D					
B1, B2, B3				100	TA7	B1	B1		10	7.5, 15, 30, 60	5.0	10, 30, 60, 90
					TA8	B1	B2					
					TA9	B1	B3					
					TA10	B1	B3					
					TA11	B2	B2					
					TA12	B2	B3					
					TA13	B2	B3					
					TA14	B3	B3					
					TA15	B3	B3					
					TA16	B3	B3					
C1, C2, C3				100	TA17	C1	C1		10	7.5, 15, 30, 60	5.0	10, 30, 60, 90
					TA18	C1	C2					
					TA19	C1	C3					
					TA20	C1	C3					
					TA21	C2	C2					
					TA22	C2	C3					
					TA23	C2	C3					
					TA24	C3	C3					
					TA25	C3	C3					
					TA26	C3	C3					
									26	104		416

Fig. 4 Research experiment design for CFD test of twin-adjacency combinations

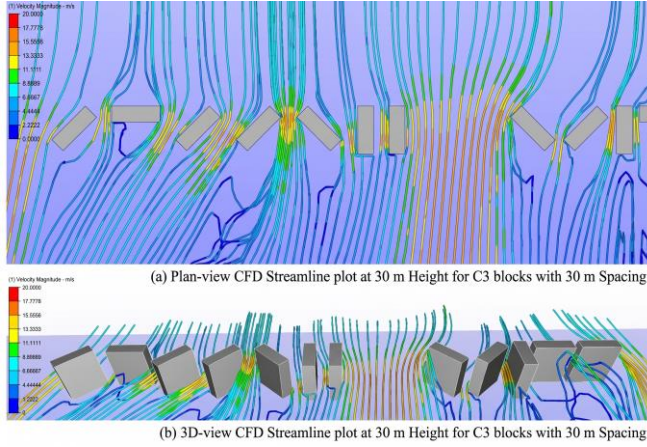


Fig. 5 CFD streamline plot of C3 blocks at 30 m spacing

3.6. Assessment of Ventilation and Energy Potential

The CFD results are compared across 26 designs and 4 spacings at four heights. The increment or decrement in the inter-block (gap) wind velocity (V_{gap}) is quantified using Ventilation Amplification Factor (VAF), a dimensionless parameter independent of the magnitude of the incoming wind velocity. VAF is defined as the ratio of V_{gap} to incident wind velocity (V_i) representing relative velocity amplification across cases, and is calculated using Equation 6:

$$VAF = V_{\text{gap}} / V_i \quad (6)$$

3.6.1. Assessment of Ventilation Potential: (Table 4)

Indoor Air Velocity (IAV) is calculated using a ventilation effectiveness coefficient (K) of 0.1 for wind parallel to the openings with porosity ratio 1.5 and indirect shear-induced cross ventilation, together with the corresponding gap wind velocity (V_{gap}) values, to assess indoor comfort levels [88, 112, 113].

3.6.2. Assessment of Energy Potential: (Table 4)

For available Wind Power (P_w) at a location in Pune, air density ($\rho = 1.15 \text{ kg/m}^3$), and a wind turbine with a swept area ($S = 1 \text{ sqm}$), the power is evaluated at the gap wind velocity (V_{gap}). The power output (P) for both HAWT and VAWT is

estimated (Equation 3), with typical power coefficients (C_p) of 50% and 20% respectively using Equation 7 (for HAWT, average $C_p = 0.5$ and for VAWT, $C_p = 0.2$):

$$P = C_p \times P_w \quad (7)$$

Amplified gap wind velocities enhance both natural ventilation potential and wind energy generation feasibility. Gap velocities of 5 m/s and above can support ventilation through fenestrations in inter-block spaces when wind flows parallel to openings. The same velocity range also indicates potential for power generation using micro-turbines, which may be deployed in multiple units depending on site conditions.

4. Results and Discussion

Twin-adjacency Designs with varying spacing or gaps are simulated within the urban wind environment recreated through CFD modelling. The incremental Wind Speed Profile of Pune, derived from the city's average Westward wind speed of 5 m/s, is used as the input condition.

Results for each case are analysed using wind velocity contour plots in plan at significant heights and sectional views of the domain. Wind flow patterns around the buildings are interpreted through velocity vector arrows, with particular focus on wind velocities within the inter-block gaps between adjacent buildings. Maximum gap wind velocities are assessed using VAF to evaluate variations in wind velocity caused by different adjacent block design combinations and spacing configurations, and to further examine their potential for indoor ventilation and wind energy generation.

4.1. Observation Method

The colour scale of the velocity contour plots is used to identify gap wind velocities across twin-adjacency designs and spacing configurations at different heights. Referring to the velocity magnitude scale in CFD result set, represented through nine velocity contour levels, the corresponding colours are correlated with maximum gap wind velocity values and VAF ranges (Figure 6).

Table 4. Assessment of ventilation and energy potential at mean wind speed of Pune

V_i (m/s)	VAF (V_{gap}/V_i)	V_{gap} (m/s)	IAV (m/s) K = 0.1	Indoor Comfort level	HAWT Feasibility (cut-in speed)	P_{HAWT} (W) $C_p = 50\%$	VAWT Feasibility (cut-in speed)	P_{VAWT} (W) $C_p = 20\%$
5	0.25	1.25	0.13	low	No	0.6	No	0.2
5	0.5	2.5	0.25	low	No	4.5	Yes	1.8
5	1	5	0.5	minimum	Yes	35.9	Yes	14.4
5	1.5	7.5	0.75	minimum	Yes	121.3	Yes	48.5
5	2	10	1	comfortable	Yes	287.5	Yes	115.0
5	2.5	12.5	1.25	comfortable	Yes	561.5	Yes	224.6
5	3	15	1.5	desirable	Yes	970.3	Yes	388.1
5	3.5	17.5	1.75	desirable	Yes	1540.8	Yes	616.3
5	4	20	2	desirable	Yes	2300.0	Yes	920.0

Velocity Contour color		Observed Wind Velocity (m/s)	VAF for input wind velocity 5 m/s
Dark blue		1.25	0.25
Blue		2.5	0.5
Light blue		5	1
Cyan		7.5	1.5
Green		10	2
Yellow		12.5	2.5
Orange		15	3
Dark Orange		17.5	3.5
Red		20	4

Fig. 6 Correlation of CFD velocity contour levels and VAF

4.2. Analysis Method

Gap wind velocity readings observed across 26 twin-adjacency designs, four spacing values, and four specific heights for 100 m tall buildings are compiled in tabular form.

VAF values are calculated (Equation 6) and correlated with the CFD plot velocity colour references to facilitate interpretation of the results (Figure 6, Figure 7).

TA4		1.5	1.5	1.5	2.0	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.0	2.0	2.5	2.5	31.0
TA2		1.5	1.5	2.0	2.0	1.5	2.0	2.0	2.5	1.5	2.0	2.0	2.5	2.0	2.0	2.0	2.5	31.5
TA5		1.5	1.5	2.0	2.0	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5	31.5
TA6		1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5	32.0
TA3		1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5	33.0
TA1		1.5	2.0	2.0	2.0	1.5	2.5	2.5	2.5	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5	33.5
TA21		1.0	1.0	1.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	2.5	2.5	3.0	3.0	35.0
TA16		2.0	2.0	2.0	2.5	2.5	2.0	2.0	2.5	2.5	2.0	2.0	2.5	2.5	2.0	2.5	2.5	36.0
TA13		2.0	2.0	2.0	2.5	2.0	2.5	2.5	2.5	2.5	2.5	2.0	2.5	2.5	2.5	2.5	2.5	37.5
TA12		2.5	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.5	2.5	2.5	2.5	2.5	39.0
TA23		2.0	2.0	2.0	2.5	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	2.5	2.5	3.0	39.5
TA10		2.5	2.5	2.0	2.5	2.5	2.5	2.5	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.0	40.5
TA15		2.0	2.0	2.5	2.5	2.5	2.5	2.5	3.0	2.5	2.5	2.5	3.0	2.5	2.5	2.5	3.0	40.5
TA26		2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.0	41.0
TA7		2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5	3.0	2.5	2.5	2.5	2.5	41.5
TA9		2.5	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.5	2.5	2.5	2.5	2.5	42.0
TA8		2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	42.5
TA11		2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5	3.0	2.5	2.5	2.5	2.5	42.5
TA14		3.0	2.5	2.5	2.5	3.0	2.5	2.5	3.0	2.5	2.5	2.5	3.0	2.5	2.5	2.5	3.0	42.5
TA17		2.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.0	2.5	2.5	2.5	2.5	42.5
TA25		2.5	2.5	2.0	2.5	3.0	3.0	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	45.0
TA18		2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.0	3.0	3.0	2.5	3.0	3.0	3.0	45.5
TA19		2.5	2.5	2.5	2.5	3.0	3.0	3.5	3.0	3.0	3.5	3.5	3.5	2.5	2.5	2.5	3.0	46.5
TA22		3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	3.0	46.5
TA20		2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.0	3.0	3.0	3.5	3.0	3.0	3.0	3.0	48.5
TA24		3.0	3.0	3.0	3.0	3.5	3.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	3.0	3.0	48.5
SUM		55.5	55.5	58.0	62.5	64.0	65.5	66.5	71.5	66.5	66.5	66.5	74.0	64.0	63.0	65.0	71.0	

Fig. 7 CFD-derived VAF results for 26 designs at four spacings and four heights

4.3. Analysis

Statistical analysis is conducted on 416 CFD-derived VAF readings across 26 twin-adjacency designs, four spacing conditions and four height levels. Pearson's Chi-Square test using IBM SPSS Statistics for Windows, Version 26.0 [119] is employed to evaluate the association between independent variables: Design and Spacing and dependent variable: VAF, and to determine the statistical significance (p) of their relationship.

Test-1: Chi-Square Test of Association between Twin-Adjacency Design and VAF

Test reveals a statistically significant association between Twin-Adjacency Design and VAF, with an asymptotic significance (2-sided) value of $p < 0.001$. The likelihood ratio test further supports the significant association between twin-adjacency configurations and VAF distribution.

Test-2: Chi-Square Test of Association between Block Spacing on VAF

A statistically significant association is observed between Block Spacing and VAF, with both the asymptotic significance and likelihood ratio indicating $p < 0.001$. The linear-by-linear association test further indicates a significant trend in VAF variation with changing block spacing ($p = 0.001$).

Test-3: Chi-Square test of Combined Association between Twin-Adjacency Design and Spacing with VAF
The Chi-square analysis indicates a significant combined association between Twin-Adjacency Design, Block Spacing and VAF. Variations in adjacency configuration and spacing influence VAF distribution and wind amplification behaviour across the tested cases.

4.4. Findings

The velocity vector plots of The CFD simulation results for 26 pre-determined designs, evaluated at four spacing values and four heights using Pune's annual average wind conditions (5 m/s from the West), along with Chi-square cross-tabulation analysis of variable associations, suggest the following:

4.4.1. Association between Twin-Adjacency Design and VAF: (Table 4)

- Wind accelerates while passing through inter-building gaps due to the "Venturi Effect"; this amplification further increases when deeper funnel-shaped gaps are formed by vertical-oblique and oblique-oblique building faces on the windward side (Figure 8)
- A1-A2-D group of square-circular twin-block combinations exhibits the lowest gap wind velocities, with VAF values predominantly between 1.5 and 2, and rarely exceeding 2.5

- C1-C2-C3 twin-adjacency group comprising blocks with a 1:3 width-to-depth ratio produces the highest gap wind velocities, with VAF values ranging from 1 to 3.5
- B1-B2-B3 twin-adjacency group comprising blocks with a 1:2 width-to-depth ratio exhibits moderate gap wind velocities, with VAF values ranging between 2 and 3
- The lowest VAF is observed for TA4, while the highest VAF for T24 design (Figure 9(a))

4.4.2. Association between Block Spacing on VAF: (Figure 9(b))

- At all block spacings, gap wind velocities also increase with building height due to the "Height Effect", and hence higher VAF values are observed at higher elevations
- 7.5 m produces the lowest gap wind velocities, with VAF values ranging from 1 to 3
- 30 m spacing produces higher gap wind velocities, with VAF values ranging from 2 to 3

4.4.3. Combined Association between Twin-Adjacency Design and Spacing with VAF: (Figure 10)

- All VAF values range from 1 to 3.5 across all heights; dimensionless VAF values remain unchanged with variations in local wind speed.
- VAF 2.5 shows the highest frequency 42.8% across all 416 readings; VAF 1 shows the lowest frequency, followed by VAF 3.5 and 1.5
- VAF values of 2, 2.5, and 3 occur in 92.3% of 416 cases, higher than other values
- For Designs TA7, TA8, T10-T16, TA22, T23, TA25, TA26, all VAF values lie within 2-2.5-3
- At 60 m Spacing, all VAF values lie within 2-2.5-3; while at 30 m Spacing 92.3% of cases

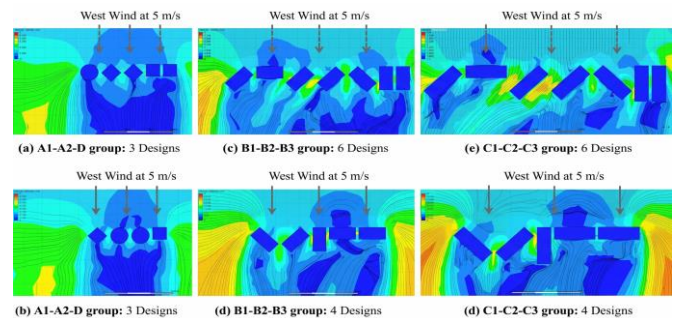


Fig. 8 Plan-view CFD simulation plots for 26 designs at 7.5 spacing and 10 m height

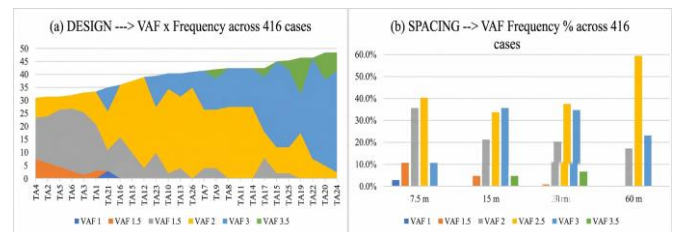


Fig. 9 Frequency of VAF (a) Across 26 designs, and (b) Across four spacing categories.

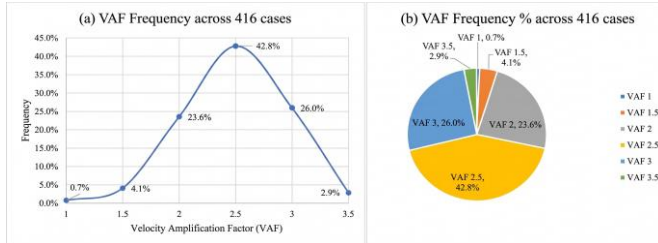


Fig. 10 VAF values of 416 cases (a) Frequency Graph, and (b) Frequency Percentage.

4.4.4. Ventilation Potential of Gap Wind Velocities:

Findings are limited to CFD results based on Pune's average wind velocity ($V_i = 5.0$ m/s) and assumed inter-block façade opening conditions for indirect cross- and shear-induced ventilation ($K = 0.1$); results may vary under different wind and ventilation conditions.

- Range of V_{gap} and VAF values are observed within a gap, contributing to wind flow
- Gap wind velocities used as observations represent the maximum values within the inter-block gap, suitable for estimating ventilation potential; along the block façade within the gap, VAF values are typically 0.25 within 0-0.4 m, 0.5 between 0.4-0.8 m, and 1.0 beyond 0.8 m from the façade across all CFD results
- Lowest VAF (1), corresponding to $V_{gap}=5.0$ m/s, results in minimum IAV; hence, all 104 scenarios ensure at least minimum ventilation through openings along the gap, at all heights above 10 m
- Highest VAF (3.5), for $V_{gap}=17.5$ m/s, produces desirable ventilation conditions with IAV of approximately 1.75 m/s, observed mainly in the C1-C2-C3 design group, where twin-adjacency configurations form deeper funnelling for incident wind
- Frequently occurring VAF values (2, 2.5, 3), observed in 92.3% of cases for twin-block Designs and at Spacings of 30 m and above, provide comfortable to desirable indoor conditions with IAV of 1-1.5 m/s

4.4.5. Energy Potential of Gap Wind Velocities

Findings are limited to steady input wind velocity ($V_i=5.0$ m/s) for Pune using micro-scale wind turbines ($S = 1$ sqm) with assumed power coefficients for HAWTs (0.5) and VAWTs (0.2); energy potential may vary with turbine design and dynamic wind conditions.

- Range of V_{gap} and VAF values observed within a gap helps determine suitable horizontal and vertical positioning of wind turbines across the gap
- Maximum V_{gap} zones can generate higher output across the gap and are suitable for installing both HAWTs and VAWTs; however, only VAWTs are suitable along and beyond 0.8 m from the block façade, considering the gap wind velocity and incident flow angle
- Lowest VAF (1), corresponding to $V_{gap}=5.0$ m/s onwards, allows operation of both micro-scale HAWT and VAWT, although with very low energy yield; VAWT may function even below 10 m height but with negligible power output

- Highest VAF (3.5), for $V_{gap}=17.5$ m/s, provides reliable energy generation potential, where both HAWT and VAWT can be effectively used, and multiple units can serve as a viable source of wind energy
- Most-likely occurring VAF values (2, 2.5, 3) provide a significant energy generation potential and are more relevant due to their high occurrence frequency of 92.3%

4.5. Recommendations

Based on CFD simulations of 26 twin-block designs across four spacing categories using average wind data of Pune and results evaluated at four building heights, the following recommendations are made:

- Rapid urban growth in Pune is expected to increase high-rise density and modify micro-climatic wind patterns; therefore, urban layouts should facilitate unobstructed wind flow for improved wind performance and potential.
- Unobstructed wind flow in the cities, from macro- to micro-level, is essential as it offers ambient air change that is instrumental in reducing urban heat island effect through moderation of air temperature, humidity and velocity and diluting pollution concentration through polluted air dispersion.
- Urban layout structure and spatial composition should orient and align the buildings not only to obstruct the wind minimally for mitigating extensive elongated wake regions, but also to provide a passage for free wind flow, typically along the roads, continuous building setbacks and separations, linear green spaces and other unbuilt layout elements, so as to function as street canyons or wind corridors.
- Wind acceleration through inter-building gaps of varying forms and heights presents significant potential for both ventilation and micro-wind energy; thus, built mass and void distribution should be optimized to enhance the velocity of gap-wind and micro-climatic wind performance.
- Gap velocities are typically 2-3 times higher than incident wind speed, particularly at spacings above 30 m and heights above 60 m.
- Inter-block wind speeds from 5 m/s and above are effective for reliable natural ventilation through along-the-gap openings.
- Wind speeds above 10 m/s in inter-block spaces are more suitable for energy generation when multiple micro-scale units are installed, considering HAWT cut-in (~ 3 m/s) and VAWT operation (~ 2 m/s).
- HAWTs demonstrate higher wind energy conversion efficiency than VAWTs but are less suitable for close-proximity urban installations due to spatial and operational constraints.
- VAWTs are more suitable for urban micro-generation due to lower noise and installation flexibility, enabling multiple units to be deployed along façades in both horizontal and vertical arrangements.

5. Conclusion

This research systematically examines the influence of urban morphology and inter-building spacing on wind behaviour and micro-climatic wind patterns in a growing city like Pune using CFD. Twenty-six twin-adjacency configurations across four spacing categories are analysed under steady-state conditions using average wind data, with results evaluated at four heights, generating 416 observations. Gap wind velocity is used as a key indicator of wind amplification relevant to ventilation and micro-wind energy potential.

Results indicate consistent wind acceleration within inter-block spaces, with velocities reaching 2-3 times the incident wind speed, particularly at larger spacings and higher elevations. Gap velocities above 5 m/s support natural ventilation, while those exceeding 10 m/s indicate potential for micro-wind energy harvesting.

Comparative assessment shows HAWTs offer higher efficiency but limited urban applicability, whereas VAWTs are more suitable for distributed façade-based installation due to flexibility and lower impact.

The study demonstrates the relevance of CFD-based urban wind analysis for evaluating wind-responsive urban form. However, findings are limited to steady-state conditions and average wind data for Pune. Overall, the results highlight the significance of integrating wind-responsive strategies in sustainable design and wind-driven architecture to enhance ventilation performance and micro-wind potential.

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