APPLICATION AND EVALUATION OF THE EFFECTIVENESS OF IMPROVING AIR QUALITY BY WIND TOWERS FOR TOWNHOUSES IN DA NANG

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Abstract - This study investigates the effectiveness of wind towers, an ancient Persian architectural feature, for natural ventilation and air quality improvement in townhouses in Da Nang, Vietnam. This study employs Computational Fluid Dynamics simulations to evaluate the performance of wind towers under various parameters, including tower shape, wind direction, height, and inlet/outlet ratios. The simulations compare different wind tower designs, such as two-sided, four-sided, and eight-sided towers, and analyze the impact of varying wind angles (0°, 45°, and 90°). The results demonstrate that wind towers can enhance indoor air velocity and ventilation flow rates, leading to improved indoor air quality and reduced pollutant levels. Notably, four-sided wind towers exhibit the most consistent performance across different wind directions. The study also finds that increasing tower height and inlet area positively affects ventilation efficiency. This study provides valuable insights for implementing wind towers as a sustainable solution for natural ventilation in urban buildings.

Key words - Wind tower; natural ventilation; CFD simulation; air quality improvement; ventilation flow rate

1. Introduction

In the context of increasing urbanization, the demand for sustainable living environments has become a top priority for modern buildings. Da Nang, a coastal city in Central Vietnam, experiences a tropical monsoon climate characterized by distinct wet and dry seasons. The dry season, from February to August, is marked by high temperatures ranging from 25°C to 36°C, with peaks reaching 39°C in June and July. This period is also characterized by high humidity, limited rainfall, and oppressive heat. Consequently, designing effective ventilation systems in buildings, especially in townhouses with limited land area, is crucial.

Many modern residential buildings, particularly townhouses in Vietnam, rely heavily on air conditioning systems for thermal comfort due to spatial constraints. Natural ventilation design is often overlooked. However, excessive reliance on air conditioning is costly and environmentally taxing. Buildings are responsible for nearly 40% of global greenhouse gas emissions, with HVAC systems accounting for almost 60% of total energy consumption [1].

One potential solution to reduce this reliance is the wind tower, an architectural method from ancient cultures that effectively enhances ventilation in buildings. This research aims to assess the effectiveness of wind towers under various conditions and propose suitable wind tower shapes and dimensions for the study area.

This study seeks to answer the following research questions: How effective are wind towers in improving indoor air quality in Vietnamese townhouses? What are the optimal design parameters for wind towers in Da Nang's climate? How can physical effects enhance the performance of wind towers?

The objectives of this research are to propose suitable forms and technical parameters for wind towers, integrate physical effects to enhance natural ventilation, evaluate the effectiveness of improving indoor air quality, and reduce environmental impact while saving energy.

This paper will first provide an overview of studies on wind towers, then discuss the research methodology, including CFD simulations. Subsequently, the results of various simulations under different parameters will be presented. Finally, the findings will be discussed, with conclusions.

2. Literature review on wind towers and it modern applications

2.1. Wind tower and it origine

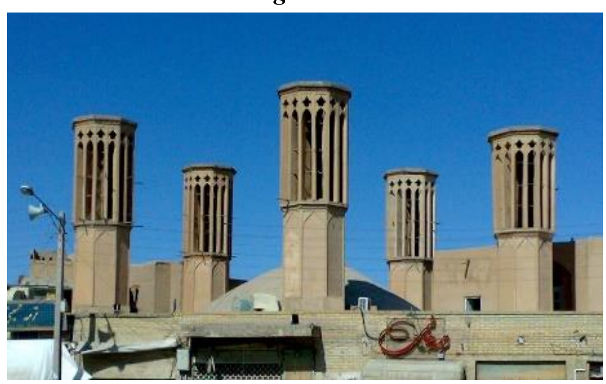

Figure 1. *Windcatchers in Yazd province, Iran (© Ms96, creative commons 4.0 license)*

A wind tower, also referred to by various names across different cultures such as wind catcher, wind scoop, Malqaf, or Badgir, is a traditional architectural element ingeniously designed to harness the natural power of wind for ventilation and cooling in buildings [2]. The fundamental mechanism by which wind catchers ventilate and cool buildings relies on basic principles of fluid dynamics and natural pressure differentials (see Figure 1). Archaeological findings, such as chimney-like structures without ash in a Persian fire temple dating back to 4000 BC, hint at a very early Iranian origin. Drawings from around 1300 BC in Egypt also depict what appear to be wind catchers, leading to the dispute over the exact birthplace. Regardless of the initial invention, wind catchers were significantly developed and widely utilized in Persia (ancient Iran) to adapt to the hot and arid climate of the central plateau and the humid conditions of the coastal regions [3].

Design of wind towers can be broadly categorized into unidirectional, multi-directional, and roof-mounted variations, with each type exhibiting distinct features and functionalities (see Table 1).

Table 1. *Comparison of Different Wind tower Designs*

Feature	Unidirectional Wind Catcher	Multi-directional Wind Catcher	Roof-Mounted Wind Catcher
Openings	Single, facing prevailing wind	Multiple (4, 6, or 8), capturing wind from various directions	Integrated into roof, number varies
Internal Structure	Simple, may have basic channeling	Internal walls or blades to direct airflow	Internal ducts, potentially with integrated components
Functionality	Directs cool wind down; can exhaust air using suction	Acts as both wind scoop and heat sink (exhaust)	Provides ventilation and cooling to spaces below roof
Best Suited For	Regions with consistent, predictable wind patterns	Areas with varying wind directions and stronger wind speeds	Modern buildings where roof integration is desired
Examples	Ardakani (Iran), Malqaf (Egypt)	Yazdi (Iran), Baudgir (Persian Gulf)	Monodraught systems, modern commercial wind catchers

2.2. Previous studies on airflow characteristics and applications of wind towers

One of the most significant advantages of wind catchers is their ability to reduce the reliance on mechanical air conditioning systems, leading to substantial energy savings. Studies have reported potential reductions in building energy consumption ranging from 20% to 50% through the effective use of wind catchers [4].

Studies have indicated that the use of wind catchers can lead to an improvement in indoor air quality by as much as 20% to 40% [4]. This enhanced air quality is vital for the health and well-being of building occupants, potentially reducing the incidence of sick building syndrome associated with inadequate ventilation.

Calautit and Hughes [5] studied the cooling performance of wind catchers incorporated with heat pipes using CFD, a wind tunnel experiment and a field test. A cooling potential of up to 12 ˚C of supply air temperature was identified in this study.

Another study by Elmualim [6], employing Computational Fluid Dynamics (CFD) and wind tunnel experiments, demonstrated the potential applicability of wind catchers for buildings in temperate climates such as the UK. However, their findings suggested that these systems should be designed with integration into Heating, Ventilation, and Air Conditioning (HVAC) systems and operated in a hybrid mode, allowing for natural ventilation utilization during the summer months.

Nevertheless, these studies present limitations regarding specific implementation strategies for modern residential buildings and lack a comprehensive evaluation of the performance of individual wind catcher configurations to identify suitable and practical solutions, particularly for the urban conditions prevalent in Vietnam.

Vietnam is situated within the tropical monsoon climate zone, characterized by a hot and humid climate. Consequently, ventilation for residential buildings is of paramount importance. Although numerous studies have explored natural ventilation to enhance air quality through various methods, such as the utilization of courtyards by Nguyen & Le [7], or the research by Pham & Pham [8] on ventilating tube houses using single-sided ventilation, cross-ventilation combined with vertical ventilation, and Nguyen's investigation into the application of solar chimneys for residential ventilation using CFD [9]…, there is a noticeable absence of published research specifically addressing the implementation of wind catchers for townhouse dwellings in Vietnam.

3. Research methodology

3.1. CFD simulation framework

CFD simulations were utilized to analyze airflow patterns, velocity, and ventilation flow rates. This approach was chosen for its cost-effectiveness and accessibility compared to physical wind tunnel testing, while still providing detailed quantitative data. CFD simulation method is gradually becoming popular, with low cost, easy access, accounting for more than 70% of the methods applied in flow research with popular software such as: Ansys Fluent, OpenFOAM, Autodesk CFD, Simscale, Phoenics... [10]. Two software platforms were employed: Autodesk CFD for the primary simulations and SimScale for validation purposes.

3.2. CFD model development

A 2-story townhouse model with built density compliant with Vietnam building code QCVN 01:2021/BXD, was constructed within a representative urban block measuring 270m x 270m. This block includes 352 typical townhouse structures with high-density coverage (99.97%). The surrounding environment was modeled to capture the urban context. This is a typical coastal neighborhood in urban Da Nang, featuring high building density and many low-rise houses squeezed tightly together. The simulation domain extended three times the width and five times the height of the whole model to minimize boundary effects. 3D models were generated using Revit 2023 software. Variations of the townhouse model included wind towers with two, four, and eight faces (see Figure 2).

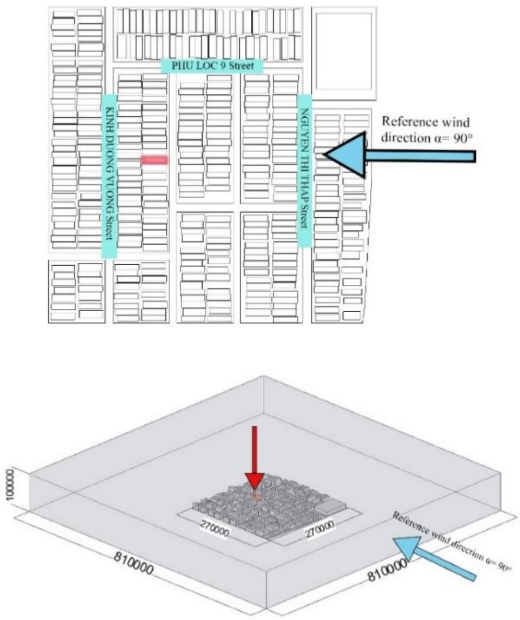

Figure 2. *CFD simulation domain, reference wind direction and location of the house being modeled in the urban area near Nguyen Tat Thanh beach*

3.3. Turbulence modeling

The Reynolds-Averaged Navier-Stokes (RANS) equations were solved using the k-ε turbulence model. This model was selected for its robustness, computational efficiency, and ability to accurately predict turbulent flows in complex geometries. Convergence criteria were set to ensure solution stability, with typical simulations requiring 600-1200 iterations.

3.4. Material properties and boundary conditions

The building structures were assigned to the material properties of "Solid-concrete," while the surrounding air domain was defined as "Fluid-Air." The prevailing wind direction was set at α= 90° (where α is the angle between the wind direction and the wind tower's face) with a reference wind speed of 3.5 m/s at a height of 10m, based on meteorological data from Da Nang International Airport in 2021 [11]. A power-law wind profile was used to account for the variation of wind speed with height:

$$\frac{U_z}{U_r} = \left(\frac{z}{z_r}\right)^{\alpha} \quad (1)$$

where U_z and U_r are the wind speeds at heights z and z_r, respectively, and α is the power-law exponent (set to 0.15 for an urban environment [12]). The outlet boundary was defined with a static gauge pressure of 0 Pa.

3.5. Mesh generation

The computational domain was discretized using an unstructured mesh. An "autosize" mesh was initially generated, followed by mesh refinement regions concentrated in areas of high flow gradients and around the wind tower structures. The average mesh consisted of 6.5 million elements, with some complex cases reaching 8.2 million elements. This resulted in average simulation times of 16-20 hours per case on a workstation Intel core i7 14700K Ram 16GB.

3.6. Validation study

To ensure the reliability of the simulations, wind movement in and around a simplified model (**Figure 3**) was simulated using both Autodesk CFD and SimScale. Wind speed measurements were taken at 1.1m height at 0.5m intervals (Figure 3). Comparison of the results (Figure 4) showed good agreement between the two platforms, with minor discrepancies at position 3.5m attributed to differences in turbulence modeling and mesh resolution.

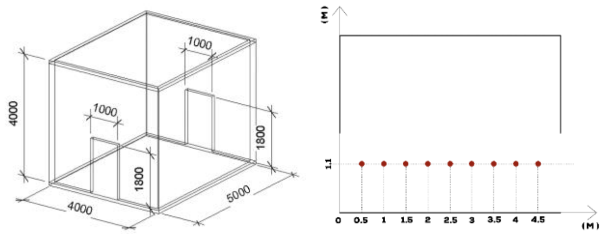

Figure 3. *The model using to evaluate the reliability of simulations and survey points*

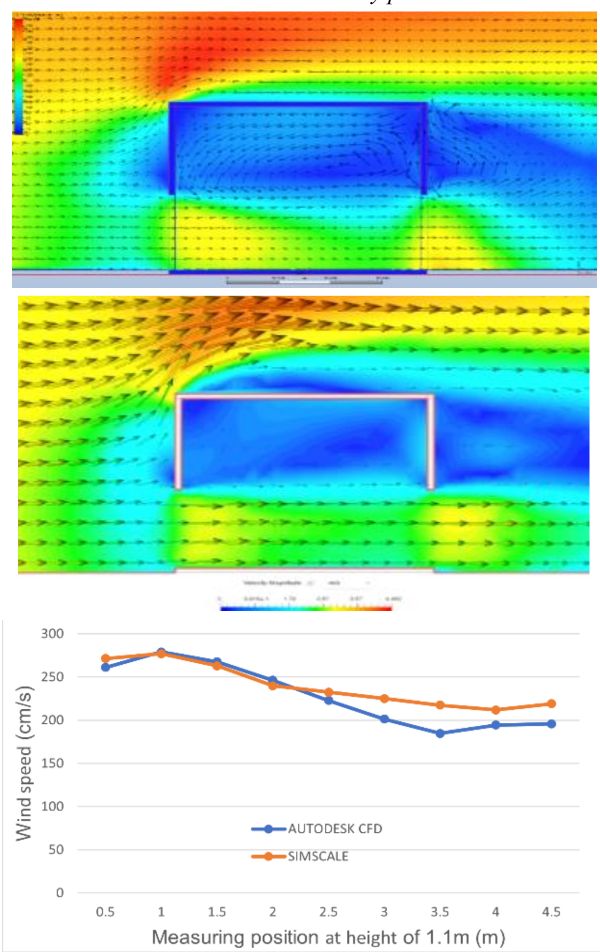

Figure 4. *Comparison of wind speed at 9 locations at height 1.1m in Autodesk CFD (upper right) and Simscale (upper left) simulations*

3.7. Monitoring position and calculation rules

Air velocity was measured at 9 points within the townhouse model at a height of 1.1m (representing seated head height), as per ISO 7726 recommendations (Figure 4). Velocity magnitudes, average velocities, and standard deviations were calculated to assess the airflow distribution. Ventilation flow rates (Q) were determined using the formula Q = V_{avg} x S, where V_{avg} is the average velocity at 9 points at the wind tower inlet (Figure 5) and S is the inlet area. It should be noted that this is a simple house model without interiors, so it may not fully reflect the diverse reality of houses. Cases other than this model require specific investigation.

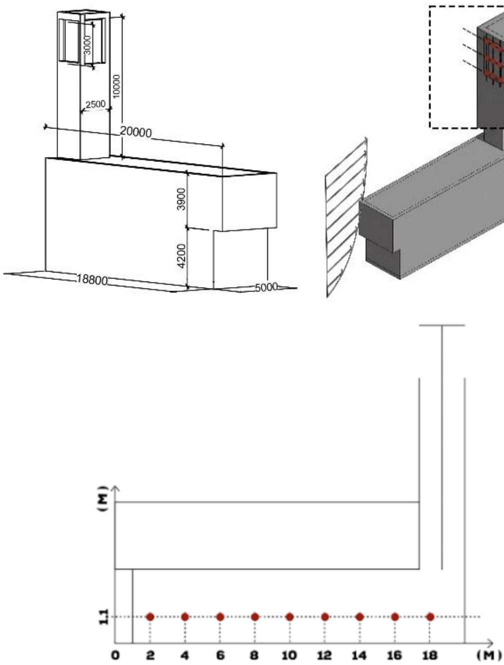

Figure 5. *The house model (upper left), location of 9 monitoring points on the wind tower inlet (upper right) and 9 monitoring points inside the house*

4. Result analysis

4.1. Wind Tower Types and Wind Direction

Computational Fluid Dynamics (CFD) simulations were conducted to analyze the performance of three distinct wind tower types: 2-sided, 4-sided, and 8-sided. These simulations were performed under varying wind angles of 90°, 45°, and 0° relative to the tower's primary façade (see result in Figure 6).

- 90° Wind angle: At a 90° wind angle, the 8-sided tower exhibited the highest average internal wind speed, registering at 17.7 cm/s. However, the 2-sided tower demonstrated the highest average ventilation flow rate of 405 cm^3/s (see Figure 7).

- 45° Wind angle: When the wind angle was set to 45°, the 4-sided tower achieved the highest ventilation flow rate, measured at 750 cm^3/s. It's worth noting that overall wind speeds were generally lower across all tower types at this angle.

- 0° Wind angle: With a 0° wind angle, the 4-sided tower recorded the highest average wind speed at 16.7 cm/s.

Overall, the 4-sided tower displayed the most consistent performance across the different wind angles, suggesting its adaptability to varying wind directions.

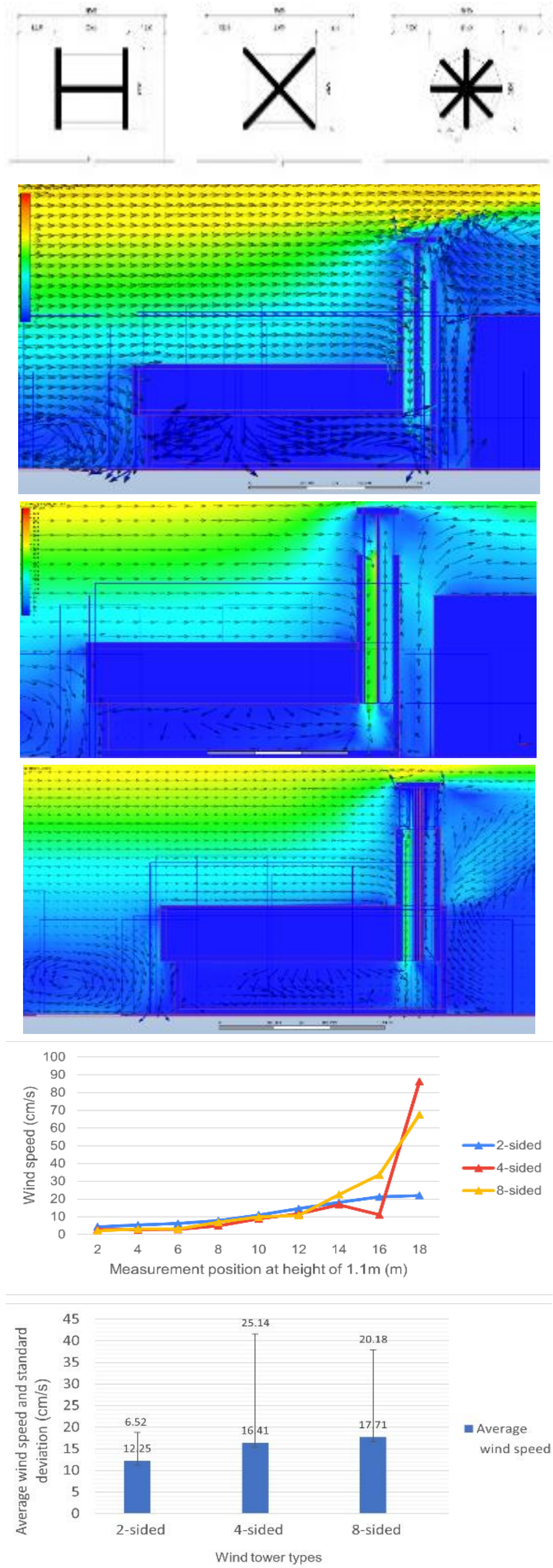

Figure 6. *Simulation result of three distinct wind tower types: 2-sided, 4-sided, and 8-sided (images of case α= 90°)*

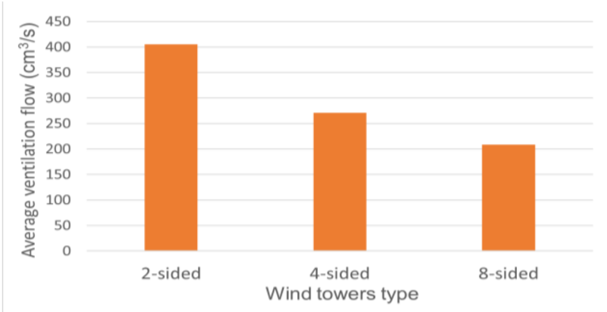

Figure 7. *Average ventilation flow rate of three distinct wind tower types: 2-sided, 4-sided, and 8-sided*

4.2. Wind Tower Height

Simulations were carried out to assess the impact of wind tower height on ventilation efficiency. Tower heights were varied from 5 meters to 15 meters (This height is measured from the top surface of the roof). The results indicated a general trend: taller towers led to increased internal wind speeds. Specifically, the 12-meter tower demonstrated the highest average wind speed and ventilation flow rate, measured at 282 cm^3/s (Figure 8).

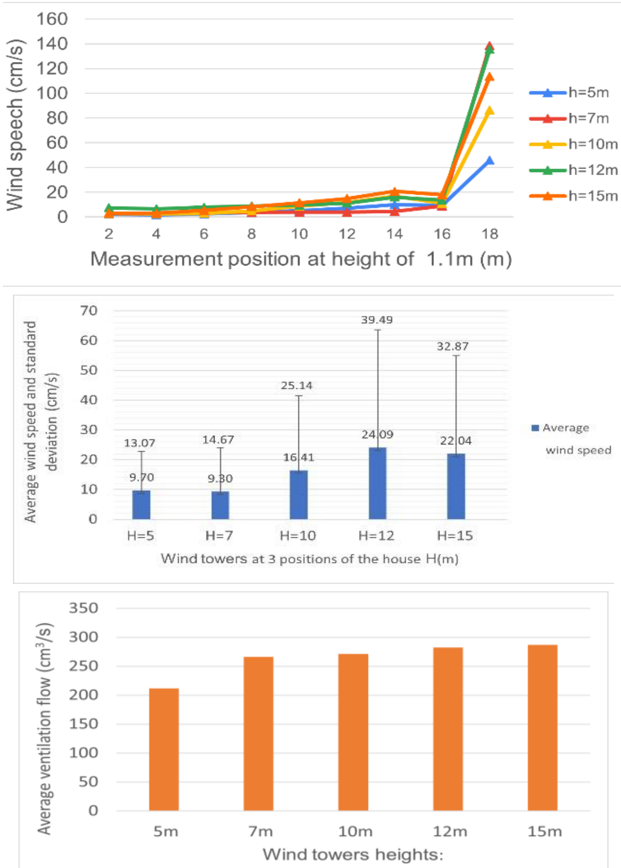

Figure 8. *Simulation results of wind towers with different heights: 5m, 7m, 10, 12m, 15m*

4.3. Wind Tower Placement

The placement of the wind tower on the house model was also investigated. Three positions were considered: front, middle, and rear. Placing the wind tower at either the front or middle of the house resulted in higher average wind speeds, recorded at 32.4 cm/s and 34.1 cm/s, respectively. These values were notably higher compared to placing the tower at the rear of the house. Ventilation flow rates, however, remained relatively similar across all three placement positions (see Figure 9).

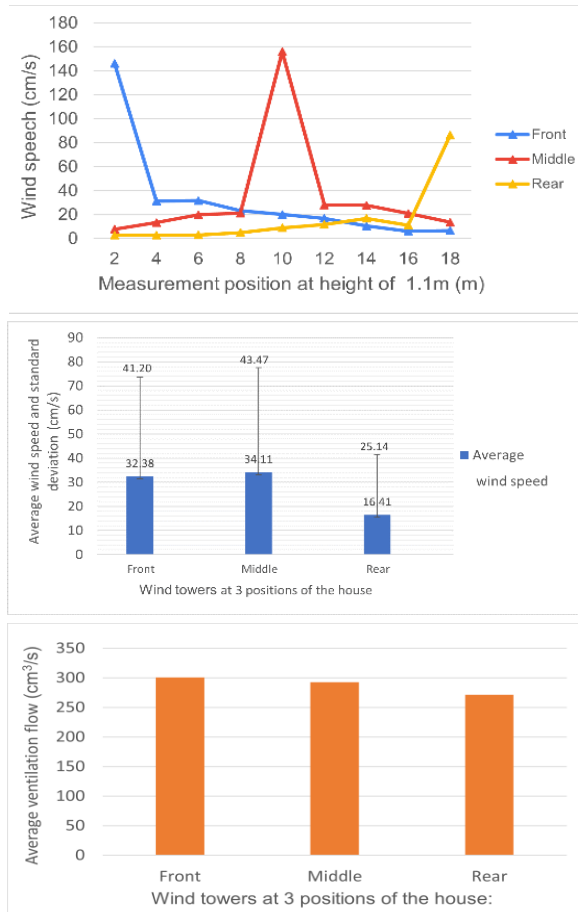

Figure 9. *Simulation results of wind towers at 3 positions of the house*

4.4. Wind Tower Opening Size

The influence of the wind tower opening size was examined by varying the height of the opening from 1 to 5 m. Increasing the opening height led to higher average wind speeds and ventilation flow rates. The largest opening size of 5 m yielded the highest value of 460 cm^3/s (Figure 10).

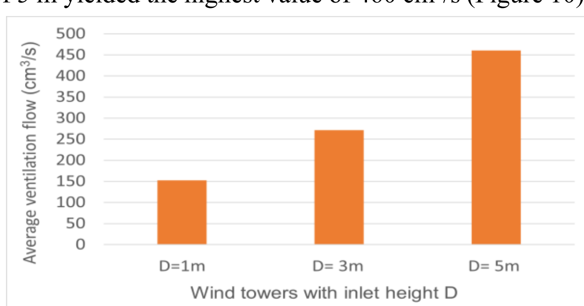

Figure 10. *Average wind flow rate at the inlet of wind towers with inlet height D of 1m, 3m, 5m respectively*

4.5. Inlet and Outlet Ratio

The ratio between the inlet and outlet opening areas of the wind tower was analyzed. Different ratios, denoted as 'M', were tested. A ratio of M = 2, where the inlet area was twice the outlet area, resulted in the highest average wind speed of 26.3 cm/s and a ventilation flow rate of 430 cm^3/s.

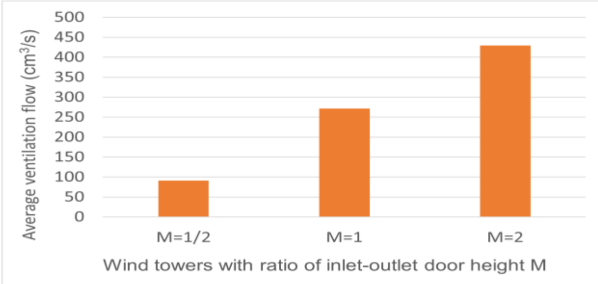

***Figure 11.** Average vetilation flow rate of wind towers with ratio of inlet-outlet door height M=1/2, 1, 2*

Similarly, the ratio of inlet to outlet duct volumes, denoted as 'K', was explored. The results showed that a ratio of K = 2, where the outlet volume was twice the inlet volume, led to the highest ventilation flow rate of 370 cm^3/s.

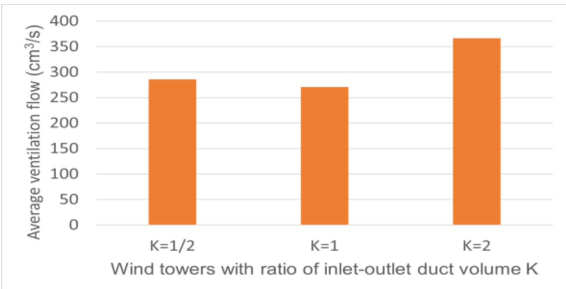

***Figure 11.** Average ventilation flow rate of wind towers with ratio of inlet-outlet duct volume K=1/2, 1, 2*

4.6. Venturi effect and Coanda effect

The integration of the Venturi effect into the wind tower design was examined. In most cases, incorporating the Venturi effect resulted in a decrease in average wind speed and ventilation flow rate. However, a slight increase in these values was observed when the Venturi effect was implemented below the tower. It's important to note that this particular configuration also exhibited high flow instability (see Figure 12).

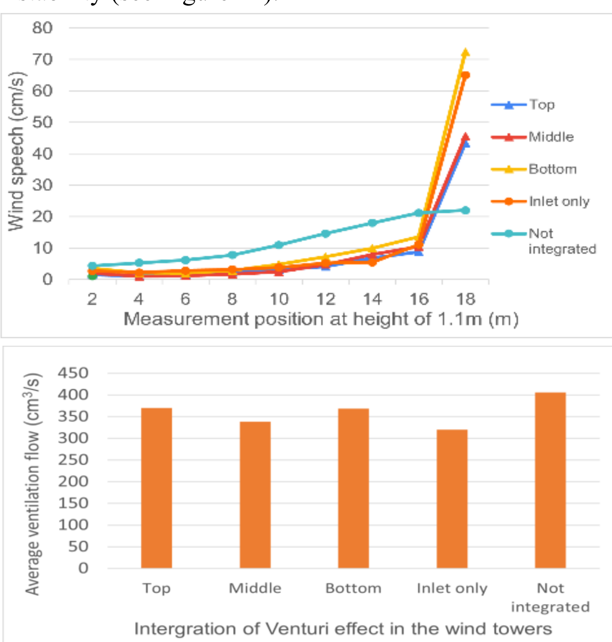

***Figure 12.** Integration of Venturi effect in the wind towers and its simulation results*

The integration of the Coanda effect was also investigated. While it increased wind speed at certain localized points, it generally decreased the average wind speed and ventilation flow rate within the simulated space.

4.7. Discussion

This study investigated the effectiveness of wind towers in enhancing natural ventilation for townhouses in Da Nang city, a region characterized by a tropical monsoon climate. CFD simulations were employed to analyze various wind tower designs and operational parameters. The results provide valuable insights into optimizing wind tower performance in urban residential settings.

Influence of Wind Direction:

The simulations revealed that wind direction significantly impacts the performance of different wind tower configurations. Four-faced wind towers demonstrated the highest overall effectiveness, particularly when the wind direction was at a 90° angle to the tower face. This configuration consistently achieved the highest wind speeds and flow rates within the townhouse model. Two-faced wind towers were effective only when the wind direction was directly aligned with the opening, while eight-faced towers offered more consistent performance across varying wind angles but with slightly lower peak values. When the wind angle deviated by 45°, the ventilation efficiency of all towers decreased significantly, highlighting the importance of tower orientation and design in relation to prevailing wind directions.

Wind Tower Height:

The height of the wind tower was found to be a critical factor in its performance. Taller towers captured higher wind speeds due to the vertical wind profile, leading to substantially increased airflow within the house. Towers with heights between 7 to 12 meters were identified as optimal for the typical two- to three-story townhouse structures in Da Nang. This height range balances the benefits of increased wind capture with practical considerations of cost, construction, and aesthetic integration into the urban environment.

Tower Placement:

The position of the wind tower on the townhouse significantly influenced airflow patterns. Towers placed at the front or middle of the house generally resulted in higher average wind speeds and flow rates compared to those placed at the rear. This is attributed to the uninterrupted airflow path from the tower inlet to the outlet in these positions. Rear placement often led to airflow disruptions and reduced efficiency due to the need for air to navigate around the building's interior. However, the optimal placement also depends on the prevailing wind direction, as rear placement could be advantageous if the wind primarily comes from the back.

Inlet Size and Area Ratio:

The size of the wind tower inlet and the ratio between the inlet and outlet areas directly affected ventilation flow rates. Larger inlet openings led to increased airflow, and a higher ratio of inlet to outlet area enhanced wind speeds within the house, aligning with the Venturi effect principle.

However, the increased flow also resulted in greater turbulence and flow variations, suggesting a trade-off between flow volume and stability. A balanced approach is needed to optimize both flow rate and distribution.

Duct Volume Ratio:

The ratio of the inlet duct volume to the outlet duct volume influenced airflow patterns. A smaller inlet duct volume relative to the outlet duct volume tended to increase wind speeds near the tower but reduced overall flow uniformity. Conversely, a larger inlet duct volume resulted in a more even airflow distribution, suggesting that duct design should prioritize uniform airflow rather than solely focusing on maximizing local velocities.

Integration of Physical Effects:

The incorporation of Venturi and Coanda effects into the wind tower design didn't yield good results. While Venturi effects could significantly increase wind speed at specific points, they often led to uneven airflow distribution and reduced overall ventilation efficiency. Coanda effects, primarily aimed at directing airflow, did not significantly enhance wind speed or flow rates in this study.

Construction methods and investment costs:

Townhouses without wind towers have a simpler design and lower initial construction costs, but they might face issues with ventilation and air quality. This can lead to higher operating costs due to reliance on air conditioning. Conversely, townhouses with wind towers require more complex designs and structures, specialized materials, and higher initial investment costs. However, wind towers significantly improve indoor airflow and air quality, potentially reducing operating costs and increasing property value.

Architectural aesthetic:

Incorporating wind towers into townhouses can bring significant aesthetic value and deeper meaning. With the creativity of architects, they can create a unique, distinctive architectural landmark with its own identity, showcasing a commitment to sustainable solutions. To suit Vietnamese conditions, wind towers should feature minimalist designs, utilize shadow play, illuminate the tower body, incorporate climbing plants, and comply with local architectural management regulations.

5. Conclusion

This research demonstrates that wind towers offer a viable and effective solution to address natural ventilation demand. While the implementation of wind towers necessitates careful consideration of various contextual and site-specific factors, this study has identified relatively universal parameters suitable for the conditions of Da Nang city and potentially applicable to other regions of Vietnam.

It is recommended to utilize four-faced wind towers with a height extending beyond the surrounding airflow disturbance zone, specifically ranging from 7 to 12 meters. The inlet openings should be positioned to directly face the prevailing wind direction, and the opening area should be larger than the outlet area to enhance ventilation flow rates. The optimal placement for the wind tower is either at the windward end or the center of the house. Furthermore, integrating physical principles such as the Venturi and Coanda effects can be considered to optimize performance for specific conditions.

The use of wind towers can significantly increase airflow within the house, ranging from 20 to 65 cm/s. With precise adjustments to specific parameters, this figure can be further elevated. In practical applications, interior furnishings and layouts will also influence the actual performance. Nevertheless, wind towers provide substantial ventilation flow rates (200-750 cm3/s) to the structure, ensuring continuous air renewal, fresh air supply, and the removal of harmful pollutants. This has profound implications for improving indoor air quality.

In summary, this research underscores the potential of wind towers as a passive ventilation strategy for townhouses in tropical monsoon climates, offering a sustainable approach to enhance indoor environmental quality and reduce reliance on mechanical ventilation systems. The findings provide valuable insights for architects and engineers seeking to design more comfortable and energy-efficient residential buildings.

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