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Research article

Wind tunnel investigation of the aerodynamic performance of temporary pyramid shelters in emergency conditions

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Abstract

With the growing frequency of natural disasters, the need for sustainable emergency shelters has become increasingly urgent. This study evaluates the aerodynamic performance of pyramid-shaped shelters through wind tunnel testing of eight scaled models with hexagonal and octagonal bases at angles ranging from 0° to 180°. Surface pressure coefficients were measured to assess wind effects. While hexagonal models showed higher pressure peaks, octagonal models offered more stable aerodynamic behavior due to more uniform wind load distribution. Pressure fluctuations were most significant near the edges, with relative stability observed between 120° and 140°. These findings suggest that increasing the number of base sides improves wind resistance, offering insights for optimizing temporary shelter designs in disaster-prone regions.

Keywords: Aerodynamic performance, Wind tunnel, Temporary shelter structures, Natural disaster management, Pyramid-shaped shelter

1- Introduction

Natural Disasters (NDs) have long been recognized as a significant threat to human life and a major contributor to infrastructure destruction. In recent years, the increasing intensity and frequency of these disasters have underscored the urgent need for effective and efficient crisis management strategies [1] .Natural disasters are generally classified into six primary categories [2], including geophysical disasters (earthquakes, mass movements, volcanic activity), hydrological disasters (floods, landslides, waves), meteorological disasters (convective storms, extratropical storms, extreme temperatures, fog, tropical cyclones), climatological disasters (droughts, glacial lake outbursts, wildfires), biological disasters (animal incidents, diseases, insect infestations), and extraterrestrial disasters (impacts, space weather events). Statistical analyses indicate that between 1995 and 2022, a total of 11,360 natural disasters were recorded, averaging 398 disasters per year. Asia experienced the highest number of disasters, with 4,390 recorded events, alongside the greatest number of fatalities, totaling 918,198 deaths. Among different disaster types, hydrological disasters, with 4,969 occurrences, were the most frequent, whereas geophysical disasters, responsible for 770,644 deaths, had the highest mortality rate. Additionally, biological disasters resulted in the highest number of injuries (2,544 cases), with Africa being the most affected region [3]. Disaster and emergency management involve the systematic implementation of risk management, impact assessment, crisis response, and recovery strategies. This process encompasses pre-disaster preparedness, real-time response, and post-disaster rehabilitation. Crisis management includes multiple phases and strategic interventions, requiring not only immediate response efforts but also long-term investments in prevention, preparedness, and post-disaster recovery. A well-integrated approach ensures effective damage mitigation and enhances overall resilience against natural disasters [4]. Among the essential components of disaster management, temporary sheltering plays a crucial role in minimizing both physical and psychological impacts on affected populations. Temporary shelters offer a secure and stable environment for displaced individuals, facilitating their recovery and reintegration. As an integral part of disaster response, these shelters must be structurally resilient to ensure safety and long-term usability. The design and deployment of temporary shelters necessitate meticulous planning, sufficient resources, and skilled personnel to guarantee optimal functionality before, during, and after disasters [5, 6]. The occurrence of a natural disaster often escalates the risk and severity of secondary disasters, necessitating comprehensive post-disaster management strategies. These strategies must include thorough damage assessment, provision of immediate relief supplies, mitigation and management of secondary disaster risks, and sustainable reconstruction of critical infrastructure to prevent further deterioration and cascading impacts. This aspect is particularly crucial in shelter design, where structures must be engineered to endure extreme weather conditions, including high-velocity winds and severe storms [7]. As an example, in March 2017, in Dolakha, Nepal, strong winds overturned the tents of earthquake victims who, due to the inadequacy of permanent housing, were still residing in temporary shelters, further exacerbating the hardships faced by these disaster-stricken families [8]. Considering these issues, the structural weaknesses of the temporary shelters currently used in natural disasters are clearly evident. This underscores the urgent need to reconsider the utilization of conventional shelters and to rethink their design and implementation. Despite the critical importance of aerodynamic stability in the design of temporary shelters, research on evaluating the performance of such shelters with different geometries under emergency conditions and extreme wind forces remains either nonexistent or highly limited. One innovative approach to enhancing the stability of temporary shelters involves employing structures with specialized geometric designs, such as pyramid-shaped shelters. In this study, we hypothesize that these structures, due to their aerodynamic characteristics, can significantly mitigate wind forces. Furthermore, the structural and geometric properties of these shelters may directly influence their stability under wind pressure and their adaptability to extreme environments. This study focuses on evaluating the aerodynamic performance of pyramid-shaped shelters, examining their behavior under extreme wind conditions, and proposing strategies for optimizing their design. The ultimate goal of this research is to develop shelters that, in addition to structural stability, ensure safe and effective utilization in emergency situations and disaster management. Concerning the functionality of temporary shelters in emergencies and natural disasters, this section reviews studies that have investigated various aspects of the aerodynamic performance of structures when exposed to severe winds. These studies not only analyze aerodynamic effects but also propose solutions for the design, management, and optimization of structures, which can be applied to the development of temporary shelters. The objective of this section is to identify and leverage relevant research findings to enhance the design and performance of these shelters in response to critical conditions. Ghazal et al. [9] investigated the resistance of temporary structures to extreme weather conditions using wind tunnel experiments and compared the findings with North American design codes. This study provided a comprehensive framework for improving the design of temporary shelters against destructive winds. Additionally, another study analyzed the aerodynamic behavior of storm shelters under non-synoptic wind conditions, offering valuable insights into resilient shelter design [9, 10]. Singh and Roy [11] examined the role of roof shape and slope in the structural safety of buildings against wind loads. Using Computational Fluid Dynamics (CFD) simulations, the study analyzed pressure distribution on pentagonal and hexagonal pyramid-shaped roofs in low-rise single-story buildings. The findings demonstrated that pyramid-shaped roofs exhibited superior resistance to wind loads compared to other roof forms. The building models were created and meshed using ANSYS ICEM CFD, while simulations were conducted in ANSYS Fluent utilizing the realizable k–ε turbulence model. The study included the analysis of ten building models (five with pentagonal plans and five with hexagonal plans) with varying roof slopes (20°, 25°, 30°, 35°, and 40°) and different wind angles (ranging from 0° to 45° in 15° intervals). The results indicated that buildings with hexagonal pyramid roofs had lower pressure coefficients and a higher probability of survival than those with pentagonal roofs. These findings contribute to the enhancement of wind-resistant structural design. Astha Verma et al. [12] conducted an experimental study on wind-induced pressure on low-rise structures. The research involved wind tunnel tests on single and multiple domes (two, three, and four domes arranged in parallel). Pressure coefficients were calculated under various conditions, and contour plots were generated for comparative analysis. The findings revealed that wind loads applied at a 90-degree angle had minimal impact on pressure coefficients, whereas loads at a 0-degree angle caused significant pressure variations. These results contribute to the improved design of wind-resistant structures. In another study, Roy et al. [13] used CFD simulations to examine wind pressure variations on rectangular and pentagonal pyramid roofs in low-rise buildings. The simulations were conducted using the realizable k–ε turbulence model, and wind pressure coefficients and velocity profiles around the buildings were analyzed. The results indicated that pyramid roofs, due to their geometric configuration, experienced lower wind pressures compared to sloped roofs, with suction forces developing across different roof sections. This study highlights the advantages of pyramid roof designs in reducing wind pressure effects. Deqian et al. [14] employed Large Eddy Simulations (LES) to investigate wind interaction between tandem hemispherical domes with varying center-to-center distances. The simulation results were compared with wind tunnel experiments, and wind pressure distribution on dome surfaces was analyzed. Changes in dome spacing altered wind flow patterns and localized pressure, leading to either increased or decreased flow separation and pressure fluctuations. The study demonstrated that upstream-downstream structural interactions significantly influence wind loads on domes. These findings provide valuable insights for optimizing wind-resistant dome designs. Luisa Pagnini et al. [15] studied wind pressure on vaulted canopy roofs, emphasizing the critical role of accurately replicating structural geometry and details, including edges and skylights, to ensure safety under wind loads. Another study, regarded as one of the pioneering works in this field, conducted a more detailed analysis of the effects of geometry and structural details on wind pressure distribution. These investigations offer practical solutions for improving wind-resistant structural designs. Taylor [16] examined wind pressure on hemispherical domes, analyzing aerodynamic pressure distribution in boundary layer flows. The study measured mean values, standard deviations, minimum and maximum pressures, and mean regional pressure coefficients using free-stream static pressure. The results showed that increasing Reynolds numbers led to variations in mean pressure and turbulence intensity. This study identified critical pressure zones for design purposes and underscored the significance of Reynolds number effects and turbulence intensity in optimizing dome structure designs. Kharoua et al. [17] used vortex simulation methods to analyze the effects of wind loads on turbulent flows around smooth and rough domes. This study provided a detailed examination of how dome surface geometry influences wind pressure distribution and identified differences between smooth and rough domes in terms of wind load responses. The findings of this research can inform the optimal design of wind-resistant domed structures. NIE Shaofeng et al. [18] investigated wind loads on gable roofs of low-rise buildings using wind tunnel experiments. The study analyzed variations in wind pressure coefficients and fluctuations in various parameters affected by factors such as roof shape, wind direction, roof slope, and overhang length. The results highlighted the significant role of these parameters in optimizing the design of wind-resistant gable roofs. Xiaoying Sun et al. [19] examined wind loads on membrane structures with oval arch supports using wind tunnel experiments. This study analyzed wind pressure distribution characteristics and evaluated the effects of parameters such as span-to-rise ratio and wind load direction on mean, fluctuating, and peak pressure coefficients. The findings provide valuable information for optimizing the design of wind-resistant membrane structures. Several studies have explored the aerodynamic behavior and wind pressure effects on dome structures using wind tunnel experiments and CFD simulations. Research by Yin et al. [20] and Chen et al. [21] examined the influence of rise-span and height to span ratios on wind loads and fluctuating wind pressures in dome roofs. Additionally, Cheon, Kim, and Yoon [22] proposed wind pressure coefficients for dome structures with openings, while Horr, Safi, and Alavinasab [23] performed computational wind tunnel analyses on large domes using CFD techniques. Further evaluations by Li et al. [24] compared CFD simulations with wind tunnel testing, confirming that dome structures exhibit complex wind flow behaviors. Studies such as Al-Hashimi et al. [25], and Sun et al. [25] have modeled wind pressure spectra and conducted numerical simulations to assess wind effects on spherical domes. Additionally, Khosrowjerdi et al. [27] analyzed wind loads on heritage domes, providing insights into their structural resilience. Meanwhile, Zilliac and Cliffton [28] conducted wind tunnel studies on observatory domes, focusing on the effects of aperture size on aerodynamic stability. Moreover, Cheon et al. [29] carried out experimental studies to investigate wind pressure characteristics on dome cladding, contributing to an improved understanding of structural performance under wind loads. As mentioned earlier, the objective of this study was to evaluate the aerodynamic performance of temporary pyramid-shaped shelters for use in emergencies and disaster management. Although numerous studies have been conducted on the effects of wind loads on domed and spherical roofs, there has been no targeted research specifically examining the impact of wind loads on pyramid structures with various polygonal bases, particularly in the context of temporary shelter applications. Therefore, in this study, eight scaled models were constructed, including four with a hexagonal base and four with an octagonal base. Using an experimental approach and wind tunnel testing, pressure coefficients were examined and analyzed. The pyramid models were designed with varying heights while maintaining a constant base for all samples. The height-to-base ratios in this study were defined as 0.25h, 0.5h, 0.75h, and 1h, respectively. This study aims to provide experimental data and offer practical recommendations for designing more resilient and efficient structures that can withstand overturning and damage in emergency conditions, including extreme winds and storms. The findings of this research can contribute to the improvement of shelter design and construction, enhancing safety for vulnerable communities.

2- Materials and Methods

For this study, wind tunnel experiments, fluid dynamic pressure conversion equations, and the construction of scaled models were utilized. The following provides a brief overview of these methods.

Wind tunnel test

All experiments were conducted in an open-circuit wind tunnel with a blow-down flow configuration. The wind tunnel used in this study has a total length of 18 meters, with a test section measuring 80 cm in width, 80 cm in height, and 200 cm in length. It is equipped with a centrifugal fan and a three-phase motor with a power capacity of 45 kW, capable of generating wind speeds of up to 35 m/s. The turbulence intensity of the free stream at the maximum wind tunnel speed is 0.05%, which increases as the tunnel speed decreases, reaching 0.2% at the minimum speed of approximately 2 m/s. In this study, the turbulence intensity profile was analyzed as a function of velocity at the center of the test section. Additionally, the wind flow pattern at different heights within the wind tunnel and a schematic diagram of its components are presented in Fig 1. These features create ideal conditions for assessing the aerodynamic behavior of the studied models, providing precise data on pressure distribution and wind flow patterns.

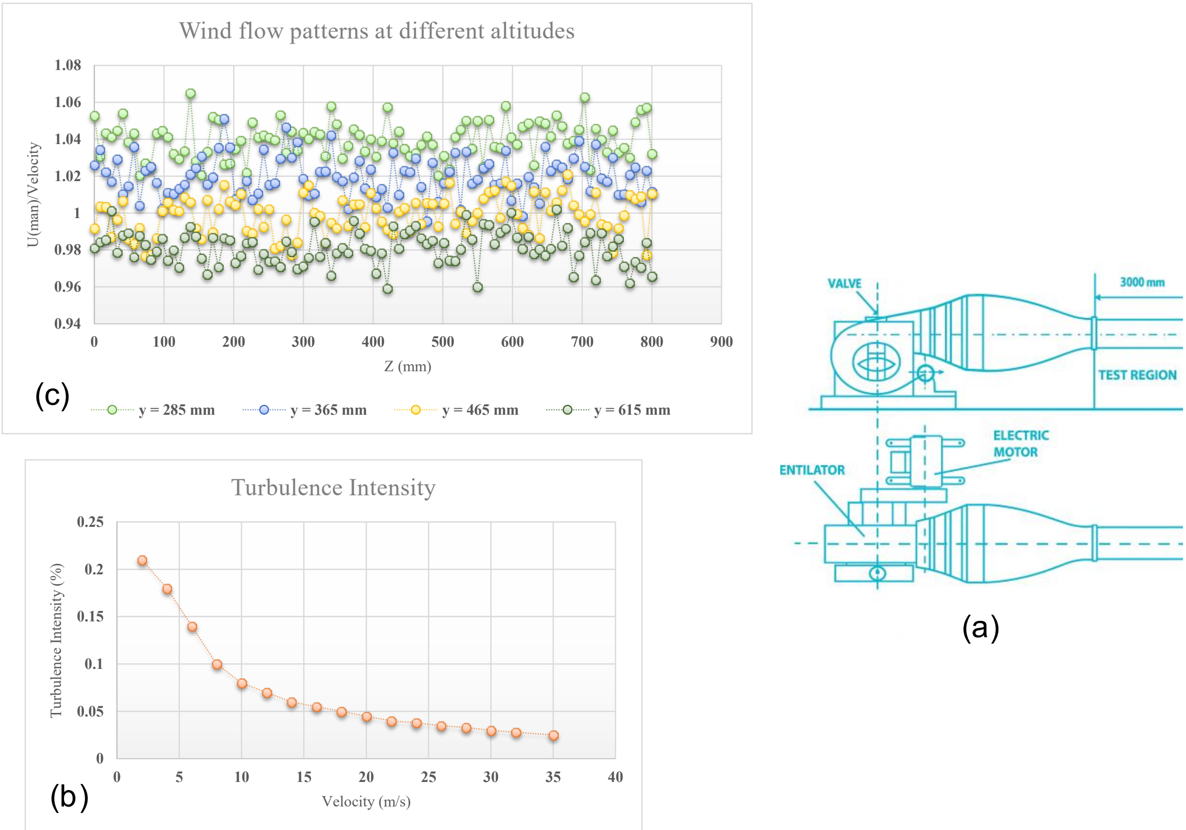

Fig. 1 (a) Schematic of wind tunnel components, (b) The profile of turbulence intensity percentage of wind tunnel based velocity in the center of the test section, (c) The velocity distribution of wind tunnel

In Fig. 1 (b1), the variations in turbulence intensity as a function of wind speed are presented. As observed, at lower wind speeds, turbulence intensity remains relatively high; however, as wind speed increases, this value decreases significantly, particularly in the range exceeding 10 m/s. At wind speeds above 25 m/s, turbulence intensity approaches a nearly constant value. This behavior indicates greater airflow stability and reduced fluctuations with increasing wind speed, which is a key characteristic for ensuring the accuracy and reliability of aerodynamic studies. Fig. 1 (c2) illustrates wind flow patterns at four different heights (285, 365, 465, and 615 mm). At lower heights, significant fluctuations are observed in the calculated velocity ratio U(man) to free-stream velocity, indicating higher turbulence intensity near the surface. As the height increases, these fluctuations progressively diminish, leading to a more stable airflow. At a height of 615 mm, the wind flow becomes nearly uniform, with minimal fluctuations, signifying reduced turbulence and greater flow stabilization at this elevation.

Fluid dynamic pressure conversion equations

The pressure coefficient (Cp) is a dimensionless parameter in fluid dynamics that describes the relative pressure throughout a flow field. It has widespread applications in aerodynamics and hydrodynamics, with each point in the fluid flow field possessing a unique pressure coefficient. In many aerodynamic and hydrodynamic conditions, the pressure coefficient near the surface is independent of surface size, enabling the testing of engineering models in wind tunnels. In such experiments, pressure coefficients are determined at critical points around the model, and these values can be used to predict fluid pressure at the same critical points. The pressure coefficient (Cp) serves as a key analytical tool for studying incompressible fluids, such as air, and can be computed using analytical equations (Eq. 1) by incorporating relevant parameters such as fluid density. This parameter plays a crucial role in assessing the stability and efficiency of various structures subjected to fluid flow effects.

$$C_p = \frac{p - p_\infty}{\frac{1}{2} p_\infty V^2} = \frac{p - p_\infty}{p_0 - p_\infty} \quad (1)$$

In Eq. 1, (p-p_∞) represents the instantaneous pressure difference between the surface pressure of the dome and the reference pressure in the wind tunnel. The parameters ρ and V denote the air density and flow velocity, respectively [30].

C_p: Pressure Coefficient

p: Pressure at a specific point

p_∞: Air Density in Free Stream

V: Velocity of the airflow

p_0: Reference Pressure

Test specimens

In this study, a total of eight laboratory-scale specimens, including four hexagonal and four octagonal models, were tested using wind tunnel experiments. The specifications and naming conventions of these specimens are presented in Fig. 2. In the corresponding table and images, the parameter S represents the height-to-span ratio. It is important to note that the circumscribed circle diameter of the polygonal base of all pyramid models was 20 cm, while the heights of the specimens were set at 5 cm, 10 cm, 15 cm, and 20 cm, respectively. This precise design allows for a detailed analysis of the effects of geometric parameters on wind pressure distribution and aerodynamic performance.

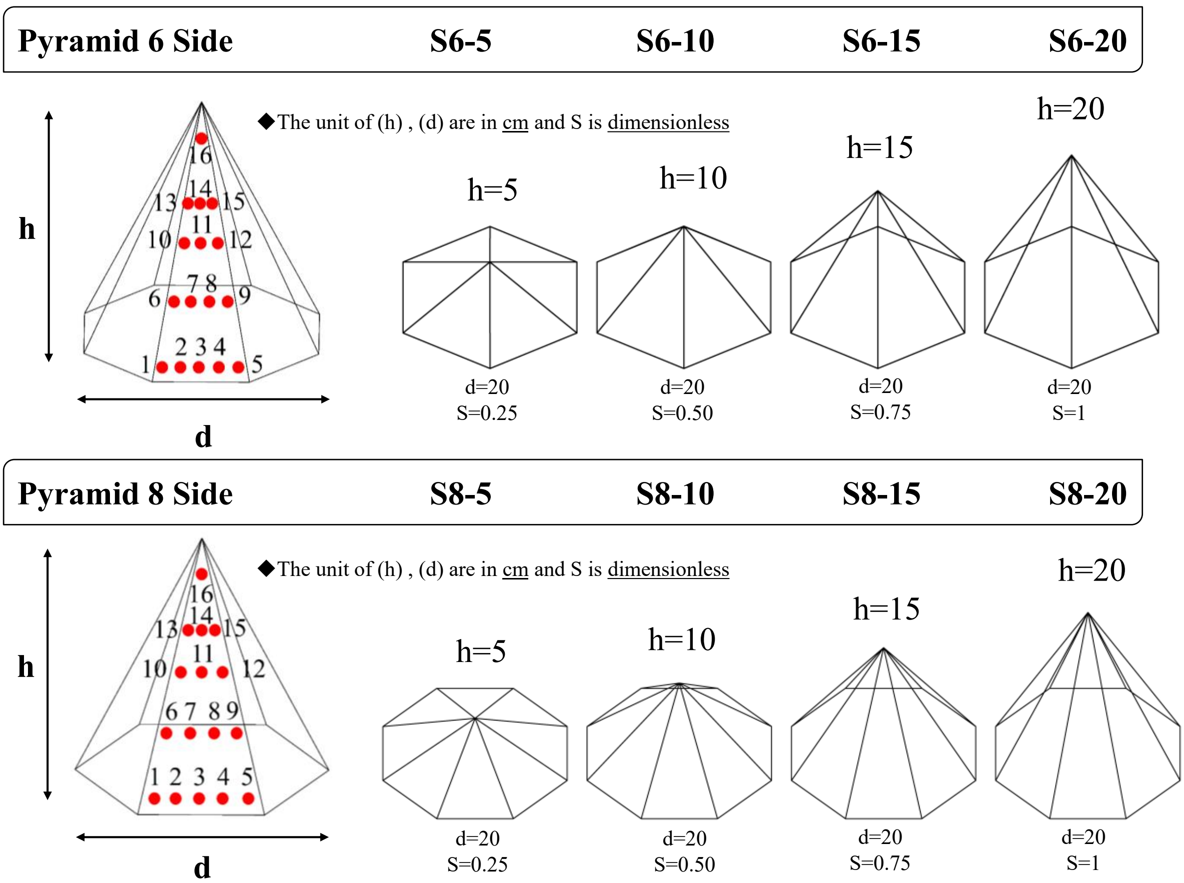

Fig. 2 Schematic image of pyramidal dome samples with a 6-sided (hexagonal) base and an 8-sided (octagonal) base investigated in the research

To measure the wind pressure on the faces of the pyramids at various angles, sensors were installed on one of the faces of each pyramid model. Considering the limitation in the number of available sensors for measuring wind pressure coefficients, sixteen sensors were strategically positioned on one face of each specimen. This configuration facilitated the precise determination of wind pressure coefficients at the specified locations. Fig. 3 illustrates the placement of the scaled shelter models within the wind tunnel, along with the tunnel equipment, sensors, and associated analytical systems. This setup is designed to ensure the collection of precise and reliable data on wind pressure distribution at the designated points. Such information is crucial for analyzing the aerodynamic behavior of the structures under wind flow conditions.

Fig. 4 The placement of domes in the wind tunnel, tunnel equipment, sensors, and analytical systems

To determine the pressure coefficients at all designated points, the models were mounted on a circular platform and rotated within an angular range of 0 to 180 degrees in 5-degree increments. The corresponding pressures at each position were recorded by the installed sensors. Subsequently, the pressure coefficients were calculated using the fluid dynamic pressure conversion equations. Fig. 4 illustrates the applied loading conditions and the sensor connections.

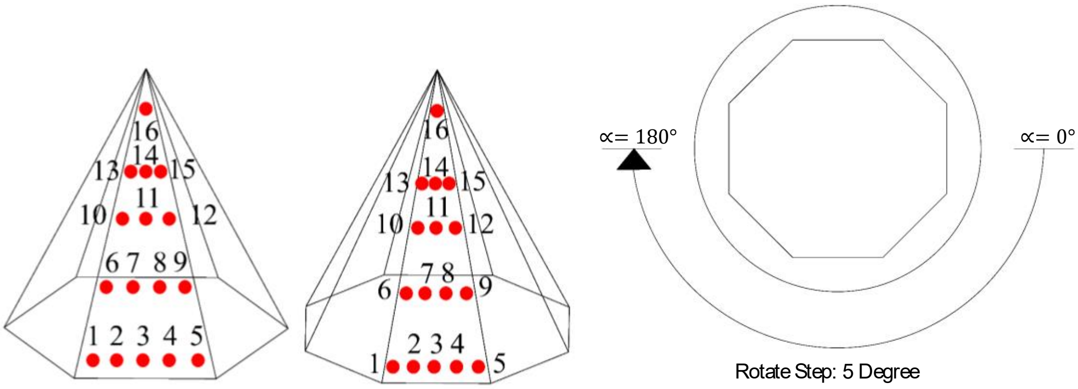

Fig. 4 The evaluated sensors and how to apply wind force

3- Results and Discussion

Wind tunnel experiments were conducted on both hexagonal and octagonal models, and pressure coefficient data were recorded at various points. Comparative pressure coefficient graphs were then plotted and analyzed for each corresponding sensor location on the hexagonal and octagonal specimens to evaluate their aerodynamic performance.

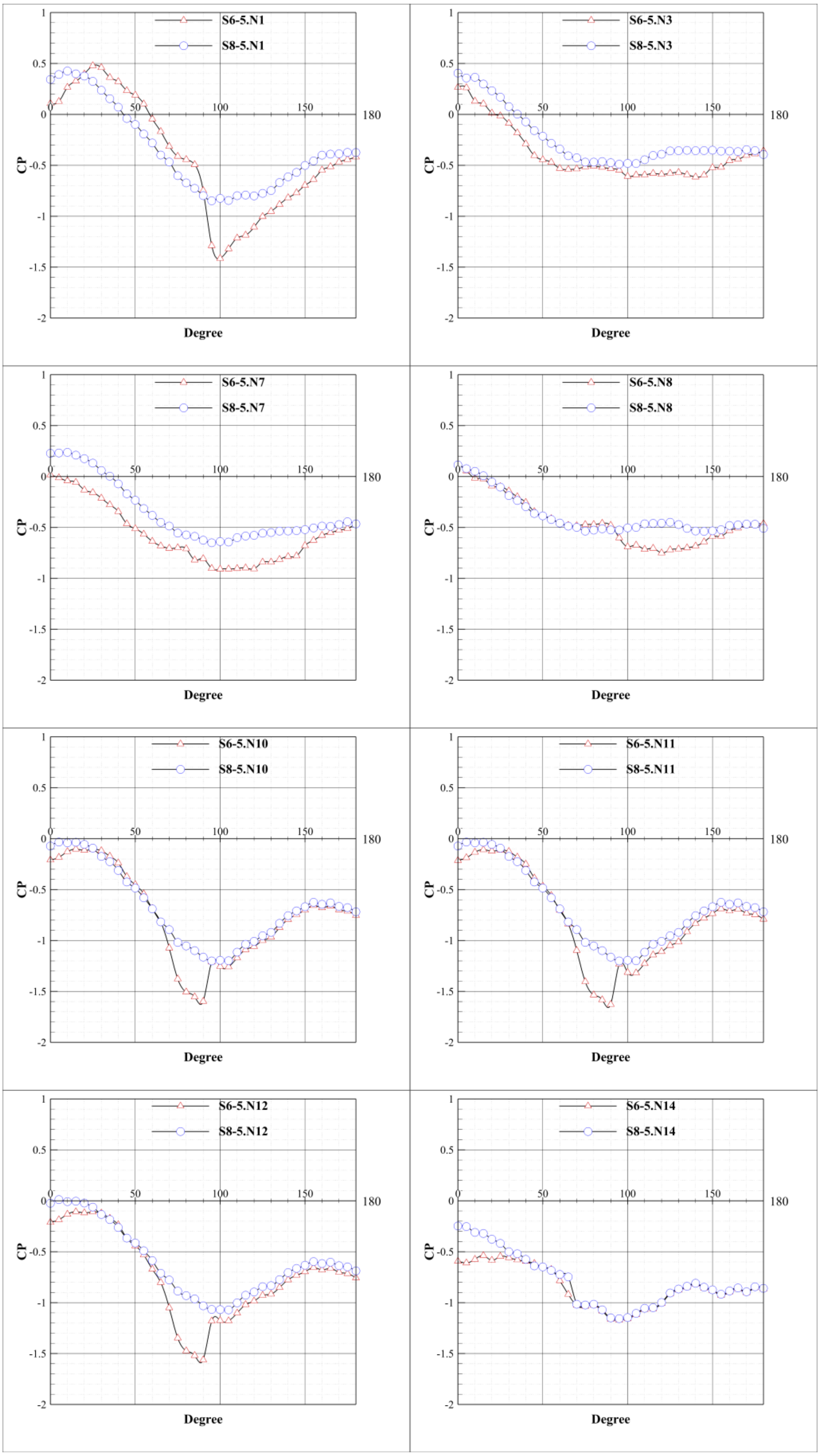

Fig. 5 The distribution of wind pressure coefficients on pyramids with a height-to-span ratios of 0.25 (height of 5 cm) obtained from wind tunnel experiments.

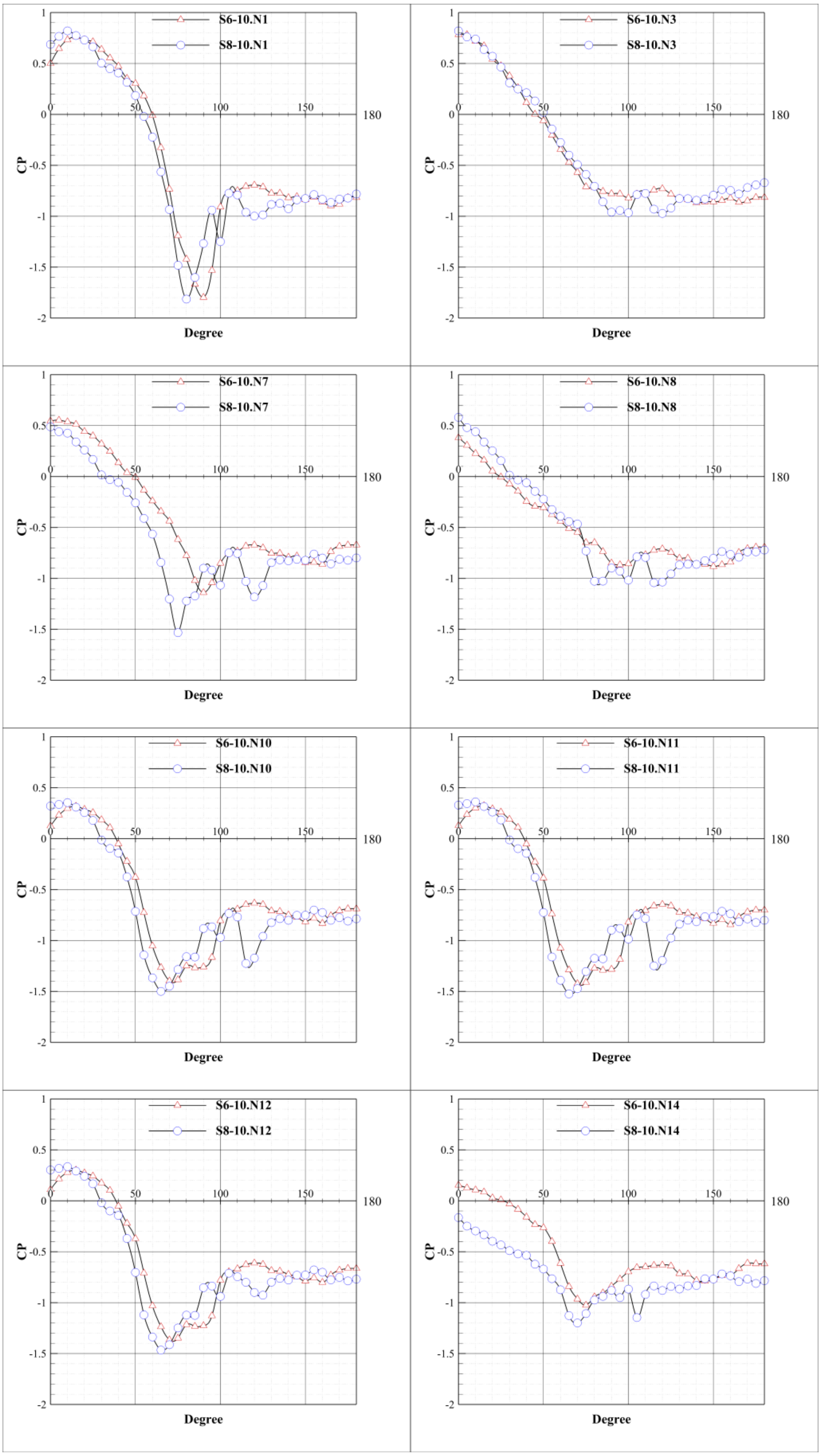

Fig. 6 The distribution of wind pressure coefficients on pyramids with a height-to-span ratios of 0.5 (height of 10 cm) obtained from wind tunnel experiments.

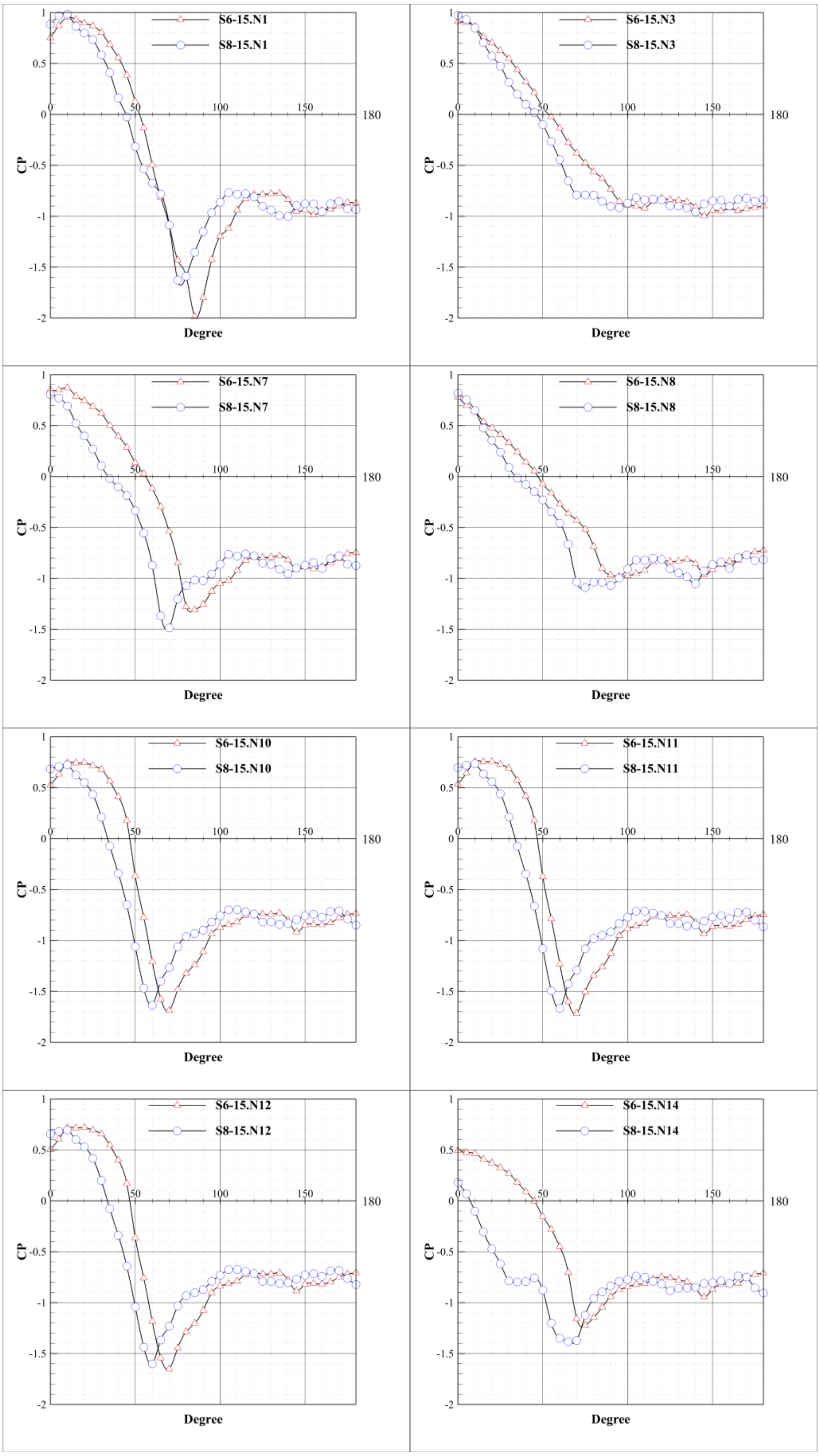

Fig. 7 The distribution of wind pressure coefficients on pyramids with a height-to-span ratios of 0.75 (height of 15 cm) obtained from wind tunnel experiments.

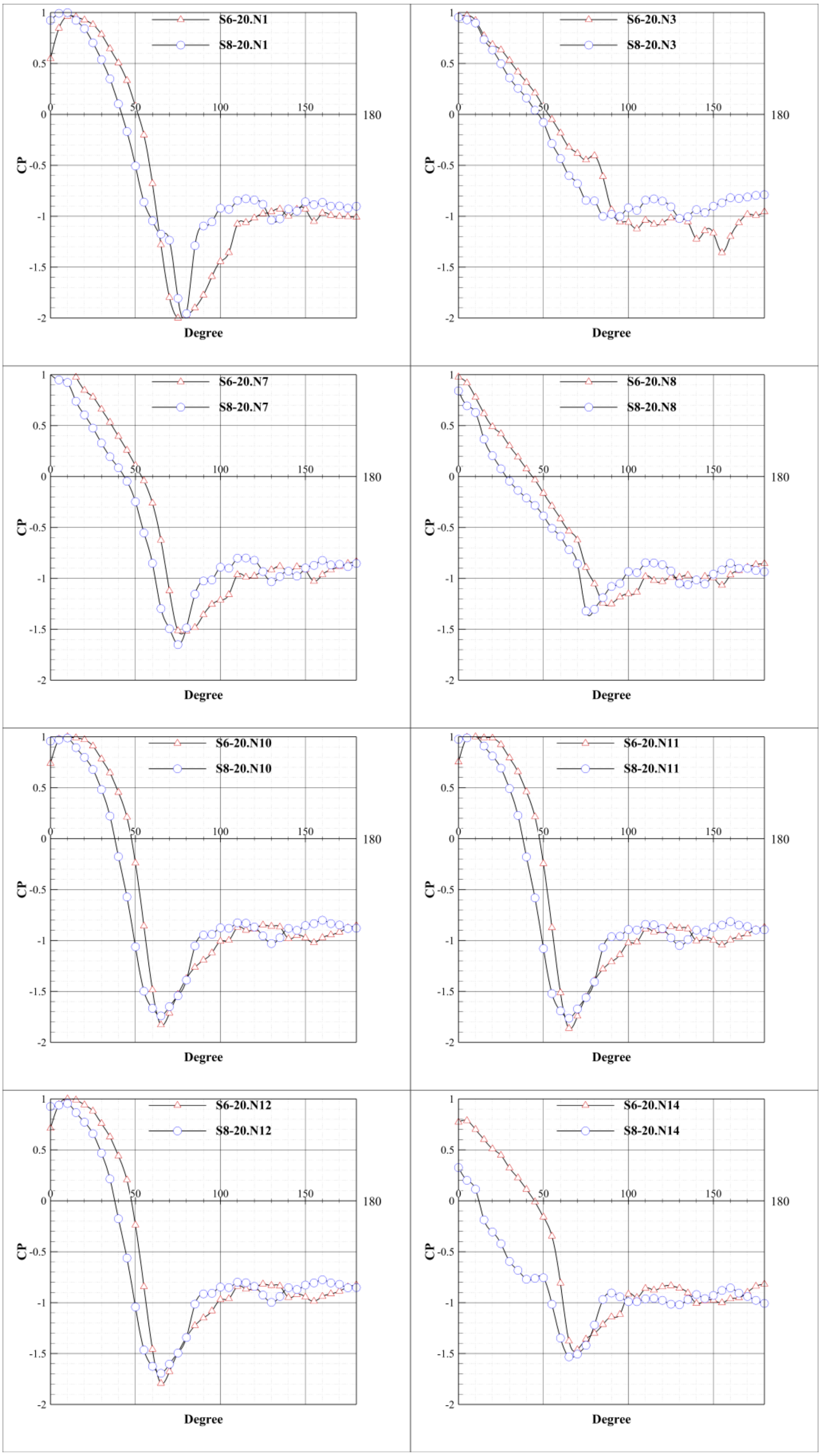

Fig. 8 The distribution of wind pressure coefficients on pyramids with a height-to-span ratios of 1 (height of 20 cm) obtained from wind tunnel experiments.

Figs. 5 to 8 illustrate and analyze wind pressure coefficients for hexagonal and octagonal domes with varying heights. Fig. 5 presents pressure coefficients for domes with a height of 5 cm, Fig. 6 for 10 cm, Fig. 7 for 15 cm, and Fig. 8 for 20 cm. These coefficients were calculated and plotted for different points, considering variations in wind force application angles. In each case, the maximum suction and maximum pressure were comparatively analyzed between hexagonal and octagonal domes, with the results summarized in Tables 1 and 2. These findings further elucidate the influence of dome geometry and height on wind pressure distribution and aerodynamic performance.

Table 1: Maximum pressure and suction coefficients in the 6-sided sample and different heights

S6-5	S6-10	S6-15	S6-20	
0.48	0.78	0.95	1.14	Cp(max)
-1.63	-1.79	-1.99	-2	Cp(min)

Table 2: Maximum pressure and suction coefficients in the 8-sided sample and different heights

S8-5	S8-10	S8-15	S8-20	
0.43	0.82	0.96	1	Cp(max)
-1.48	-1.81	-1.67	-1.96	Cp(min)

During the experimental study, hexagonal and octagonal pyramid-shaped structures were tested in a wind tunnel by rotating them in 5-degree increments from 0° to 180°. Pressure coefficients (Cp) were measured at various nodal points on the surfaces of the models to evaluate aerodynamic performance under different wind attack angles (α). These measurements were analyzed for structures with varying heights (5 cm, 10 cm, 15 cm, and 20 cm), and the results are presented in Figs. 5 through 8.

Each subfigure represents the variation of Cp across a specific nodal point for both hexagonal (S6) and octagonal (S8) pyramids at a given height. The curves illustrate how Cp evolves with changing α, thereby capturing the windward and leeward aerodynamic behavior of the structures.

General Observations Across All Heights and Nodal Points:

1. **Windward vs. Leeward Behavior:** At low angles ($\alpha \approx 0°–30°$), the windward surfaces of both geometries exhibit positive Cp values, indicating pressure buildup due to direct wind impact. As the angle increases ($\alpha > 60°$), Cp values transition into negative regions due to suction effects on the leeward side, reaching peak suction typically between 90° and 120°.

2. **Maximum and Minimum Cp Values:**
   - The **maximum suction** recorded across all heights reached up to **-2.0**

for hexagonal pyramids and **-1.96** for octagonal pyramids.

- The **maximum positive Cp** was **1.14** for the hexagonal shape and **1.0** for the octagonal structure. These values indicate that hexagonal pyramids generally experience both higher positive pressures and deeper suction, suggesting more abrupt aerodynamic transitions compared to octagonal counterparts.

3. **Effect of Pyramid Height:** An increase in height corresponds to higher Cp magnitudes for both positive and negative peaks. This implies that taller pyramids are more susceptible to intense wind-induced pressure fluctuations due to increased surface exposure and sharper inclination angles.

4. **Influence of Geometric Configuration:** Across nearly all nodal comparisons, octagonal pyramids demonstrated smoother and more stable Cp curves, with fewer abrupt changes than hexagonal ones. The additional faces in the octagonal structure help distribute wind loads more uniformly, reducing pressure concentration at any single node.

Node-Specific Trends:

N1, N10, and N12 (Edge/Corner Regions):
These nodes consistently exhibited sharp transitions in Cp values, particularly in the α = 60°–90° range. This is attributed to flow separation and reattachment phenomena that typically occur near geometric discontinuities such as edges and corners. These points represent critical locations for design considerations as they experience localized peak suctions and abrupt pressure shifts.

N3, N7, N8, N11, N14 (Mid-Face and Lateral Regions):
These nodes demonstrated more gradual transitions in Cp, reflecting more stable aerodynamic behavior across wider surface areas. However, significant dips in Cp can still be observed as α approaches 90°, consistent with expected wake effects and reverse pressure zones forming on the leeward sides.

Height-to-Base Ratio Effects:
As the height-to-span ratio increases (i.e., from 0.25 to 1), the peak values of both pressure and suction coefficients increase, emphasizing the role of geometry in wind load sensitivity. Conversely, lower structures (e.g., 5 cm height) display flattened Cp profiles with reduced extremes, indicating lesser aerodynamic excitation.
Additionally, closer spacing of contour lines in these regions (as also evident from Cp contour plots not shown here) denotes steep pressure gradients, particularly near the wind separation zones. This effect becomes more pronounced in taller hexagonal pyramids due to sharper edges and fewer planar transitions compared to octagonal pyramids.

In summary, it can be concluded that:

- Hexagonal pyramids demonstrate **greater Cp variability**, indicating higher aerodynamic instability and pressure sensitivity.
- Octagonal pyramids benefit from **distributed loading**, resulting in **lower pressure fluctuation intensity**, smoother aerodynamic

behavior, and thus better overall performance under wind loading.

- The **transition from positive to negative Cp** is more abrupt in hexagonal pyramids, likely due to fewer faces and sharper transitions in surface angle.

For a comprehensive analysis, pressure coefficient contours were generated for all pyramid faces, as shown in Figs. 10 and 11. These contours provide detailed information on pressure distribution across different surfaces of the structures.

In Figs. 9 and 10, wind pressure coefficient (Cp) contours are illustrated for hexagonal and octagonal domes at four different heights (5, 10, 15, and 20 cm). These results were derived from wind tunnel experiments and visualized using **Tecplot 360 Ex** software. As previously described, pressure sensors were installed on a specific sector of each dome model, and the domes were incrementally rotated in the wind tunnel from 0° to 180° to capture pressure distribution at various angles. Specifically, at α = 60°, pressure coefficients were recorded for the first left and right sectors; at α = 120°, for the second lateral sectors; and at α = 180°, for the leeward sector. The collected Cp values were then projected as two-dimensional contours on the surface geometry of each model, providing a clear visual representation of pressure distribution. The results indicate that increasing dome height leads to higher positive pressure on the windward face and intensified suction on the leeward side. This trend is observed across both geometries, although the hexagonal domes exhibit more pronounced pressure fluctuations and concentrated suction zones. For instance, in model 6S.20, darker regions near the bottom of the dome correspond to strong suction, with Cp values approaching -2.0. In contrast, models like 8S.20 show smoother pressure distributions and more uniform Cp gradients, reflecting more stable aerodynamic behavior.

Pressure variations in the contour maps are influenced not only by geometry but also by the spacing between contour lines. Areas with closely spaced lines indicate steeper pressure gradients, typically occurring near edges and face transitions. This phenomenon is more pronounced in hexagonal domes due to their fewer faces and sharper angular transitions. The more uniform pressure distribution observed in octagonal domes suggests that wind loads are spread more evenly across the surface, reducing localized force concentrations.

From a technical standpoint, this analysis is valuable for identifying high-pressure and high-suction zones, offering critical insights for optimizing structural design. Zones with elevated positive pressure on the windward side may be more vulnerable to direct wind loads, whereas regions with intense suction on the leeward side may experience flow separation and aerodynamic instability. Such data can inform the design of temporary or wind-resistant shelters, especially in regions prone to high wind loads or where natural ventilation, structural stability, and pressure mitigation are of paramount importance.

Overall, the Cp contour analysis reveals that increasing structural height amplifies pressure intensity on both windward and leeward surfaces. Furthermore, the octagonal geometry demonstrates superior aerodynamic performance due to more balanced wind load distribution, smoother pressure gradients, and reduced suction concentration. These findings underscore the aerodynamic advantages of symmetrical polygonal geometries—such as octagonal domes—as viable solutions for the efficient and resilient design of temporary structures in challenging environmental conditions.

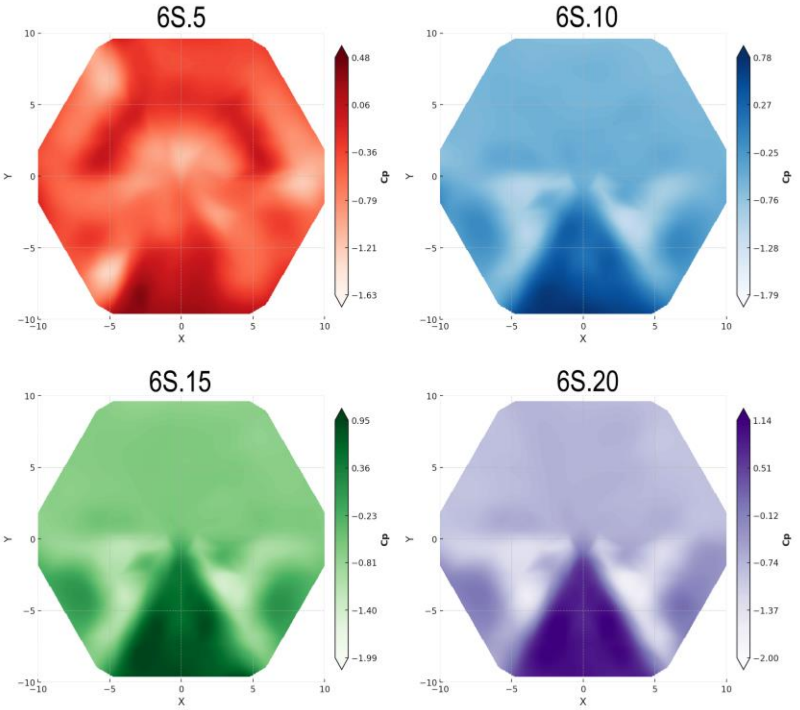

Fig. 9 Contours of wind pressure coefficients on hexagonal pyramids obtained from wind tunnel tests

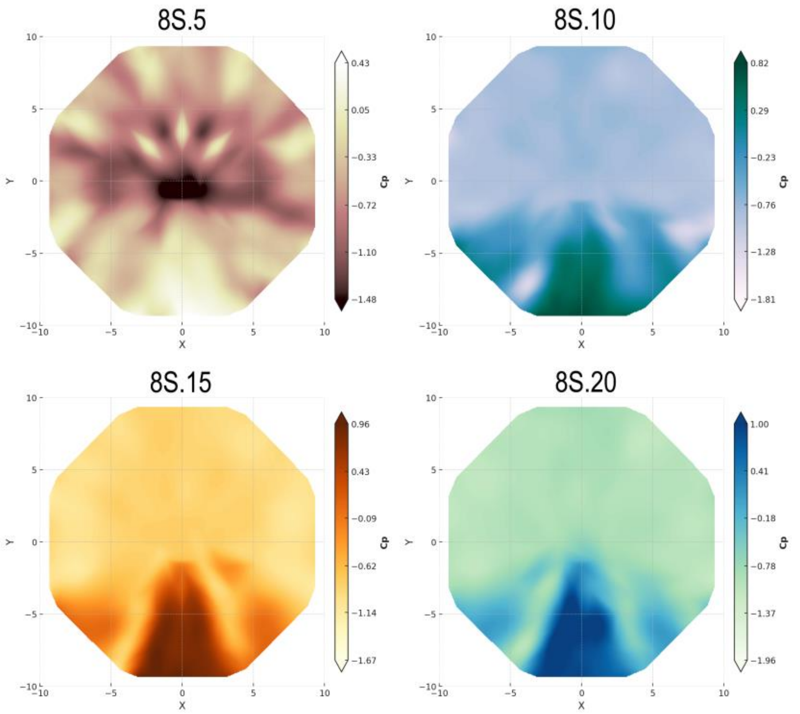

Fig. 10 Contours of wind pressure coefficients on Octagonal Pyramids obtained from wind tunnel tests

Site selection and spatial arrangement of temporary shelters

In the process of site selection for temporary shelters, after evaluating the wind forces on a single shelter, the focus shifts to assessing the arrangement of the entire shelter system. At this stage, it is crucial to pay particular attention to the effects of wind and its prevailing direction as a key factor. Wind, being one of the most important atmospheric elements, can have a significant impact on the stability and performance of temporary structures. Similar to other environmental factors, wind can have both positive and negative effects on the shelters. The prevailing wind direction in a given area directly affects airflow distribution and natural ventilation within the shelters. This factor is crucial for both the site placement of shelters and the ventilation of the shelter's internal environment. Particularly in open areas and conditions with strong winds, it is essential to select locations where the wind can be properly directed and air stagnation is prevented. On the other hand, wind speed plays an important role in air dispersion and ventilation within the shelters. Wind speed can also affect the structural stability of shelters, especially in temporary shelters that may be more vulnerable to strong winds and rapid changes in weather conditions. Properly conducted site selection and spatial arrangement of shelters can significantly enhance the structural resilience against environmental changes and prevent issues caused by wind exposure. For this, areas should be selected where the shelters are not exposed directly to the prevailing wind, thereby minimizing the negative effects of wind [31]. Drawing inspiration from bee hives for the arrangement of temporary shelters, especially in pyramid shapes, can be an interesting and innovative approach. Bee hives, due to their pyramid-like and coordinated structure, provide an efficient and stable arrangement for housing bees. These characteristics can be utilized in the design of temporary shelters to tackle environmental challenges such as wind, structural stability, and optimal space usage.

In a pyramid-shaped arrangement, the use of structures similar to bee hives can improve stability and optimize airflow. Pyramids, especially when combined with polygonal geometries, can create independent and resilient spaces that prevent strong winds and rain while also contributing to natural ventilation. This organized arrangement can provide sufficient space for displaced individuals while maintaining resilience against environmental pressures such as wind and rain. As a result, if the shelters are designed based on pyramid-shaped patterns resembling bee hives with an orderly and coordinated arrangement, the topology of this setup can contribute to creating sustainable, resilient, and functional shelters that perform well, especially under stormy conditions and strong winds. Moreover, this design can help in optimizing the use of available space and fostering a better interaction between the shelters and their surrounding environment.

4- Conclusions

This study evaluated the aerodynamic performance of temporary shelters with pyramid-shaped structures, particularly in the form of hexagonal and octagonal bases, under the influence of strong winds. For this purpose, in wind tunnel experiments, 4 hexagonal structures and 4 octagonal structures with height-to-base ratios of

0.25, 0.5, 0.75, and 1 were simulated under laboratory conditions. The results showed that octagonal shelters, due to more uniform wind load distribution, were more stable against wind forces compared to hexagonal shelters. Moreover, hexagonal shelters experienced higher pressure compared to octagonal shelters. Pressure coefficients on the windward faces increased positively, while on the leeward faces, negative values were recorded, indicating suction in these areas.

The study demonstrated that octagonal shelters perform better against strong winds due to their unique geometric features. The pyramid structure of these shelters, with uniform wind load distribution, reduces pressure on the surface and prevents severe suction. Particularly, at angles of 120 to 140 degrees, octagonal shelters exhibited the most stable pressure coefficients and delivered the best performance. Another significant advantage of pyramid shelters is their high aerodynamic stability. The design of these structures allows wind forces to be more evenly distributed across the surface, reducing direct pressure. Additionally, geometries that lean toward a cone shape can help reduce suction on the leeward faces. This leads to decreased pressure fluctuations in octagonal shelters, as the increased number of faces and the lack of force concentration at a single point provide greater stability against wind variations. The structural integrity of pyramid shelters was also improved. The pyramid geometry and the presence of multiple faces result in better wind load distribution and reduce concentrated forces at connection points, making these shelters more resilient compared to simpler base structures. In particular, the advantages of octagonal shelters make them perform better against intense winds. Economically, the pyramid design allows for more efficient use of materials while maintaining the same level of strength, reducing both costs and construction time. Furthermore, the installation of these structures is simpler than more complex designs, which leads to lower costs and faster construction processes. Considering these advantages, it can be concluded that geometric pyramid designs, especially octagonal shelters, due to their high aerodynamic stability, structural strength, reduced pressure fluctuations, and resistance to severe weather conditions, are one of the best options for temporary shelters in emergency conditions. These designs not only guarantee safety and stability but are also cost-effective and perform better in crisis conditions. Therefore, the use of these designs in disaster management and the construction of temporary shelters can be considered an effective and ideal option.

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Conflict of Interest

There are no conflicts of interest associated with this publication.

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