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ASSESSMENT CRITERIA FOR FORM ENVIRONMENTAL PERFORMANCE OF BUILDING ENVELOPE IN HOT ARID CLIMATES

Ahmed Elseragy[1], Amira Elnokaly[2]

[1,2] Assistant Professor -Architectural Engineering and Environmental Design Department
Arab Academy for Science and Technology - AAST- Alexandria - Egypt.
ahmed.elseragy@aast.edu; amira.elnokaly@aast.edu

ABSTRACT: This paper represents the methodology carried out for the investigation of a part of a multiphase experimental research work that examines the effect of various forms and geometries of building envelope elements on indoor environments under given summer or winter conditions. The research also includes the influence of outer envelope form upon indoor thermal conditions, external and internal solar behaviour, natural ventilation and day lighting performances under particular climatic conditions. The different phases aim at investigating large number of roof and wall forms using different measurement tools and techniques; onsite and experimental investigations, laboratories rigs, and computational simulations. The research-project considers the environmental properties of spaces enclosed by different architectural forms and geometries in order to find out their Forms' Environmental Performance (FEP). The lack of appropriate tools for environmental investigations of some building-envelope forms and their internal and external environmental respond scenarios are identified along with better understanding of form environmental benefits. This research has been carried out on various curved roof forms being the most popular roof form in hot arid regions; in this paper the conical roof form will be discussed in more detail.

Keywords: Building Envelope - Form Environmental Performance - Solar Radiation – Air Flow - Egypt

1. INTRODUCTION

Limitations in the understanding of environmental and thermal performances of architectural forms have to some extent hindered their acceptance by building clients and the building industry. The research-project focuses on the form and geometry of traditional building-envelope elements and the environmental behaviour of their enclosed or semi-enclosed spaces. Roof and walls as elements of building-envelope are unequally exposed to the sun and receive various amounts of solar radiation. Therefore, forms and shapes of building-envelope elements can influence the received amount of solar radiation, thermal transfer, and outer/inner aero-patterns, consequently enhance the indoor environments in buildings. Traditional building-envelope forms; conical-tents (fabrics), domes, and vaults have been used for a long time in different parts of the world for historical, cultural, climatic, and structural reasons.

The paper investigates the effect of various forms, configurations and orientations of curved roof and wall forms such as conical fabrics and domes on the solar and airflow behaviour under, around and above these structures in hot arid climates. In addition, to other climatic and physical factors, thermal comfort in hot-arid climates is significantly influenced by the amount of solar radiation it receives and by airflow behaviour and airspeed in the enclosed or semi-enclosed space.

In addition to the lighting and shading functions that curved roof forms provide, the topology of the construction type offers exciting opportunities to lend additional functionality, and possibilities for their use as microclimate modifiers as will be discussed in this paper.

The conical form is chosen in this study being one of the simplest and most frequently used tent or fabric membrane form used in the built environment, thus it was decided to use this form for the empirical study carried out for the purpose of this research. The conical shape has also been used in several projects in hot regions e.g., the Haj terminal, the Medina Umbrellas and the Mina Pilgrims in Saudi Arabia, the Hussein Mosque Umbrellas in Cairo, Egypt [1].

In order to evaluate the FEP to predict the thermo and aerodynamic scenarios of outer and inner building-envelope surfaces with different geometrical configurations and orientations, parametric studies and mathematical modelling were carried out. The results of these investigations are followed by extensive investigations of the same models in CFD (computational fluid dynamics software) "FLUENT 6" where it is faster to test much more forms after the validation of the used software. Previous research has been carried out by the authors on domed and vaulted roofs and has been presented in other research papers. In this paper work done on conical forms with similar geometrical resemblance and form finding methodology will be discussed in more detail. The final results of these investigations will be disseminated in forthcoming publications.

2. POTENTIALITIES OF FEP INVESTIGATION

This work aims at establishing sound theoretical and technical bases for the validity of various claims of the environmental design advantages of different vernacular and traditional forms (Tent-shape, Domes, and Vaults) in different climatic regions and especially in hot-arid regions. There is an urging need to figure out number of environmental and sustainable potentials of building-envelop forms, which is believed to be novel contribution to the architectural knowledge and the understanding of vernacular and traditional forms climatic and environmental behaviours. These forms are being used today in contemporary architecture due to social or cultural aspects without a full understanding of their environmental privilege in such climates. Investigations carried out on domes and vaults [2] had shown that they have environmental potentials and other research on conical forms is discussed in this paper.

3. INVESTIGATION METHODOLOGY, PROCEDURES, AND PHASES

Previous research works have been carried out to calculate the day-lighting, air movement, solar, and thermal performances of planar surfaces; horizontal and oblique. However, it is not an easy task to clarify the environmental performance of arbitrary building-envelope forms and shapes, especially in terms of predicting the received amount of solar radiation intensities and air-patterns and velocities above and around their outer and inner surfaces.

3.1 Form Finding and Geometrical Resemblance

Form finding of arbitrary building-envelope is quite a complex process. It is also a very important stage in the FEP investigation process, not only because it determines the form and its geometrical configurations, but also because it accurately simplifies the outcomes. It also abridges its simulation and understanding in different computer soft wares.

a. Previously Tested Curved Forms

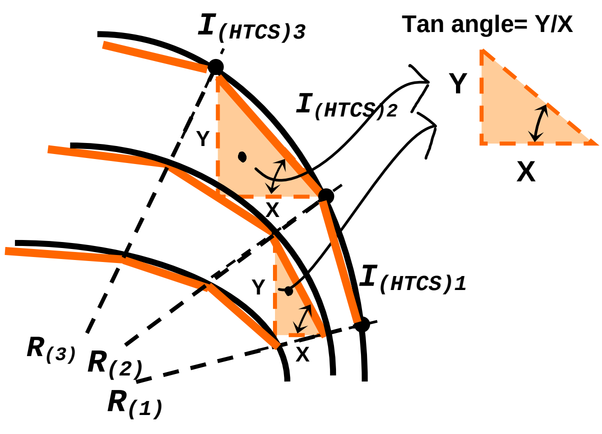


Figure 1 Geometrical resemblance & form finding methodology of tested curved roof geometries

b. Conical Tent-shaped Forms

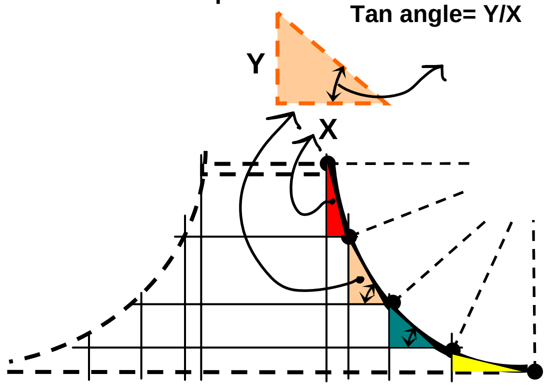


Figure 2: Geometrical resemblance & form-finding methodology of conical tent-shaped forms

There are a number of methods used for form finding and analysis of arbitrary forms, such as dynamic relaxation, force density, and soap film models. This requires the employment of computer generated digital models for the form finding and CAD tools. Architects and engineers are quite familiar now with form finding computer software and geometrical resemblance techniques in order to retrieve such arbitrary forms to their initial shapes. Advanced form finding techniques and geometrical analysis of the complex three dimensional shapes of building-envelope elements has been employed in this research, as the geometrical resemblance of domes and cones shown in (Fig. 1 & 2) but due to the fact that this paper is only concerned with general illustration of the research-project proposition phase. The detailed review of these analytical techniques will not be discussed in detail.

3.2 Computer Simulation and Mathematical Modelling

Furthermore, computer simulation is very similar in concept to the experimental tests in terms of having a number of assumptions and simulations, which may not be similar to the real situation. Besides providing relative less time and effort to run [3], controlling the inputs in computer simulation is easy to control which is not an easy task to provide most of the time in physical models and lab work.

In order to validate the computer simulation outcomes, physical and experimental laboratory tests have been carried for conical-tent forms. Therefore, establish an advance verification of the outer-surface temperatures variation along the different parts of the building-envelope form. In addition to curved-roof forms, curved walls

Theoretical and experimental investigations have been conducted in order to predict the solar and airflow performances of such arbitrary surfaces. However, it is not an easy task to define the solar and airflow performances of conical–tent or curved forms, especially in terms of predicting the received solar radiation intensity above their outer surfaces, apparently due to the nature of their geometries.

Therefore, the proposed project includes three different phases representing various investigation and measurement tools for the environmental performances of building-envelope elements' forms and shapes.

These investigations include computational tests as well as experimental rigs. The computational ones are conducted using SRSM [4], ECOTECT [5] and IES (Integrated Environmental Solutions), at the school of built environment, University of Nottingham. In order to examine the FEP of different building envelope elements, both walls and roofs have been employed. The conical shape tested is shown in (Fig. 3 & 4).

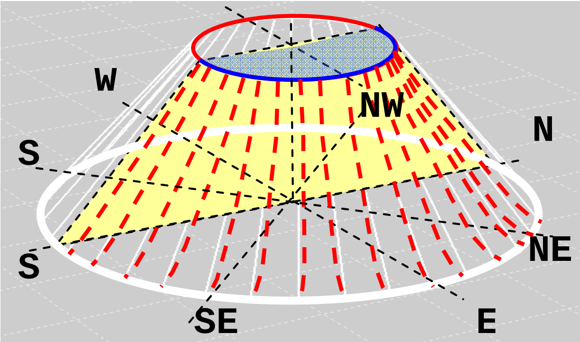


Figure 3: Multifaceted arches of conical-tent form; different sloped angles at different orientations

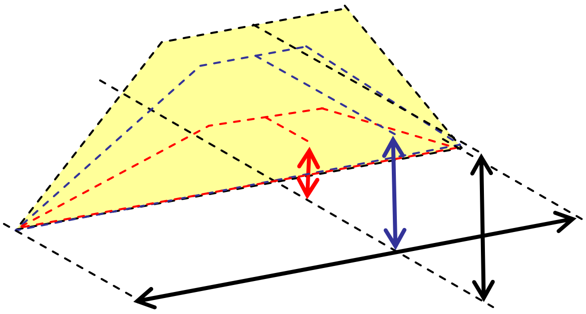


Figure 4: Conical-tent shape Cross-section Ratio CTCR (Height-to-span)

Computational calculations have proved that it is possible to undertake calculation of different environmental and climatic parameters in order to simulate the building-envelope environmental performance scenarios. Aerodynamics and received solar radiation of building-envelope forms and shapes can be computationally simulated and examined in order to find out their influences upon indoor and outdoor environments. Such complicated calculations can be computed on a large number of tilted planar segments that resembled the arbitrary forms as shown in (Fig. 2).

Different computer tools can be employed to figure out the environmental performance of surface's geometry (tilt-angle and orientation azimuth-angle) against various climatic parameters. The proposed research-project suggests number of several climatic parameters to be considered. Therefore, internal and external surface convection heat transfer calculations and detailed indoor thermal findings and outer/inner aero patterns of different arbitrary geometries are also investigated. Moreover, the research contemplates indoor air temperature and mean radiant temperature throughout the day in summer and winter. The effect of form and geometry on building-envelope external and internal solar, thermal, and aero behaviours under given summer and winter conditions is thus investigated thoroughly. This will facilitate the thermo and aerodynamics predictions of spaces enclosed by building-envelope with arbitrary forms, and thus increase their wider acceptance for different architectural applications in different climatic regions. It is also recommended that computer simulation packages must identify the geometrical parameters of such conical-tent, curved, and arbitrary forms of roof and walls in details in a similar way as the presented above.

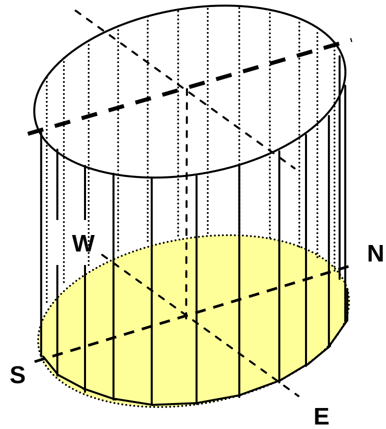


Figure 5: Different azimuth angles and orientations of multifaceted curved-wall react variously to climatic parameters

In addition to curved-roofs (domes and vaults), conical tent-shape forms and many other forgotten architectural and constructional vocabularies; such as Malqaf "wind-catcher", courtyard, and Mashrabya "windscreen" (such as those shown in (Fig. 6)) were representing regional architectural, urban and building identities. These vocabularies were not only a symbol for architectural identity, they successfully responded to their social, cultural, and climatic features, and successfully provided environmental design and sustainable key-elements in buildings. The FEP of some of their forms is recommended to be tested in future work in order to figure out the role of their geometrical configuration to provide comfortable indoor environments.

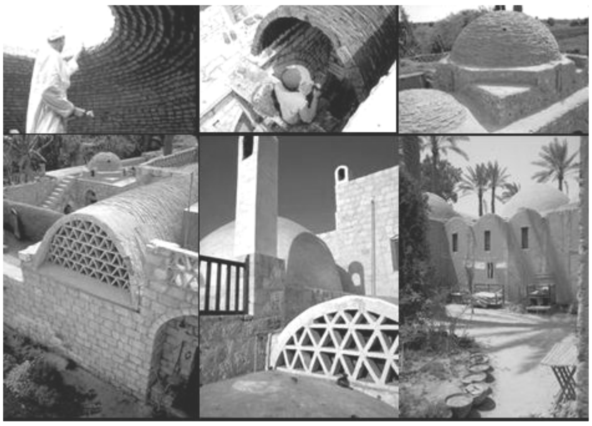
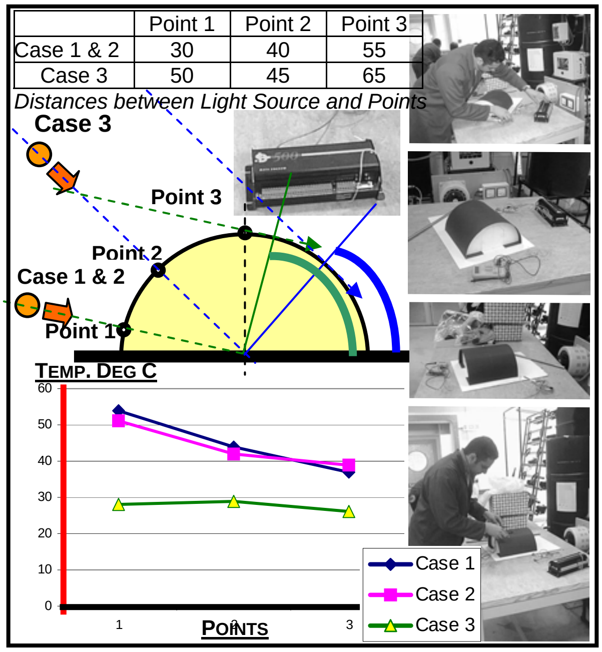


Figure 6: Traditional architectural vocabularies representing regional building identities.

3.3 FEP of Physical Scaled Models (Experimental Rigs and Laboratory Tests)

Despite their availability and viability, physical scaled models (PSM) in artificial skies are restricted to the conditions of laboratories simulation and their validation results.

Number of PSM rigs are built and tested in order to find out the FEP of building-envelope. As this research project investigates the direct impact of form and geometry morphologies of building-envelope on indoor environments. Therefore, number of climatic parameters is being examined in order to figure out the influence of surfaces' geometrical configurations on indoor environments conditions.



	Point 1	Point 2	Point 3
Case 1 & 2	30	40	55
Case 3	50	45	65

Figure 7: FEP of Physical Scaled Model PSM *(Curved-forms Solar Radiation Rigs)*

The solar radiation rig (Fig. 7), which measures the solar intensity at several points above various roof and wall forms identifies the role of building-envelope form on the received amount of solar radiation above these surfaces. Therefore, the inner-surface and indoor temperatures are influenced by difference in solar intensity along the surfaces. This solar radiation-form rig is carried out in support with radiation sensors and measurements tools (Pyranometer).

(Fig. 7) sketch the proposed PSM for solar and thermal tests in hot desert-alike climates. For indoor thermal measurements, data loggers shown in (Fig. 7) and thermocouple are required for monitoring the effect of roof and walls forms on the indoor temperature and mean radiant temperature. No openings to be created in order to make the inner volume sealed as much as possible. This, however, could require special materials for assembling the PSM, as well as uniform and invariable indoor conditions during the measurement process. Both solar and air flow performances have been considered. The outcomes in (Fig. 7) show significant differences on outer-surface temperatures from one point to another along curved-roof. The temperature value at each point was not taken into consideration due to the positioning of two different light sources with different distances from the PSM. However, pointing out the temperature difference between the three points at each case was worthwhile. This test was carried out using light sources (simulating the sun), temperature sensors (Thermocouples T type) at different points along the roof curvature, a data logger and computer. The distance between the light source and each point has been taken into consideration while comparing each point temperature.

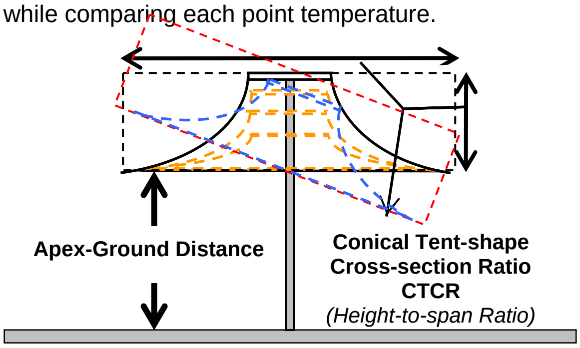


Figure 8: Diagram of Conical Tent-shape Cross-section Ratio (CTCR) and Apex-Ground Distance

The cones tested in experimental work and in the computational fluid dynamics varied in heights and inclination as shown in (Fig.8) and this highly influenced their environmental performance. The structure tested in the wind tunnel consisted of a conical fabric structure with an adjustable cone height. The cone's apex could be either opened or closed in order to investigate the effect it might have on the airflow pattern and rate (Fig. 9). The height of the supporting mast was adjustable. The cone could be inverted to represent an inverted cone, and its base could be either opened or closed as well. The height of the straight or inverted cone from the ground was kept constant in experiments at all times.

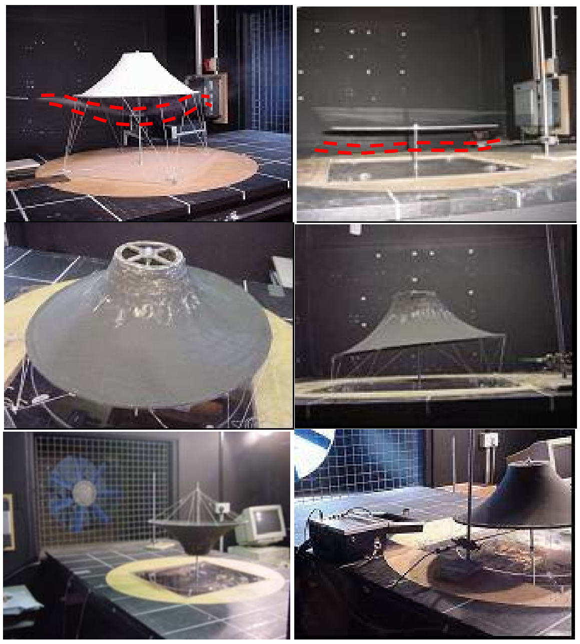


Figure 9: Photos depict the conical structure PSM tested in the Wind tunnel; *Straight, Inverted and Inclined.*

3.4 FEP of Full-Scaled Investigational Boxes

This phase has been proposed in order to create more validated results and outcomes, but due to actual reason of this paper, the detailed results of this phase will be presented in another paper.

Scaling is also one of the limitations of both computer simulation and experimental lab tests. However, in computer simulation some of these limitations are overcome due to the fact that it employs real dimensions and sizes for tested objects and spaces. On the other hand, predicting the intensity of received solar radiation on curved forms by different solar radiation calculation tools and simulation software can be very satisfactorily performed by the proper geometrical resemblance technique. Consequently, full-scale models can be built in real climatic conditions to avoid the previous disadvantages and difficulties of experimental lab tests.

As explained previously in the physical scaled models and experimental rigs, data loggers and thermocouple are required for monitoring the effect of roof and walls forms on indoor thermal measurements. It is also recommended to avoid creating wall openings in order to eliminate ventilation effects and to make the inner volume sealed as much as possible. This, however, could require special materials and fixed indoor conditions during the measurement process, a schematic proposal is shown in (Fig. 10).

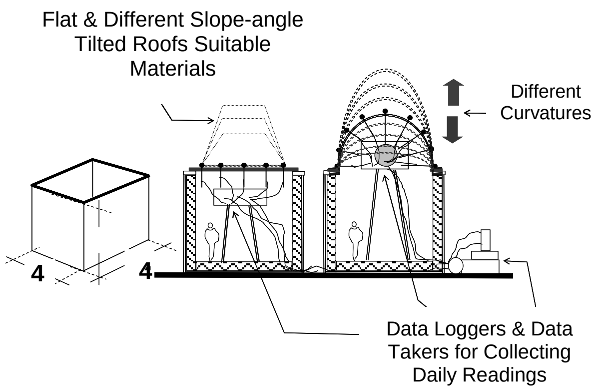


Figure 10: A schematic proposal for full scale model monitoring, Onsite Environmental Box (OEB)

The suggested solar and thermal investigations have to be carried out using various full-scale roof and walls forms. In addition to a flat (horizontal) roof, the proposed full-scale model may represent an extended curved-roof cross-section (vault), a rotated one (dome) with test cells placed along the outer surface, a tent-shape, and different sloped roofs. The purpose of such full-scale study is to facilitate better understanding of FEP of building-envelope outer surfaces and to compare to the simulated findings. It may also test the curved roofs thermal performances. Therefore, this section discusses number of recommendations for such tests. As concluded in previous researches, other factors like building-envelope colour, layers components and thickness and thermal properties of construction-materials can significantly influence the amount of gained solar heat by receiver surfaces. Moreover, all full-scale models features and components have to be taken into account throughout the full-scale measurements (i.e. full-scale models must be erected from similar materials and colours). A sample sketch of full scale model is shown in (Fig. 10).

3.5 FEP of Existing Building-Envelope Elements

In addition to the previous tests, this research work aims to monitor the solar behaviour above number of existing buildings roofs in different climatic regions in general and in hot-arid climates in particular, especially those with curved-roof forms (Vaults and Domes) in order to find out their FEP. This is to validate and be compared with the full-scale and computer simulation results and will reflect true conditions. This helps to have a better understanding of the behaviour and the effects of these forms in the built environment and can also be useful for post occupancy evaluation.

This will take place using the same employed instrumentation in the physical-scaled-model tests. The monitored buildings will be in the southern part of Egypt which is the proposed area of case study, which is a hot arid climate. Egyptian government aims to develop several areas of the southern part of Egypt, in order to go out of the narrow valley. The harsh climatic conditions of these areas represent one of the main obstacles to do so [6]. The construction techniques, materials, forms and shapes have a great role in order to tackle such harsh climate. Therefore, such forms should be used for roofing in new communities with harsh climatic conditions in Egypt (Tushka for Example see Egypt's Map (Fig. 11)).

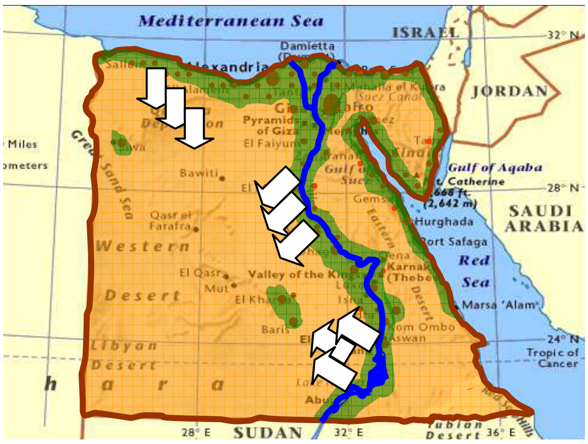


Figure 11 Tushka and Egypt's Southern Areas Development and New Urban Extensions away from the Nile Narrow Valley

However, due to the fact that this paper is only concerned about disseminating the successful proposal and methodology of work, the detailed review of these analytical techniques will not be presented in this paper. Beside the full-scale investigations, the research suggests number of enhancement ideas, which could be incorporated into the proposed research-project.

Solar and thermal performances of traditional vaulted and domed roofs can be enhanced when they integrate with other architectural elements. This has been proved in Vernacular and traditional architecture. Further studies on the effect some architectural elements such as a small opening in the apex of different curved-roof forms, a doubled layer curved-roof, or both elements together are planned to be tested with the environmental investigation of vaulted and domed roofs on a later stage.

4. ROLE OF CONICAL TENTS TO ENHANCE THE MICROCLIMATE IN ITS VICINITY

The topology and form of the fabric conical structure can be used to alter the quantity and direction of solar radiation entering the enclosure. These can also be used to modify the airflow underneath the structure and in its vicinity [7]. Conical Fabric materials can be merely used for creating an intermediate climate or meso-climate that acts as a buffer between the external climate and the environmentally controlled interior of the building to moderate and regulate them rather than shutting it out completely. Some forms of conical structures where the main aim of the structures was to modify the microclimate within the opened or enclosed space are shown in (Fig. 12), in addition to providing dramatic, attractive modern pieces of architecture.

Figure 12 Photos depict different fabric membrane structures for opened, semi-enclosed, and enclosed space as microclimate modifiers

A number of traditional passive cooling systems can be effectively used in conjunction with fabric membranes, such as: evaporative cooling using water cascades, mist sprays or fountains, cooling towers, fans, stack effect and self shading shown in (Fig. 13). All of these strategies can be used to enhance the benefit of conical fabric structures in hot climates [8].

Incorporating movable sunshades or insulation into the design can prevent unwanted excessive heat gains, which might be caused by this approach even in cold climates.

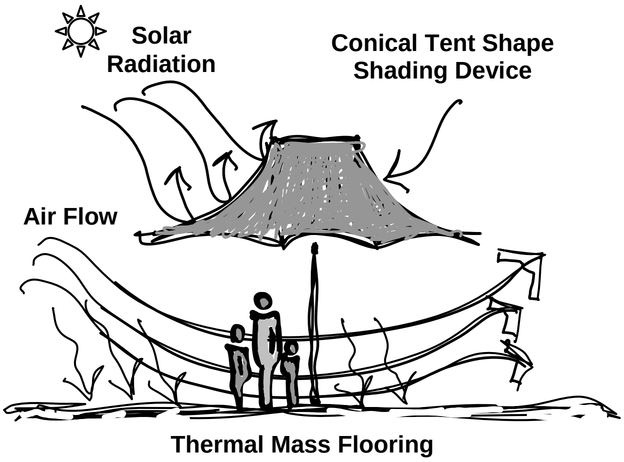


Figure 13: Environmental Design Potential of Conical Tent-shaped Forms

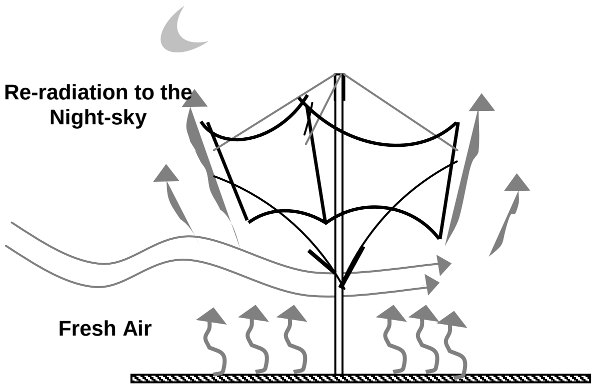


Figure 14: Conical tent-shaped forms' capability for different defensive scenarios as passive cooling and environmental design enhancers

A variant of this is illustrated in (Fig. 13), where a retractable structure can be used to provide comfort for the occupants and protect them from the sun in the daytime by reflecting most of the sun's heat. At night the umbrella structure is closed to expose the interior to the night sky for cooling as seen in (Fig. 14). These fabric structures are reminiscent of trees, which is one of the reasons why they can be embraced to enclose courtyards, public spaces or in front of buildings. Thus, they offer man made sources of shade and channel wind, while maintaining the natural feel. This idea has been applied in the Holy Prophet's Mosque in Madinah, Saudi Arabia, and in front of El-Hussein Mosque in Cairo, Egypt, and has proved very effective.

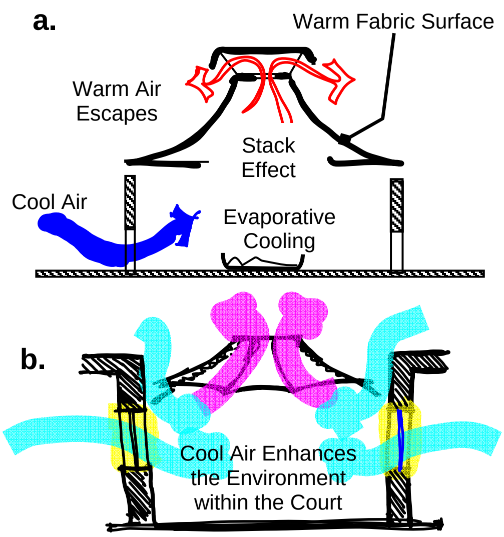


Figure 15: Passive cooling and environmental design strategies of conical tent-shaped forms

Another phenomenon that can be successfully applied to conical structures is Stack effect [9]. Radiation from membrane surface can also accelerate stack effect. During a warm sunny day, warm air will migrate to the highest points due to the heating caused by fabric tent surface, induced by the solar radiation (Fig. 15a). As a result the stratification will maintain a cooler layer of air in the inhabited zone. The hot air at high levels can then be discharged through the upper vents drawing in air at low levels; this phenomenon is the thermal stack effect is presented in (Fig. 15a) which can also be successfully used along with evaporative cooling techniques. A conical tent can also be used to cover a courtyard within houses or public spaces to enhance the environment underneath as shown in (Fig. 15b).

5. CONCLUSION

Building-envelope elements; walls and roof are variously exposed to the sun. Roof receives a high amount of solar radiation, which is the main cause of summer overheating in different climatic regions and especially in hot-arid climates. Traditional domed, vaulted, and curved roofs have been used for a long time in different parts of the world for historical, cultural, and structural reasons without a full documented understanding of their environmental behaviour. This paper presented the methodology undertaken for exploring the different explanations of the climatic effects of such arbitrary shapes, forms, and geometries such as domes, vaults and cones. The environmental behaviour of the enclosed spaces of such building-envelope forms can be experimentally and computationally figured out using the techniques presented in the paper. In general, the research tests the solar, thermal, and airflow performances of Vernacular Roof forms. Also the computer modelling plays a crucial role in the effective evaluation of subsystems and in the extrapolating of the results to other applications, along with monitoring and scale modelling. In short, experimentation alone does not lay solid basis for environmental predictions and applying design guidelines, and need along side it computer simulation and analysis [10].

The paper also presented alternative ideas for the use of conical structures to enhance the environment within their enclosed or semi-enclosed spaces. The use of the conical roof form and topology for the manipulation of ventilation strategies within the semi-enclosed spaces is discussed.

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