ENVIRONMENTAL ASPECTS OF TENSILE MEMBRANE ENCLOSED SPACES

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ABSTRACT: Buildings enclosed by fabric membranes are very sensitive to changes in environmental conditions as a result of their low mass and low thermal insulation values. Development in material technology and the understanding of the structural behaviour of tensile membrane structures along with the vast progress in computer formfinding software, has made it possible for structural design of tensile membrane structures to be approached with almost total confidence. On the contrary, understanding of the environmental behaviour in the spaces enclosed by fabric membrane and their thermal performance is still in its infancy, which to some extent has hindered their wide acceptance by the building industry. The environmental behaviour of tensile membrane structures is outlined and the possible use of the fabric's topology and geometry particularly to enhance ventilation rates and airflow velocities within the enclosed space is discussed. A need for further research in this area is identified in order to fully realise the potential benefits offered by these structures.

Key words: Environmental Behaviour; Tensile Membrane Structures; Fabric Membrane Skin; Fabric Topology and Geometry

1. INTRODUCTION

Fabric membrane structures such as the building shown in figure 1, are a form of lightweight structural systems, where there structural components such as masts, cables, connecting joints or roofs are exhibited making them visible from the inside or outside or from both sides. Fabric structures have been used throughout history. They were originally used to provide shelter where materials were scarce or mobility was required. Nowadays, the issue of resource scarcity applies not only to materials but also to energy and here tensile membrane structures can have a potential role to play. When adopting fabric membranes as part of the building enclosure it is important that the designer should fully understand the environmental implications implicit in their use. In order to apply the technique effectively and to increase their acceptability, their environmental and micro-climatic behaviour should be clearly understood and capable of being predicted by the building design team.

Fig.1

Figure 1 shows the exterior of the Inland Revenue Amenity Building in Nottingham, UK, which is one of the most successful tensile membrane projects in the United Kingdom.

Tensile membrane structures provide the advantage of enclosing large spaces without intermediate supports, using a minimal amount of material and rapid erection. Recently, the need for such widespan enclosures has greatly increased in both developed and developing countries, to accommodate and facilitate the multifunctional, collective activities of society.

For membranes, the excitement of their exterior sculptural form, beauty of their interior space, purity of their structural system, suitability of the materials used and the apparent comfort of their internal climatic conditions are the fundamentals in securing this aim.

In addition to the lighting and shading functions normally associated with tensile membrane structures, the topology of the construction type offers exciting opportunities to lend additional functionality and higher levels of comfort to the enclosure. They can be used as climate modifiers in both hot and cold regions, offering in some circumstances, conditions suitable for human occupation and in others, a protected microclimate within which conventional buildings may be sited and operated in a more efficient manner.

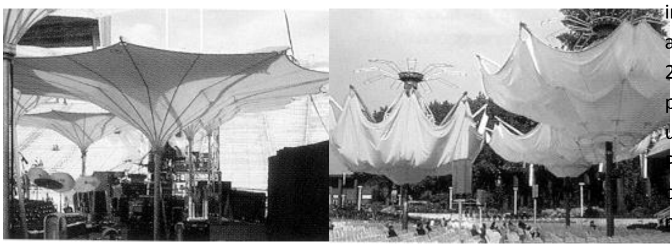

Fig.2 (Source: Frei Otto, Bodo Rasch[1])

As these are light and flexible structures there is also potential for folding the fabric membranes to change their function at different times of the day or seasons of the year. Figure 2 shows some of the foldable umbrellas at the 1971 Cologne Federal Garden Exhibition. These simply constructed but beautiful umbrellas inspired many subsequent projects.

This paper reviews the environmental properties of the fabric membrane skin, highlighting the optical differences between the fabric material and those of glass. The paper also discusses the environmental behaviour of tensile membrane structures and the possible use of the fabric's topology and particularly its geometry to enhance ventilation rates and airflow velocities within the enclosed space. The physical properties of the fabric membrane skin and the environmental behaviour of spaces enclosed by them are reviewed. Subsequently, the possibility of employing a number of architectural strategies commonly applied to conventional building types to enhance their environmental performance is discussed. Some that is made possible by the unique nature of the tensile membrane structural type are also outlined.

2. ENVIRONMENTAL PROPERTIES OF A FABRIC MEMBRANE SKIN

Fabric membranes have very little thermal mass and as a consequence react very quickly to the changes in the environment around them. They mirror the prevailing ambient radiant temperature, heating rapidly during periods of bright direct sunshine and cooling quickly to reflect the external radiant temperature at night[2].

2.1. Materials

Woven fabrics have been used to provide shelter since ancient times. Leather tents were used by the Romans in their campaigns. Nomadic cultures have used fabrics in their shelters for thousands of years and are still using them, be it in the black goat hair tent of the Bedouin, the North American tepee, or the Mongolian yurt. Although, all these traditional tents rely on materials with a durability of just a few years, they achieve high levels of comfort for the occupants. In the industrial age, fabrics are generally not acceptable as building materials because of their ephemeral nature.

These types of materials were revisited in the nineteen sixties due to cultural interest in inflatable, instant cities and new lifestyles[3]. Through the pioneering lightweight structures of Frei Otto in Germany, the influences of the tensegrity structures of Richard Buckminster-Fuller, and then the inflatable structures of Walter Bird in the United States, 20th century fabric structures were born. Otto[2] used cotton canvas and polyester fabrics for his early garden show structures, and Bird[2] used urethane-coated polyester for his early radome enclosures. Eventually PVC coated polyester fabric was adopted by both, which is the ancestor of today's polyester fabrics, and is currently the most widely used membrane structure material.

The chronology for the development of membrane materials covers a long period of history. Started in 1933 with the industrialisation of poly vinyl chloride (PVC) production, but it did not become the standard coating for the tensile membrane structures industry until the late sixties. In, 1947 the industrialisation of polyester fibre took place[4]. As the demand for more permanent membrane enclosures increased in the early 1970s, poly tetra-flouro-ethylene PTFE (Teflon ™) coated fibreglass was introduced as a durable alternative to PVC coated polyester. PTFE with a life expectancy of at least 20 years compared with approximately 10 to 15 years for PVC coated polyester, considerably extended the life span of membrane structures.

In the 1990s Ethylene Tetra Fluoro Ethene (ETFE foils is a thermoplastic copolymer derived from the polymerization of ethylene and tetra fluoro ethylene monomers) was introduced to architecture. However, the material is not currently being used for single layer membranes, its application instead being in the form of foil cushions.[5]

2.2. Optical Properties

The thermal optical properties of a material distinguish its radiant behaviour within the thermal spectrum[2]. Contrary to most of the structural materials commonly used in the building industry, fabric membranes present the advantage of translucency. The transmittance of coated woven fabric membranes typically ranges from 0 to 25% although it may be even higher. This allows penetration of a significant amount of solar radiation through the whole surface of the building, while the rest is either absorbed by the membrane or reflected back. Exact transmittance values depend on the material used, the solar angle of incidence and the wavelength of the radiation.

Fabric membranes can be quite translucent, however, their optical properties differ significantly from those of glass[2]. Glass tends to have much higher solar transmittance and lower reflectance than that of fabric membranes. This means that the effect of the solar reflectance is higher in fabric membranes than for glass. Harvie has shown that there is a tendency for fabric membrane properties to change more significantly at higher angles of solar incidence. One of the main advantages of fabric materials is that they have acceptable levels of translucency, allowing daytime lighting to be dramatically reduced or eliminated.

The reflectivity of some membrane materials such as Teflon coated fibreglass is typically around 70%, which is advantageous in hot climates as it reduces heat build-up within the enclosure due to insolation, yet it discharges heat at night reducing the load on air-conditioning plant.

The solar optical properties of both PVC coated polyester samples and PTFE coated glass samples display very similar trends. However, these trends differ significantly from the displayed behaviour of glass[2] (see figure 3). As a consequence, shading coefficient, which is used to describe the thermal optical properties of glass is not as applicable to fabric membrane materials.

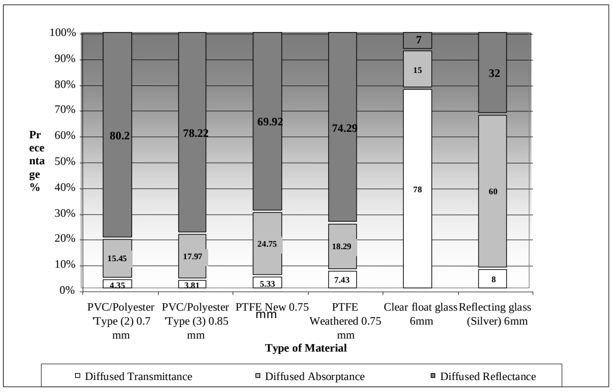

Fig.3

Figure 3 shows the comparison of solar optical properties of the following membrane samples measured by Harvie[2] and typical glass products as quoted in Button [et al[6]]:

1. Type 2 PVC coated polyester, gauge 0.7mm.
2. Type 3 is PVC coated polyester, gauge 0.85 mm,
3. Verseidag Indutex PTFE coated glass (new), gauge 0.75 mm,
4. Verseidag Indutex PTFE coated glass (weathered), gauge 0.75 mm.
5. Typical float glass surface 6mm gauge[6]**.** Reflective glass surface 6 mm gauge

2.2. Thermal Properties

Structural efficiency of membrane enclosures is essentially based on the minimum use of material for the building skin. The thickness of the membrane skin is typically about 1mm and weighs about 1 kg/m^2. This keeps the dead loads imposed on the supporting structure to a minimum, thus allowing large spaces to be spanned without any intermediate supports.

However, the inevitable consequence of this lightweight form of construction is the very low thermal mass of the building skin. The membrane reacts extremely quickly to external heat inputs, such as air temperature changes and solar radiation, and is unable to damp temperature swings occurring in its environment, as traditional heavyweight structures do.

The thermal properties of fabric materials are quite different from conventional buildings. The large surface area of membranes compared to their thickness means that they have insufficient mass to significantly affect their thermal behaviour. Consequently, their thermal behaviour derives almost entirely from their convection surface heat transfers and their optical absorbtance[2]. The combination and specific nature of fabric membrane materials suggests a design potential, precisely in relation to form and location. Heat transfer through fabric materials is quite a complicated issue and depends on a number of changeable factors. The amount and direction of the conduction of heat through the fabric structure depends greatly on the internal and external air temperatures, the wind speed, U-value, the thickness of the fabric and whether it is a single or double membrane[7].

Wu[8]states that there are three specific properties of fabric materials that influence to a great extent the heat transfer through them:

1. solar transmission and absorption
2. emissivity in relation to long wave radiation, and
3. light transmission and characteristics.

The fabric membrane material has a very low thermal resistance. That is why solar transmission, solar reflectance/absorbency, and the surface wind velocity all play important roles in the heat transfer and its calculation.

The U-value is a function of the surface resistance effects and thermal resistivity of the materials from which the building envelope is made. In a conventional structure, the material resistance term is dominant and heat conduction across the building envelope is therefore proportional to the difference in temperature of the air on either side of it. Surface resistances are dependent on a great number of environmental parameters in addition to air temperature and as a consequence their effect is usually approximated when estimating the U-values of conventional construction materials. The dominance of the material resistivity ensures reasonable accuracy.

The same assumption does not hold for membranes. Their negligible thickness results in heat flow being determined by the surface effects. To be described properly therefore, surface heat transfer should be expressed in terms of the difference between the temperature of the membrane surfaces and the environmental conditions that exist on either side of them[2]. Most of the membrane manufacturers today tend to express the thermal performance of their product in terms of these two quantities and will often quote two U-values: one for standard winter conditions and one for standard summer conditions. Although this may help to account for some variation in the surface effects, the approach is far from satisfactory for accurate prediction of thermal behaviour. Conventional U-values are dominated by the conductance term, which is related to the material, and approximate surface effects. For membranes, where negligible thickness means that conductance is minimal it is important to describe the surface effects such as long wave infrared radiation and convection, which dominate heat transfer more accurately.

Where shading coefficients suppose that the solar optical properties of membranes are directly comparable to those of glass, experimental work[2] has proved that this is not true. For glass it is assumed that the amount of heat entering an enclosed space as a result of solar radiation falling on its external surface is linearly related to the intensity of that solar radiation. Whilst this is a reasonable assumption for glazed enclosures, it has been shown[2,9,10]that in the case of membranes, the proportion of absorbed solar radiation subsequently radiated into the enclosed space is dependant, not only on the solar intensity, but also on the difference between the temperature of its surface and the environmental conditions on either side of them.

Thus, it can be seen that in case of fabric membranes, both the thermal transmission and solar heat gain are dependent upon the nature of the internal and external environments as well as the thermal state of the membrane. Techniques developed for the analysis of conventional construction types do not adequately account for these effects and so can not be expected to give reliable predictions of tensile membrane structures thermal performance[2].

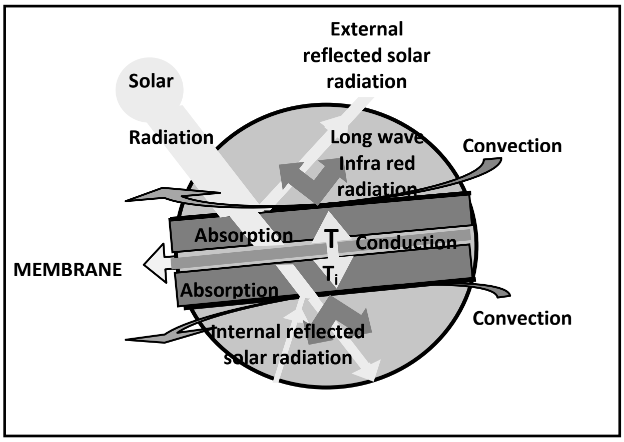

Fig.4

Figure 4 shows diagrammatically the heat transfer model of the thermal behaviour of fabric membranes. (After Harvie[2])

3. PARTICULARITIES OF THE ENVIRONMENT INSIDE TENSILE MEMBRANE ENCLOSURES

It is surprising to see how little published knowledge is currently available concerning the environmental behaviour of membrane skins or on their impact on the spaces that they enclose. Generally, membrane structures react very rapidly to external energy influences because of their low thermal mass. This, combined with low thermal resistivity, generally means that cooling due to winter thermal losses and excessive heating in summer by solar radiation of the inner space can only be controlled by significant expenditure on heating and cooling plant. Considerate design of the formfound curvature and external/internal form of the membrane structure also offers a means of providing appropriate levels of comfort within the enclosed space.

Exploring the potential for passive approaches to reduce reliance on active control of internal conditions is a strategy for minimising the environmental impact of this class of structure. This will assure increased importance, as the growing range of applications for which tensile structures are being applied means that the designer has to provide comfort as well as shade and shelter for the occupants.

Environmental properties of the membrane skin and the spaces that they enclose can be divided into the following categories:

3.1. Highly responsive building skin

The space inside a fabric membrane structure is enclosed by a highly thermally responsive skin, whose internal surface temperature varies very quickly depending on the amount of solar radiation that reaches it. As a result, high contrast in surface temperature is likely to occur inside the building between different areas of the membrane skin exposed to unequal solar radiation. The same happens between the lightweight membrane and the thermally heavier floor slab or internal building walls or the internal thermal mass.

Consideration of this phenomenon is of great importance in assessing the thermal comfort of the occupants, as great variation in the temperature of surrounding surfaces could be a source of discomfort for the user. This can be made worse by the increased exposure of the user to the membrane surface, due to the topology of the building.

3.2. Non uniform internal conditions

The topology of fabric membranes favours the accumulation of buoyant warm air at the high points and formation of cooler air layers at human height. Air temperature will vary greatly depending on the position in the space and on the height above floor level. Very strong thermal stratification has been observed in these enclosures and differences of up to 14°C between regions adjacent to the membrane and the floor have been monitored by Harvie[2]. However, this stratification appeared to be the result of contrasting internal surface temperature rather than simple buoyancy, as negative vertical stratification was monitored during clear sky nights[2].

Typically, during a warm sunny day, the layer of warm air will remain stable at the highest points due to the heating caused by the warm membrane surface. The stability of the upper layer can however easily be disturbed by the induced natural ventilation or by infiltration, usually resulting in large-scale turbulent air movements in the enclosure.

On a cold day with strong solar radiation, turbulent flows are even more likely to occur, as large variations in the surface temperature around the envelope might in turn produce rapid cooling of the warm air layer and generate strong downward flow of cooler air at certain points in the structure[2]. There are several factors affecting stratification in the space enclosed by tensile membrane structures, for instance:

1. Solar radiation transmitted into the internal space heats up the surroundings. This causes warm air to rise and cooler air to drop.
2. The direct heat transfer to the fabric roof contributes to the warmth of air in the immediate vicinity of the fabric membrane.

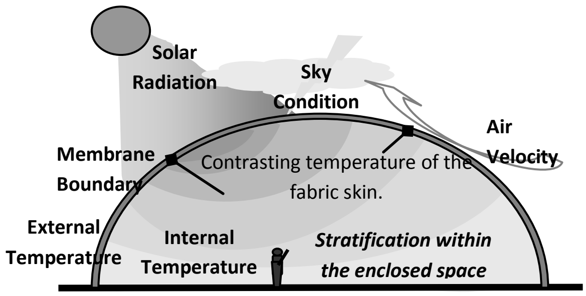

Fig.5

Figure 5 shows the stratification of air in tensile membrane enclosures.

The spanning of large spaces and the presence of high points in a membrane structure implies the enclosure of a large quantity of air in a single volume and, consequently, the existence of large-scale air movements. Particularly, because of the substantial roof heights, any source of heat within the enclosure, being either internal gains or solar gains through the translucent membrane skin, has the potential to develop into strong convection cells.

Harvie[2] observed pronounced thermal stratification in tensile membrane enclosures and differences of up to 10°C were recorded during bright sunshine, while during cold weather or at night negative stratification was observed. This negative stratification was monitored during clear sky nights. It was concluded that this stratification resulted from the contrasting internal surface temperature rather than the low thermal mass of the membrane boundary as illustrated in figure 5.

3.3. Lighting Performance

Providing natural light is a very important use of solar energy. Therefore, great care must be taken by the designer to ensure that the environmental implications of using membranes in a building envelope are understood. When comparing the performance of energy use of membrane buildings with conventional structures a more extensive energy balance than just heat gains and losses ought to be considered.

If skilfully used, the chosen degree of light transmittance of the fabric skin can provide plenty of natural light in the enclosure A bright delightful interior is one of the characteristics of buildings with membrane enclosures. The translucency of the membrane material controls the penetration of light while the interior is kept bright. The fact that sunlight striking the membrane surface is diffusely transmitted to the internal space also helps to minimise problems of glare. In addition the continuous changing of its intensity and colour qualities provide the building occupants with more information about the external weather conditions and time of the day.

It is this range of light transmission characteristics that make tensile membrane structures useful for applications such as sports facilities, outdoor shelters, music, dance and theatrical activities. It also reduces the need for electric lights. To a degree, this counterbalances the higher energy consumption due to excessive heat gains or losses through the thin membrane. Saving energy used for lighting spaces and also saves energy used for cooling in hot climates, as electric lights often contribute to internal heat gains and lead to a requirement for cooling plant.

Figure 6 (Photo courtesy of Alastair Gardner) shows the interior of the Inland Revenue, Amenity Building in Nottingham and it is clear how the space is naturally lit by the use of the translucent building skin and glazed lenticular windows. This apparently cuts down the energy consumption required for artificial lighting, in addition to a bright, glare free interior space. The luminosity of fabric membrane roofs is basically influenced by three main factors[11].

1. The availability of outside daylight.
2. The light transmission properties of the fabric roof material.
3. The reflection/absorption of the membrane surface inside the space.

Given the directional characteristics of membrane materials, the internal luminance of the fabric roof depends on the orientation of the curved surface to the sun and sky[11]. Thus the internal luminance depends on the altitude of the sun and the sky condition, which change continually during the day and from season to season.

Similarly the shape of the roof itself and its orientation plays an important role in the internal luminance. If properly oriented it can either make use of sunlight to light the interior or provide solar protection by working as an effective shading device[12]. This results in significant variation in the luminance of the internal surface of the roof. As a whole, these dynamic changes cause a considerable variation in lighting performance within the enclosed space and potentially represent a tool that may be used by the designer to manipulate the internal environment.

Fig.6

4. USING FABRIC TOPOLOGY TO MANIPULATE THE INTERNAL ENVIRONMENT

In addition to the lighting and shading functions that tensile membrane structures provide, the topology of the construction type offers exciting opportunities to lend additional functionality. The use of tensile membrane structures as microclimate modifiers may be considered as a prime objective for their use in a number of different applications.

4.1. Successful Examples In The Built Environment

There have been many architectural projects and different trials making use of the unique nature of fabric membrane structures to enhance the environment within the enclosures. The topology and form of the tensile structure can be used to alter the quantity and direction of solar radiation entering the enclosure. The structure can be shaped and oriented to allow maximum solar gain in winter by exploiting the low angle of the sun as is used in more conventional buildings. In summer the form of the building can provide shade by screening occupants from solar radiation from the higher overhead arc of the sun. In sunny parts of the world, the shape of the structure can also be oriented such that it is parallel to the sun's arc across the sky, providing shade throughout the day. There follow, some examples that have used different techniques for enhancing the environmental behaviour of their enclosures.

a. Arizona Solar Oasis at Phoenix Civic Plaza

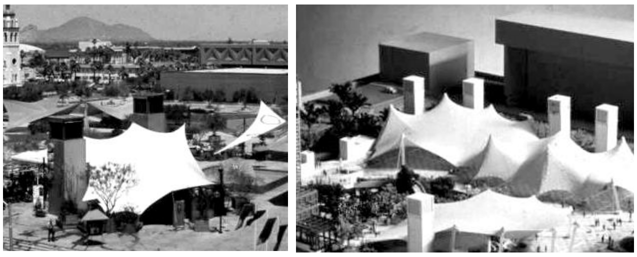

Fig. 7 (Source URL: http://www.architecture.arizona.edu/planning/PROJECT/d+d_planning/default.htm)

Figure 7 shows the Arizona Solar Oasis, built for the 1987 "Summer Invitation". This project utilised several environmental strategies for enhancing the internal climate. A large pre-stressed saddle shaped fabric membrane structure was used as a shade over the exhibition area. The membrane was placed such that its downward curvature was oriented east west, parallel to the sun's arc across the sky. It was also shaped so that the fabric ran close to the ground along the south perimeter and high on the north. This shape provided shade all day long. It also generated a strong air current beneath the membrane surface that drew in ambient air under the south edge, and resulted in continuous cross ventilation. It also used some of the passive cooling techniques used in conventional buildings, which were provided by a nearby fish pond display and an existing fountain, in addition to a mist spray cooling system which was employed in the adjacent café, some greenhouse areas, and two cooling towers. Temperatures in the

"Summer Invitation" were reduced to approximately 14°C below the ambient temperature[13].

The structure was only used for a summer installation but it is worth noting that this fabric enclosure would have worked well for winter passive solar heating. This would have been made possible by the available thermal storage media of the thermal masses like the plaza deck and the fish pond, along with the other enclosures to the north, east and west sides of the fabric enclosure. This would have absorbed solar radiation and stablised temperatures a little above ambient.

b. Haj Terminal in Jeddah

Another very good example that has used tensile membrane structures to enhance the internal climate is the Haj Terminal in Jeddah, Saudi Arabia. This project has successfully made use of the tensile membrane topology, along with techniques that are used for passive cooling in more conventional buildings.

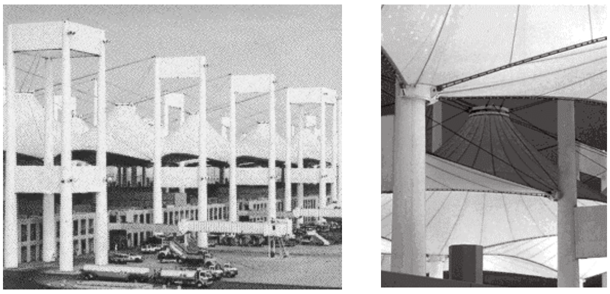

Fig. 8 (Source: Horst Berger)

The structure was to provide comfort for the pilgrims and protect them against the heat of the desert sun. A fabric structure provided a lightweight and translucent solution. The membrane chosen for the structure was Teflon coated fibreglass, which maintains its surface temperature within a few degrees of the ambient air temperature, by reflecting most of the sun's heat[12]. The fabric's translucency makes artificial light unnecessary during the daytime, and thus energy consumption is dramatically reduced. The structure is formed of ten identical modules that are arranged in two rows of five to cover a total area of approximately 42.5 hectares (105 acres). Each module consists of 21 square, semi-conical, fabric roof units of a form and height that promotes circulation of air from the open sides of the roofed area up to and through the open steel tension ring located at the top of the roof unit. Fan towers placed intermediately between columns enhance air circulation. Acoustical problems are diminished due to roof height and material. Due to its low heat transmission, the fabric allows the sun to cast a warm light over the area below. Under the landscaped central mall are located two large exhaust fans for each module to draw off the exhaust fumes of the buses.

c. GCC Conference Centre in Kuwait

The conceptual design for this project was based upon the Bedouin tent, which enjoys a great acceptance in Arab countries, due to the tradition of their use. The project is an example of the use of tensile membrane structures in an extreme hot climate, not only because it was totally exposed to the desert sun, but also because it was designed to provide an adequate environment for royalty and heads of state and had to be completed within just 17 weeks[14].

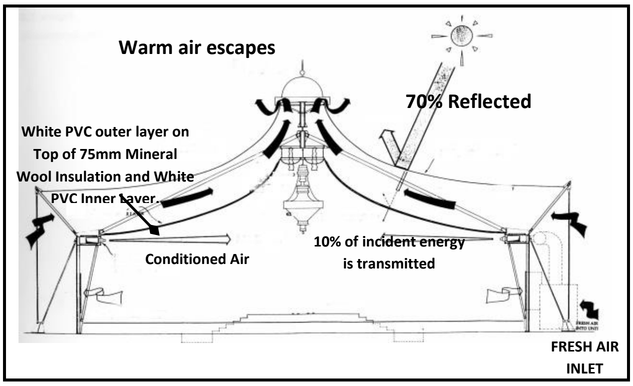

Fig.9 (After Rudi Scheuermann[14])

Three large tensile structures containing a banqueting facility, seating areas and conference rooms occupy the palace gardens and are linked together with walkways. The tensile structures are stretched PVC-coated polyester woven and mat fabric secured to lightweight steel structures. Figure 9[14] shows a detailed section through one of the pavilions at the conference centre in Kuwait. Three layers of fabric are included in each tent, the outer skin (with a reflectance of 70% to ensure a minimum of solar absorption), an insulation layer and inner skin, and finally the interior lining finish. The heat re-radiated and convected off the inner surface of the outer skin is removed by natural ventilation through large air gaps located between the interior and exterior membranes. The temperature beneath the exterior membrane skin increases due to the conduction heat gains, causing buoyancy. In return, this induces an upward air movement that vents through the top cap of the structure.

This double layer ventilated system ensures that the total transmitted incident heat does not exceed 10%, providing a high level of environmental comfort. Figure 10 shows the interior of the Banquet tent, with the lighting provided by mixed source uplights and the ventilating roof cap that completes the weather proofing.

Fig.10

(Source:URL; http://www.a10.co.uk/projects_frame.htm)

As in the case of any typical conventional building, a deep understanding of the micro-environments with their critical characteristics, is a fundamental point for designers to recognise when designing these types of structures. It is, therefore, essential to deal with fabric structures as elements that are sensibly integrated into environments and not as isolated objects.

4.2. Enhancing the Internal Environment Of the Enclosures

It is quite rational to consider lightweight membrane structures as environmental 'filters' rather than barriers to the external weather. Fabric membranes can be merely used for creating an intermediate climate or meso-climate, that acts between the external climate and the environmentally controlled interior of the building to moderate and regulate them, rather than shutting it out completely.

The membrane form and orientation and the associated thermal mass (walls, floors, terraces, water pools, fountains, etc.) can be designed to suit different seasons and climates. For example, in winter the structure should be designed to maximise the absorption of solar heat gain, and transmitting it into the enclosure. At night it should be sufficiently air tight to prevent the escape of the heat to the night sky. In summer, th opposite should occur, as the fabric structure should absorb an transmit the minimum of solar heat, and work in conjunction wit thermal mass distributed within the enclosure to stabilis temperatures. It should be designed with a number of different openings so the internal heat finds a place to escape at night, or it could also be folded at night, so as to encourage cross ventilation and escape of the heat that is stored during the day to the night sky.

A number of traditional passive cooling systems can be effectively used along with fabric membranes, such as evaporative cooling by having water cascades, mist sprays or fountains, cooling towers, stack effect and self shading. All of these strategies can be used to enhance the benefit of tensile membrane structures in hot climates.

Techniques for influencing conditions within the enclosed space are illustrated in Figs 11 to 18. These make use of a number of architectural strategies commonly applied to conventional building types, in addition to some that are made possible by the unique nature of the tensile membrane structural type.

In Figure 11 it can be seen how the unique nature of the membrane skin and the fabric's topology can help in cooling down the internal environment.

During a warm sunny day, the layer of warm air will migrate to the highest points due to the heating caused by membrane surface, which is heated by the solar radiation. 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.

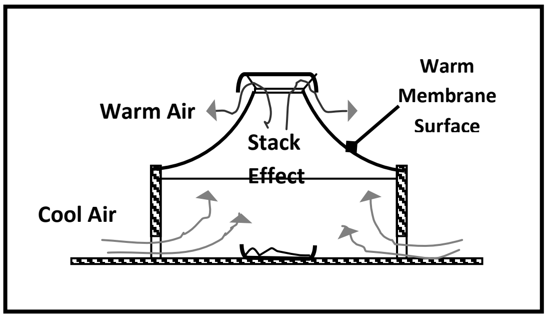

Fig.11

Using dark colour to selectively heat regions on the structure where airflow occurs could enhance this effect. When used in conjunction with a sensible arrangement of high and low vents, this will also prevent overheating, by forcing the warm air to escape through the high level vents. It can also be used in combination with ground-coupled air inlets or fountains and plants close to inlets, providing additional opportunities to pre-cool the incoming air, adding to comfort in hot environments.

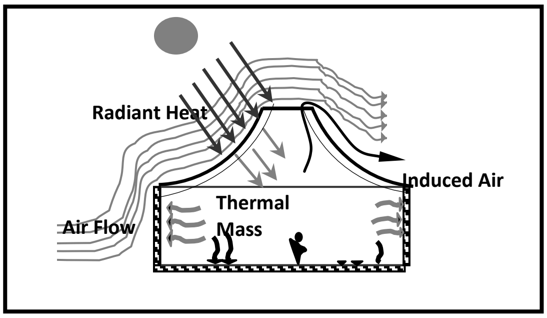

Fig.12

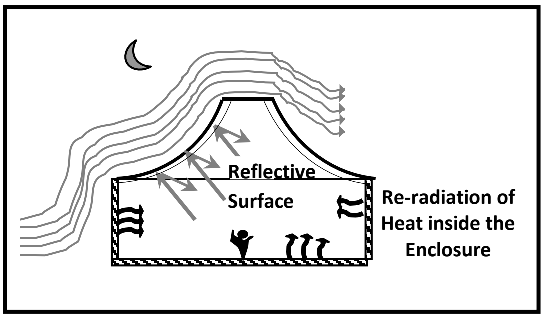

Fig.13

Membrane covered buildings can use the greenhouse effect to their advantage. In winter, or in cold countries, this can be achieved by using a transparent membrane skin, or transparent films, with a low-emissivity coating which reflects long wave radiation and transmits short wave solar radiation into the enclosure resulting in an increase of the internal temperature as shown in figure 13. 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.

Besides the greenhouse phenomenon, other techniques such as the use of thermal mass to introduce the 'thermal flywheel' effect into the enclosed space, as in figures 12 & 13, helps in moderating excessive heat loss through the membrane skin. The available thermal storage media helps in absorbing heat during the day, suppressing excessive rises in internal temperature and re-radiating the heat at night to prevent excessively low temperatures. This enables the structure to work well as a winter passive solar heating strategy.

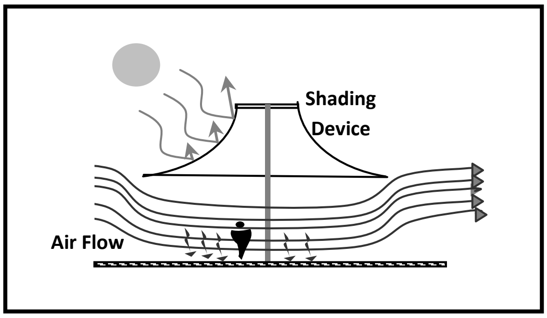

Fig.14

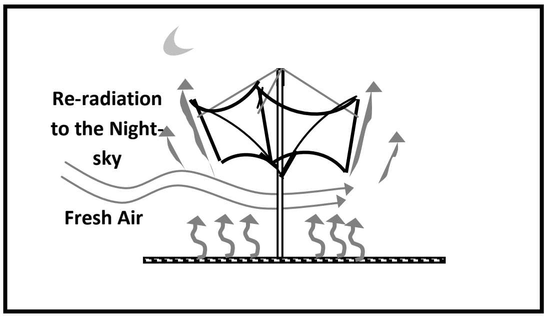

Fig.15

A variant of this is illustrated in Figs 14 and 15, where a retractable structure can be used to provide comfort for the occupants and protect them from the sun in the day time by reflecting most of the suns heat. At night the umbrella structure is closed to expose the interior to the night sky for cooling. This idea has been successfully applied in the Holy Prophet's Mosque in Madinah in Saudi Arabia, figure 16, and has proved very effective.

Fig.16 (Source: Frei Otto, Bodo Rasch[1])

Figure 17 shows how the arrangement of the thermal mass may be varied to increase the effect and to provide protected spaces within the enclosure where increased levels of shade are achieved. The membrane may also be used to induce airflow through the space to assist in controlling the climate. The ability to manipulate the form of the membrane offers possibilities to use its shape to enhance wind-driven ventilation, either through induced airflow, as shown in Figure 12 or using cross ventilation as illustrated in Figure 14.

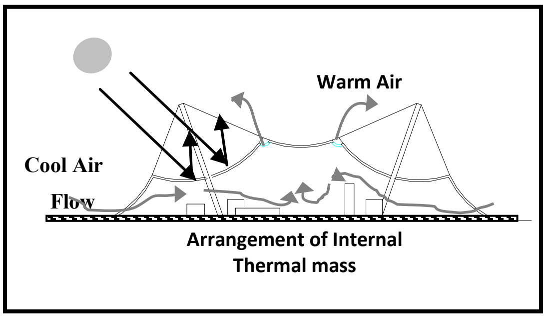

Fig.17

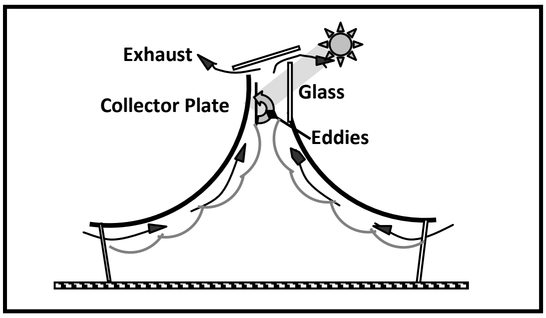

Fig.18

A solar chimney can be incorporated into a tensile structure using the stack effect as seen in Figure 18. The temperature inside the chimney needs to be higher than that of the outside air, to create a pressure difference between the inside and the outside and facilitate the exhaust. This is easily assisted by a collector plate within the chimney which gets heated up by the solar radiation.

This heats the air, making it buoyant, thus forcing an upward flow of hot air from the enclosed space to the outside keeping the inhabited area cooler. If used in conjunction with transparent insulation it reduces excessive heat gains into the enclosure thus preventing overheating in summer.

These ideas, in conjunction with additional strategies, such as the use of multiple skin membranes with thermal insulation layers, or novel membrane materials with enhanced thermal properties, are very difficult to evaluate without appropriate environmental modelling tools. Unless such tools are made widely available, their application will be inhibited – left to those prepared to take the risk of investment without a strong indication that they will function correctly.

5. THE NEED FOR FUTURE RESEARCH

It is important to note that work has been undertaken by leading consultants involved in tensile membrane structures design. This work has addressed condensation issues within the fabric envelope, airflow studies, CFD modelling, etc. However, most of the work relates to specific projects and is not in the public domain. Therefore, there is a need, recognised by the design community, both for general guidelines to inform the outline design stage of projects and for predictive tools for detailed design. For this to happen, further detailed investigations need to be carried out in this field at a number of different levels.

- More investigation into the influence of the topology of the fabric itself, and the possibility of using it to enhance the environmental performance of these structures. For example,
- Detailed investigation into the thermal and optical properties of fabric membranes and studies of internal and external surface convection heat transfer to inform modelling of such enclosures.
- The development of models (possibly as part of a CFD code) tailored to suit the particular characteristics of fabric structures and capable of accounting for the complicated topology, time variant climatic inputs and complicated internal temperature and airflow behaviour.
- Use of these models to develop general design guidance and quantitative descriptions of how these systems behave.

In addition to ensuring the appropriate and effective application of tensile membrane structures by the industry, such strategies would avoid unrealistic expectations on the part of the occupier of both comfort conditions and operating costs. Such tools would permit the continued development of environmental control strategies and tensile membrane structure materials with enhanced thermal properties.

6. SUMMARY

Fabric membranes are thin translucent materials that have insufficient mass to significantly affect their thermal behaviour. At any instant, it is reasonable to assume that their thermal behaviour results from their surface heat transfer and their characteristic thermal optical properties at that instant. Early approaches adopted for predicting the thermal behaviour of tensile membrane structures based on U-values, and shading coefficients have proved inappropriate. Alternative approaches to the problem have been explored and work is now required to develop these to the point where they may be used to inform the design process.

If fabric structures are to compete with more conventional building types, which have well established levels of environmental performance and face strict energy consumption legislation, designers and manufacturers must be able to accurately predict their environmental and thermal behaviour and ensure an appropriate comfort level for the occupiers of the spaces.

The paper has indicated how the unique nature of the tensile membrane structures topology can be effectively harnessed to achieve better environmental performance. Features like topography, local climate, sun and site orientation and wind should all have a significant role in the formfinding of a tensile structure. The possibility of using the fabric's topology to enhance the ventilation rates and the climatic performance of the interiors along with the employment of a number of architectural strategies commonly applied to conventional buildings were introduced.

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