Textile Composites and Inflatable Structures
E. Oñate and B. Kröplin (Eds)

ENVIRONMENTAL PERFORMANCE OF SPACES ENCLOSED OR SEMI-ENCLOSED BY FABRIC MEMBRANE STRUCTURES

Amira M. ElNokaly*
School of the Built Environment,
University of Nottingham,
University Park, Nottingham,
NG7 2RD, UK
Email :laxamhe@Nottingham.ac.uk

John C. Chilton and Robin Wilson
School of the Built Environment,
University of Nottingham,
University Park, Nottingham,
NG7 2RD, UK
Email:John.Chilton@Nottingham.ac.uk
Robin.Wilson@nottingham.ac.uk

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Abstract. *Since the 1960s a large evolution took place in the fabric structures industry, as they became more complex with time, and designers have been able to keep up with the structural implications of this changing situation. Sophisticated analytical models and computer software have facilitated the structural design of tensile membrane structures (TMS) and this has produced a diverse and complex range of design and form solutions. However, environmental issues continue to be dealt with in a cursory manner, which is still today unable to fully satisfy the client's requirements. With the vast interest in these structures, designers and manufacturers alike realised that if membrane enclosed spaces is to compete with other more conventional enclosures, a clear understanding of their environmental behaviour should be available to them. Moreover that if membrane enclosed spaces were to aspire to the same level of environmental performance as more conventional buildings, it would be necessary to develop tailored analytical techniques, which could be used to assess the likely performance of various design alternatives. This paper explores the thermal performance of membrane structures, and how these structures can be used as climate modifiers in spaces enclosed or semi enclosed by fabric membrane skins, providing thermal comfort for the occupiers. Analytical techniques that are used to investigate the environmental behaviour of fabric membranes and assessing their liability will be reviewed. The paper also looks at some of the work done by other researchers in the investigation of the thermal behaviour of fabric membranes by different techniques.*

1 INTRODUCTION

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, textile membrane surfaces 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 form found curvature and external/internal form of the membrane structure also offers a means of providing appropriate levels of comfort within the enclosed space.

Early quantitative research into the environmental behaviour of spaces enclosed by fabric membranes pointed out to the need for developing a technique for investigating the indoor climate of such structures. Adopting the simple steady state technique, which was initially designed for investigating the internal climate of more conventional buildings, proved to be inappropriate. Such techniques are based on the use of U- values and shading coefficient, which as discussed briefly in this paper do not have a significant affect on thin translucent fabric structures.

2 ENVIRONMENTAL PROPERTIES OF A FABRIC MEMBRANE SKIN

Fabric membranes have very little thermal mass and, as a consequence, react very quickly to 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[1].

2.1 Optical properties

The thermal optical properties of a material distinguish its radiant behaviour within the thermal spectrum[1]. The percentage of light transmittance in coated woven fabric typically ranges between 0 to 20%, with a transmittance of up to 50%, allowing daytime mechanical lighting to be dramatically reduced or eliminated. Glass tends to have much higher solar transmittance and lower reflectance than that of fabric membranes[1]. This results in the tendency of fabric membrane properties to change more significantly at higher angles of solar incidence.

As shown in fig. (1) typical solar optical properties of both PVC coated polyester samples and PTFE coated glass samples display very similar trends, whereas, these trends differ significantly from the displayed behaviour of glass[1]. As a consequence, shading coefficient, which is used to describe the thermal optical properties of glass by the materials manufacturers and the building industry is not as applicable to fabric membrane materials as their transmittance, reflectance and absorbtancy percentage differs greatly from those of glass.

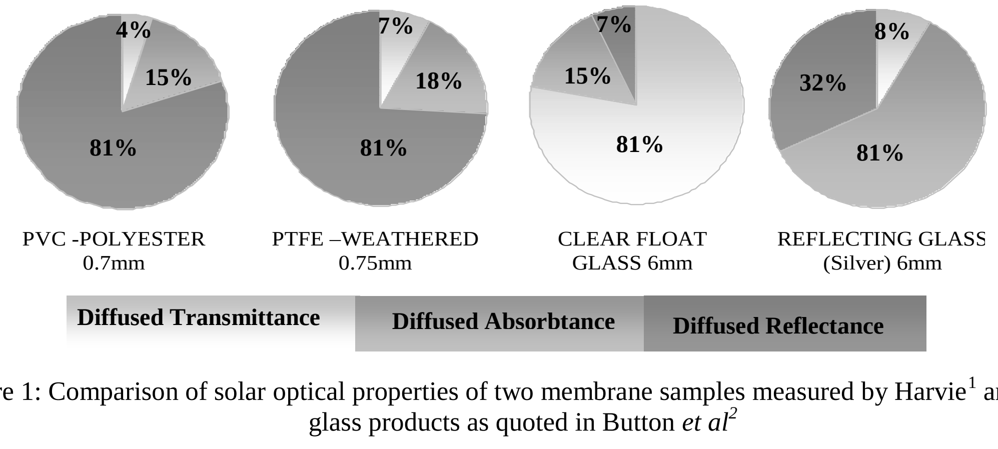

Figure 1: Comparison of solar optical properties of two membrane samples measured by Harvie[1] and typical glass products as quoted in Button *et al*[2]

2.2 Thermal Properties

The large surface area of membranes compared to their thickness means that they have insufficient mass to significantly affect their thermal behaviour, which result in their thermal properties being quite different from conventional buildings. The amount and direction of the conduction of heat through the fabric material depends on a number of changeable factors as shown in (Fig. 2); 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[3], and the difference between the temperature either side of its surface. The fabric membrane material has a very low thermal resistance. That is why solar transmission, solar reflectance/absorbency, emissivity in relation to long wave radiation[3], and the surface wind velocity all play important roles in the heat transfer and its calculation. Fabric membranes thermal behaviour derives almost entirely from their convection surface heat transfers and their optical absorbtance.[1]

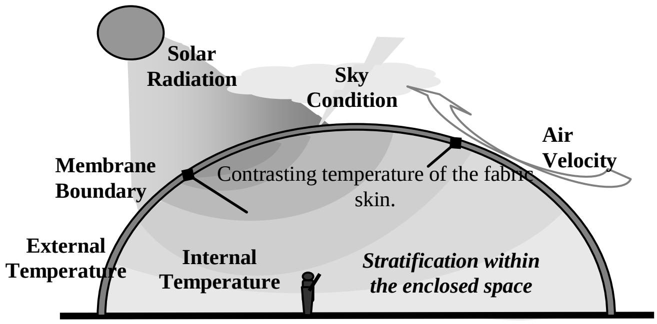

Figure 2: Factors affecting the heat transfer through tensile membrane enclosures

Most of the membrane manufacturers today tend to express the thermal performance of their product in terms of the U-values and shading coefficient 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 due to their unique nature.

3 CHARACTERISTICS OF THE ENVIRONMENT INSIDE TENSILE MEMBRANE ENCLOSURES

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

A highly thermally responsive skin, whose internal surface temperature varies very quickly depending on the amount of solar radiation that reaches it, or that radiated to the night sky in cooler conditions, encloses the space inside a fabric membrane structure. 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 and between the lightweight membrane and the heavier internal thermal mass such as floor slabs or internal walls. Moreover the internal brightness of the space depends on the clarity of the external atmosphere and sky conditions[4].

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 lower occupied levels. Air temperature will vary greatly depending on the position in the space and on the height above floor level. There are several factors affecting stratification in the space enclosed by tensile membrane structures, for instance:

- Solar radiation transmitted into the internal space heats up the surroundings. This causes warm air to rise and cooler air to drop[1].
- The direct heat transfer to or from the fabric roof contributes to the warmth or cooling of air in the immediate vicinity of the fabric membrane[3].
- The spanning of large spaces and the presence of high points in a membrane structure implies the enclosure to a large quantity of air in a single volume and, consequently, the existence of large-scale air movements. Thus 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[1].

4 STUDY USING COMPUTER MODELLING OF SPACES ENCLOSED BY TMS

In this paper computer modelling of the environmental behaviour of the Butlins pavilions carried out by BDSP (Building + Design + System + Performance) on behalf of Buro Happold will be briefly reviewed. Also the CFD modelling carried out by Gregor Harvie, as part of his doctoral research will be discussed.

4.1 Environmental computer modelling report

BDSP carried out a detailed computer modelling environmental study for the Butlins Pavilions on behalf of Buro Happold in February 1999. The analysis set out to consider a number of different ventilation strategies for the pavilions under various seasonal and external conditions to identify an optimum ventilation system. The sites are located in the UK at Skegness, Bognor, and Minehead, each comprising a new tented structure placed over an existing courtyard surrounded by existing buildings. These structures were to provide a sheltered enclosed environment, which protects the visitors of the pavilion from the external climatic conditions all year round. Figure 3 shows the exterior tent of the Skyline pavilion in Skegness, and figure 4 shows the pavilion's interior space, and it is clear how the space is naturally lit by the use of the translucent building double membrane skin.

Figure 3: Skyline Pavilion, Butlins, Skegness, UK

Figure 4: Interior of Skyline Pavilion, Butlins, Skegness, UK

BDSP simulations were all based on drawings and information supplied to them by Buro Happold[5]. They carried out four analytical environmental studies of the effectiveness of various internal environmental control designs and the occupant comfort levels provided by each. Computer modelling was used for predicting the internal and external climatic behaviour of the tented structure using dynamic thermal modelling and computational fluid dynamics (CFD).

BDSP adopted dynamic time dependant simulations in their approach to this study[5], to provide a detailed picture of the building performance under extreme conditions throughout the year. The thermal state of the building was traced through hourly snapshots, taking into account the influences of various thermal processes occurring in the enclosed space, their timing, location and interaction.

The first study considered summertime overheating in the tent enclosure, to assure that the installed air system will maintain the air temperature inside the enclosure within acceptable comfort levels. A second study considered three heating strategies namely all air heating, radiant heating and no heating, comparing them with a target occupied space air temperature of 12°C. The study concluded that all air heating was the only acceptable system to maintain the targeted temperature criteria.

Their third study considered potential condensation on the glazed façade and fabric roof. It was carried out for each of the three proposed heating systems, and once again the all air heating system showed the best performance with the fewest hours of condensation. However, condensation still occurred as a result of the low thermal insulation characteristics of both the glass façade and roof fabric.

Finally, the fourth study looked at the detailed internal environment of the tent and its results made it clear that the all air system performs well during both winter and summer season[5] providing acceptable environmental conditions. The studies concluded that the all air system works better than other systems all year round and that the de-stratification fans are essential for cold winter periods.

A detailed 3D geometrical model of each of the sites was made, representing the occupied, mid and roof levels. Each was zoned with zone names, areas, volumes and total occupied floor levels[5]. The most important construction that was considered for the pavilion was the tent fabric material, which was expected to have a large influence on the environmental behaviour inside the tented structure, which is constructed of a double skin fabric with an inert air cavity in between. Ferrari reference ‘702s’ fabric was used as the inner material, with reference ‘1502s’[5] as the outer weather skin. Thermal, solar and visual characteristics of the fabric material were based on manufacturer’s information.

BDSP also carried out three CFD simulations for the site to study in more detail the environmental conditions in the occupied space for a number of periods in the year. An all air system designs were used in these simulations; taking into consideration the specific features of the fabric membrane and the effect that the material itself will have on the internal environment of the space. These simulations showed that the summer internal environment of the tent is maintained within acceptable comfort levels, with internal temperature near to outside and velocity profiles evenly distributed. Winter simulations with de-stratification fans achieved the targeted air temperature with some macro areas that required attention. It was recommended that the de-stratification fans remain as an integral part of the all air system during winter operation.

As for those in charge of the maintenance of Skyline pavilion in Skegness, no monitoring of the actual climatic and environmental condition within the enclosed space took place after it has been opened to the public to compare the actual behaviour of the enclosure with the predicted data available by BDSP. However, as for many membrane enclosures there has been a lack of knowledge on post construction maintenance with the difficulty of access to the fabric roof to maintain and clean it, or to fix any tears in the membrane itself.

4.2 Investigation of the spaces enclosed by fabric membranes using CFD modelling

Harvie[1] used Flovent a general purpose CFD model that uses an iterative approach based on a nodal network of finite volumes or cells for the investigation of the thermal behaviour of enclosed spaces. Although, Harvie pointed to the highly dynamic thermal behaviour of membrane structures in his investigations, the lack of computer power and the software that he used at that time, the complexity of the model to be designed (and probably the lack of time) prevented him from carrying out dynamic CFD simulations. He, therefore, adopted the steady state approach for his research. In his model the double curved membrane surfaces were represented as a series of stepped horizontal and vertical panels, which meant that it was impossible to define the detail with which airflow close to the membrane surfaces was simulated, and as a result internal surface convection heat transfers were under predicted.

Harvie monitored four different relatively simple but diverse structures in the UK, Landrell Fabric Engineering, the Royal International Eisteddfod Pavilion (Main Arena), the Cheriton Passenger Terminal (Administration and Amenity Building) and the AELTC indoor tennis center. He modeled their thermal behavior, and then made a comparison between the CFD models output and the monitored data. In his simulations, generally, the predicted values followed the monitored behaviour to a great extent, where the average difference between them was generally less than 1.5°C and the maximum error was 4.5°C[1]. He concluded that in order to assess the influence that fabric membranes could have on the thermal behavior of the spaces they enclose, it is essential to determine their angular thermal optical transmittance and reflectance. Analysis of the monitored and CFD modeled data suggested that thermal gradients in the enclosed spaces were generated by contrasting internal surface temperature whereas other researchers credited it to the stratification of internal air.

Harvie's monitoring programme confirmed the findings of other research[3,4] concerning the non-uniform internal conditions within such enclosures. The data he collected during the monitoring also revealed that radiant temperatures vary significantly from place to place within the enclosure. He proposed that for practical design investigations to gain an overall impression of the thermal conditions found within these enclosures would require the development of a dynamic and holistic CFD model encompassing behavior of both the fabric membrane and the enclosed space. Further, to be modelled properly the internal radiant temperature must also be simulated.

5. CONCLUSIONS

Techniques developed for the analysis of thermal behaviour of conventional construction types do not adequately account for the effects that tensile fabric membranes have on the spaces they enclose and so cannot be expected to give reliable predictions of their thermal performance[1]. 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. 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 through post occupancy monitoring and evaluation, or computer modelling techniques.
- The development of models (possibly as part of an existing CFD code) tailored to suit the particular characteristics of fabric structures, accounting for the complicated topology and time variant climatic inputs.
- Use of these models to develop general design guidance and quantitative descriptions of how these systems behave.
- 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.

REFERENCES

[1] Harvie, G.N., An investigation into the thermal behavior of spaces enclosed by fabric membranes. *[PhD Thesis]*. Cardiff: University of Cardiff, 1995.
[2] Button, D. *et al*, "Glass in Building: A Guide to Modern Architectural Glass Performance". Oxford, London: Architectural Press/ Pilkington Glass Ltd, 1993.
[3] Wu, H.F., The Stratification in Fabric Roof Structures: A Strategy of Energy Conservation and System Design. Proceedings of the International Symposium on Architectural fabric structures; pp. 192-196. 1984;
[4] Boonyatikarn S, Wu H.F., Engen W.B., Lighting performance and prediction of fabric roof structures. Proceedings of the International Symposium on Architectural Fabric Structures; The Design Process. pp: 197-200, 1984;.
[5] BDSP, Butlins 2000 Skyline pavilions; Environmental computer modelling report. Feb. 1999. *(BDSP ref 135.r.mk.bh. 120299.001) (Unpublished report)*