10: DISCUSSION.

10:1. INTRODUCTION.

The first nine chapters of this thesis describe a piece of research the aim of which was to provide a sound theoretical base for investigations into the thermal behaviour of spaces enclosed by fabric membranes. In order to simplify this subject it was dealt with in two parts:-

- The thermal behaviour of *fabric membranes*.
- The thermal behaviour of *spaces enclosed by fabric membranes*.

This approach allowed the unusual thermal behaviour of fabric membranes to be investigated in detail using techniques developed specifically for that purpose, whilst the complex resultant behaviour of the spaces enclosed by such membranes could be analysed in a more general way using existing tools. Both of these elements however were investigated using a similar approach:-

- Their thermal behaviour was *monitored* in order to determine how such behaviour might best be represented, and to provide a comprehensive data set describing that behaviour.
- Their thermal behaviour was *simulated* using theoretical techniques, the accuracy of which was tested against the monitored data.

In this chapter the findings of the research are brought together in order that they might be compared with the work of previous researchers. A number of remaining problems are then identified, and future research necessary to address those problems is discussed. The structure of this chapter follows that adopted throughout the thesis, categorising the subject as *fabric membranes* and *spaces enclosed by fabric membranes*. The last section of the chapter then brings these two parts together to assess the development of the subject as a whole.

10:2. THE THERMAL BEHAVIOUR OF FABRIC MEMBRANES.

10:2.1 The Attempts of Previous Researchers to Investigate the Thermal Behaviour of Fabric Membranes.

Until the mid nineteen eighties, the theory relating to the thermal behaviour of fabric membranes tended to be based upon the adoption of existing *steady state* analytical techniques. These techniques had originally been developed in order to investigate the thermal behaviour of more conventional buildings, and tended to involve the use of simplified material properties such as *U-values* and *shading coefficients*. Such properties were generally determined based upon assumed standard environmental conditions such as '*summer*' and '*winter*'

It became increasingly apparent to researchers within this field that such an approach was not altogether appropriate for investigating the thermal behaviour of thin, translucent, fabric membranes:-

- Standard *U-values* overemphasised the importance of conduction across the membrane core itself whilst largely ignoring complex surface effects such as long wave infra red radiation and convection[1].

- *Shading coefficients* assumed that the solar optical properties of membranes were directly comparable to those of glass, whilst experimental evidence suggested that this was not the case[2].

During the mid nineteen eighties, a number of *dynamic* analytical techniques were developed based on more appropriate membrane properties and simple environmental conditions. On the whole however, the behaviour predicted by these techniques had then to be converted into U-values and shading coefficients in order that the thermal behaviour of spaces enclosed by such membranes could be investigated using existing thermal models.

Sinofsky recognised the inadequacies of this procedures, and suggested that thermal models should be modified in order to accept more appropriate properties information[3]. Following the decline of interest in this subject during the late nineteen eighties however, it appears that no attempt was made to follow this recommendation. Today, most membrane manufacturers continue to describe the thermal properties of their products in terms of U-values and shading coefficients.

10:2.2 The Investigation into the Thermal Behaviour of Fabric Membranes Presented in this Thesis.

In Chapter 5 of this thesis a series of test cell investigations were described in which the thermal behaviour of a range of fabric membranes was recorded. The data collected by this process agreed closely with the findings of previous researchers[4][5].

The membranes studied were seen to be highly sensitive to changes in environmental conditions, and in particular to thermal radiation. During bright sunshine membrane surface temperatures of over 40^{o}c were recorded, whilst at night, long wave infra red radiation to clear skies was seen to result in membranes becoming up to 3^{o}c cooler than the air on either side of them.

It was also apparent that this behaviour was very changeable. During periods of intermittent sunshine for example the surface temperature of an isotropic membrane panel was seen to change by up to 5^{o}c in a minute. This appeared to result from their large surface area compared to their thickness, which meant that they had insufficient mass to significantly affect their overall thermal behaviour. As a consequence of this, their thermal behaviour was seen to result almost entirely from their convection surface heat transfers and their thermal optical absorptance.

This suggested that standard steady state concepts such as U- values and shading coefficients which largely ignored the variability of convection and radiation heat transfers were inappropriate properties with which to describe their thermal behaviour. Because of the smooth surfaces of the membranes investigated, it appeared that the only property which significantly affected their thermal behaviour was their angular thermal optical absorptance. In order to assess the influence that fabric membranes could have on the thermal behaviour of the spaces enclosed by them however, it was also necessary to determine their angular thermal optical *transmittance* and *reflectance*.

It appears that none of these properties had been properly quantified by the researchers discussed in Chapter 3. The angular solar transmittance of a range of membranes had been measured by both Sinofsky[6] and also by Moseley and Croome[7], however their results were inconsistent, and their methods were unclear. Moseley and Croome for example suggested that membrane transmittance only varied significantly at high angles of incidence, whilst Sinofsky proposed that the relationship between increasing angle of incidence and decreasing transmittance was almost linear. Moseley and Croome made no attempt to explain how their results had been obtained, and Sinofsky carried out his investigation under '*real sky*' conditions, an approach which the calibration of the test cell described in Chapter 6 revealed to be inaccurate.

Sinofsky also approximated the long wave infra red absorptance of a range of fabric membranes by measuring their hemispherical emissivity. This suggested that the average emissivity of fabric membranes could be considered to be 0.88[8]. These measurements however were carried out using a D&S emissometer, a technique which was developed primarily for determining the emissivity of thin sheet metals. The investigation described in Chapter 6 suggested that this was an inappropriate method for determining the emissivity of fabric membranes because of their comparatively low thermal resistance and slightly rough surfaces.

Membrane manufactures appear to have accepted U-values and shading coefficients as a means for describing the thermal properties of their products, and were unable to provide any detailed or substantiated information regarding their thermal optical transmission characteristics. This meant that it in order to obtain accurate information for the purposes of this research, it was necessary to actually measure the thermal optical properties of the fabric membranes investigated.

These measurements were carried out according to the standard categorisation of the thermal spectrum into *solar radiation* and *long wave infra red radiation*:-

- The near normal solar optical properties of a range of membranes were measured using a Perkin Elmer solar spectrophotometer. Weighted averages of these results then provided a reference point from which it was possible to determine the angular solar optical properties of the membrane samples using an Alfred type integrating sphere. From these results, a series of standard equations were developed which could be used to calculate the angular and diffuse solar optical properties of the membrane samples given that their near normal properties were known.

  It was found that the way in which these solar optical properties varied with angle of incidence was significantly different from the angular solar optical properties of 3mm clear float glass which is used as reference material for determining shading coefficients[9]. This suggests that the effective shading coefficient of fabric membranes actually changes with angle of incidence. This serious discrepancy must bring further into doubt the use of shading coefficients for determining the influence that solar radiation has on spaces enclosed by fabric membranes.

- Techniques for determining the *angular long wave infra red* optical properties of materials are only commonly available for either transparent, or specularly reflecting opaque materials such as metals or glass. These techniques are inappropriate for highly *diffusing* fabric membranes. Similarly, techniques for determining hemispherical infra red optical properties are only commonly available for thin sheet metals and these techniques tend to be inappropriate for low conductivity, woven fabric membranes.

  It was only practicably possible to approximate the long wave infra red optical properties of the membrane samples, and this was done by measuring their near normal properties using a spectrophotometer. A standard equation was then developed based on the behaviour of similar materials, from which these near normal values could be converted into approximate hemispherical emissivities.

The measured near normal emissivities of these membrane samples ranged from 0.90 to 0.94, and their calculated hemispherical emissivities from 0.84 to 0.88. These emissivities were in close agreement with the '*average*' value proposed by Sinofsky[10] and were very similar to the small amount of additional information available from membrane manufacturers[11].

These solar and long wave infra red optical properties were then incorporated into a dynamic spread sheet model which was developed in order to simulate the thermal behaviour of isotropic fabric membrane panels. In order to generate information which might be used to predict the thermal behaviour of spaces enclosed by such membrane panels, this model was required to predict two fundamental values:-

- The intensity of solar radiation which membrane panels direct into spaces they enclose.
- The internal surface temperatures of those membrane panels.

In order to predict the intensity of solar radiation which the membrane panels directed into the space enclosed by them it was first necessary to determine the intensity and angular composition of solar radiation incident upon their internal and external surfaces. The standard equations used to describe the thermal optical properties of the membranes could then be used to determine whether this incident solar radiation was transmitted reflected or absorbed by the membrane.

The internal surface temperature of the membrane boundary panels was determined by calculating all the net heat transfers between the panel being investigated and its surroundings, and then predicting the membrane temperature at which the sum of these heat transfers would be zero.

The accuracy of these calculations was then tested against 3200 time steps of data monitored using the test cell described in Chapter 5. The absolute errors revealed by this process are summarised by the table below.

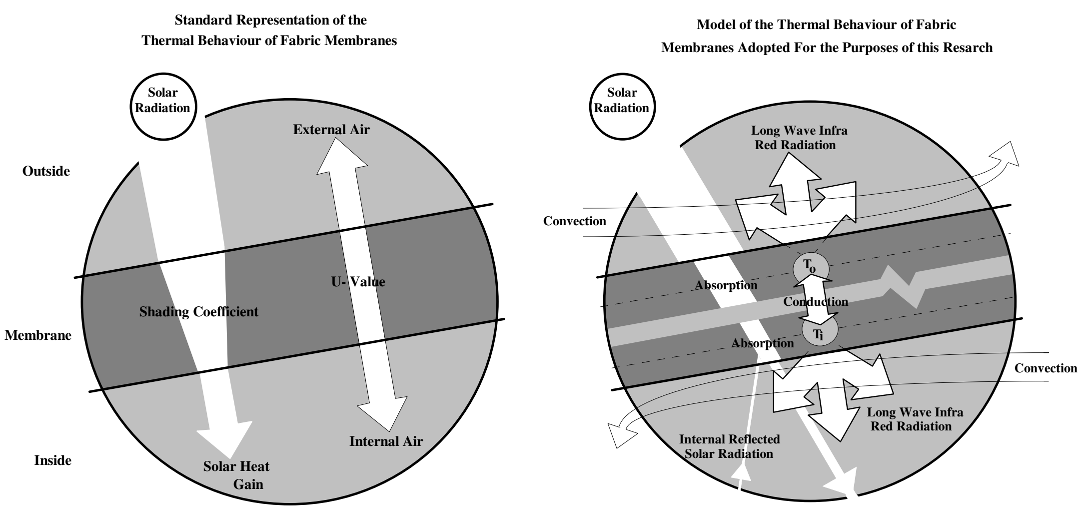
Figure 10:2.2a Table to Summarise the Overall Errors Associated with the Boundary Model Described in Chapter 7.

	Solar Radiation Reflected by Membrane Samples (W/m^2)	Solar Radiation Absorbed by Membrane Samples (W/m^2)	Solar Radiation Transmitted by Membrane Samples (W/m^2)	**Membrane Internal Surface Temp (^oc)**
Average Error	16.5	4.3	3.5	**1.2**
Maximum Error	175.5	31.2	17.4	**4.2**

Comparison between the accuracy of this approach and the work of previous researchers discussed in this thesis is only really possible at a conceptual level as much of their work was unsubstantiated. The methods they used to measure conditions and properties were measured were not made clear, and computational techniques were not fully described. This problem was compounded further by the fact that many of the techniques adopted were ultimately used to calculate *theoretical* thermal properties such as U- values and shading coefficients which were difficult to validate.

It is apparent however that there are a number of significant differences between the theoretical representation of the thermal behaviour of fabric membranes adopted for the purposes of this research, and the conventional representation still accepted by the fabric structures industry. This is illustrated clearly by the two diagrams below.

Figure 10:2.2b Diagrams to Illustrate the Difference Between the Conventional Model of the Thermal Behaviour of Fabric Membranes, and the Model Considered Necessary for the Purposes of this Research.

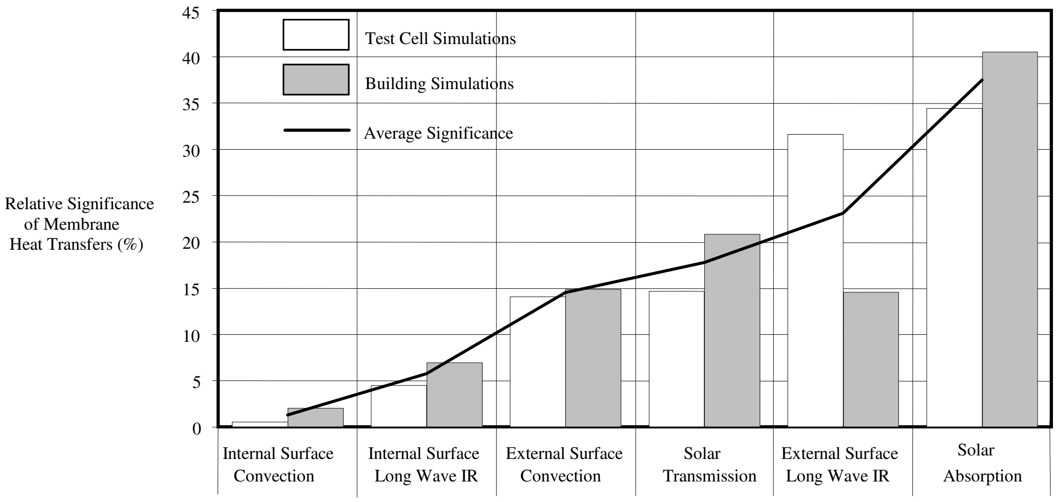


It must be considered that this research represents a significant leap forward, providing a method which accurately and appropriately represents the thermal behaviour of fabric membranes. The findings of this research add further weight to the increasing body of evidence which suggests that the current industry standard is unacceptable. If the designers of fabric structures are to be able properly to consider environmental issues, they must be provided with more appropriate properties information and more realistic analytical tools.

Analysis of the data generated by the model simulations presented in Chapter 7 suggested that the thermal behaviour of the membranes investigated using the test cell were most significantly affected by solar and long wave infra red radiation. As a consequence of this, it was found that the external environment had a significantly more profound influence on their overall thermal behaviour than conditions inside the test cell itself.

It was considered however that in practice, the thermal mass of actual fabric buildings, would result in the significance of internal surface heat transfers being much greater than had been found with the test cell. When the predicted behaviour of the test cell membranes was compared to that predicted for the buildings investigated in Chapter 9 this was found to be the case, as is shown clearly by the diagram below.

Figure 10:2.2c Diagram to show the Relative Significance of the Membrane Heat Transfers Predicted Using the Thermal Model Described in Chapter 7.



It can be seen that both of the predicted internal surface heat transfers were more significant for the buildings investigated than was the case with the test cell, whilst the significance of external surface long wave infra red radiation was considerably reduced. It was likely that this resulted from the fact that the test cell investigations could only be carried out during dry conditions, when there was likely to be little cloud cover.

Despite the general reliability of the model it was apparent that its overall accuracy was very sensitive to the slight changes in environmental conditions and that it tended to overestimate the membrane temperatures during periods of bright sunshine. It was considered that these difficulties resulted from two basic problems:-

- The model was required to predict certain environmental conditions which had not been monitored.

- Some of the surface heat transfer calculations adopted had originally been developed for investigating the thermal behaviour of more conventional materials, and these were a little oversimplified when applied to highly sensitive, low mass fabric membranes.

These difficulties will be discussed further in section 4 of this chapter.

10:3. THE THERMAL BEHAVIOUR OF SPACES ENCLOSED BY FABRIC MEMBRANES.

10:3.1 The Attempts of Previous Researchers to Investigate the Thermal Behaviour of Spaces Enclosed by Fabric Membranes.

The early attempts of previous researchers to investigate the thermal behaviour of spaces enclosed by fabric membranes were generally based on the assumption that internal conditions were entirely uniform. This meant that the overall thermal performance of the spaces could be predicted from a simple assessment of the net heat transfer across their boundaries. These boundary heat transfer calculations tended to be based on U-values and shading coefficients as discussed in the previous section.

Researchers who actually monitored the behaviour of such spaces however discovered evidence to suggest that this approach was inappropriate. During the day, positive thermal stratification of up to 7^{o}c was common in spaces enclosed by fabric membranes[12][13] and in very large spaces stratification of 20^{o}c had been recorded[14], whilst at night, or during cold weather slight negative stratification was seen to exist. It was considered that this unusual thermal variability resulted primarily from the low thermal resistance of the fabric membranes themselves[15].

It appears that only two previous attempts were made to carry out simulations which took account of this thermal stratification, both of which were very simplistic in their approach. Wu et al. attempted to simulate the thermal behaviour of the University of Northern Iowa's Unidome, developing an empirical algorithm of stratification based on monitored data[16], whilst Bazjanac et al. attempted to model thermal stratification theoretically by dividing the enclosed space into three horizontal layers with a notional thermal resistance between them[17]. The accuracy of these attempts however is difficult to evaluate as neither was based on quantifying actual physical phenomena, and the precise methods adopted are neither substantiated nor validated.

In 1984, Moseley and Croome suggested that properly predicting the thermal stratification within such spaces would require a model that was able to accurately simulate internal air movement patterns. They proposed that this could be done by finite difference analysis of a nodal grid mesh based on the Navier Stokes equations of fluid flow[18]. It appears however that no attempt was made to carry out a simulation of this type.

In 1985 Sinofsky admitted that '*To the author's knowledge, stratification in large spaces of complex geometry has yet to be predicted quantitatively*'[19] and warned that designers should be aware of the modelling errors that this omission would produce.

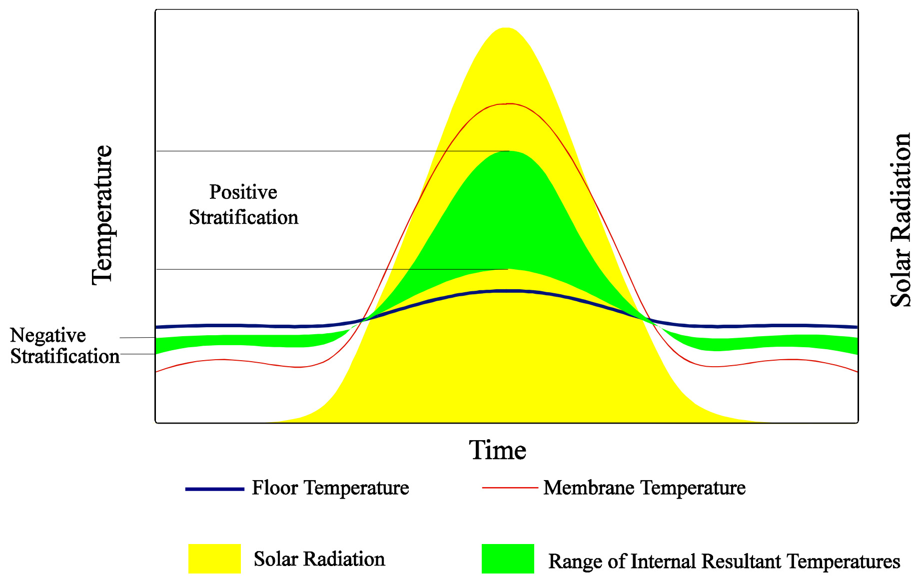
10:3.2 The Investigation into the Thermal Behaviour of Spaces Enclosed by Fabric Membranes Presented in this Thesis.

In Chapter 8 of this thesis, a programme of monitoring was described which was undertaken in order to investigate the thermal behaviour of spaces enclosed by fabric membranes. The vertical stratification of internal resultant temperatures within four unheated spaces was monitored under a range of different environmental conditions. It was found that the data obtained by this process agreed broadly with the findings of previous researchers.

The thermal behaviour of the spaces investigated was extremely sensitive to changes in environmental conditions. Positive thermal stratification of over 10^{o}c was recorded during periods of bright sunshine, whilst during cold weather or at night negative stratification was observed.

Previous researchers appear to have assumed that these thermal gradients were caused by the low thermal mass of the membrane boundary which allowed heat rising from the floor to quickly escape through to the outside. Because of this, they considered that thermal gradients were produced by the stratification of internal air[20]. Analysis of the data presented in this thesis however suggests that these thermal gradients are actually generated by contrasting internal surface temperatures as illustrated schematically below.

Figure 10:3.2 Diagram to Illustrate the Characteristic Thermal Behaviour of Unheated Spaces Enclosed by Fabric Membranes.



During periods of bright sunshine, fabric membranes were seen to heat up quickly and significantly, whilst at night or during cold clear weather, they could rapidly become considerably cooler than their surroundings. The contrast between this and the relatively stable thermal behaviour of more *'massive'* internal surfaces such as the floor, meant that low level temperatures were likely to respond more slowly to changes in environmental conditions than temperatures closer to the membrane. The affect of these different response rates was to produce internal stratification.

Because this stratification was motivated by contrasting surface temperatures, it was seen to be composed of variations in both internal air temperatures and internal radiant temperatures. The significance of variations in internal *radiant* conditions in this respect had not been recognised by previous researchers.

As previous researchers had assumed that these temperature variations resulted primarily from the stratification of internal air, they considered that it would be possible to accurately predict the thermal behaviour of space enclosed by fabric membranes if internal air movement patterns could be simulated. The observed thermal behaviour of the spaces described in this thesis however suggested that properly predicting the thermal behaviour of such spaces, requires that both internal air movement patterns and internal radiant temperatures are simulated.

In Chapter 9, an attempt to simulate this complex thermal behaviour was described, based upon the monitored data presented in Chapter 8. This was done using *Flovent*, a general purpose CFD model which uses an iterative approach based on a nodal network of finite volumes or cells. Within each cell, air temperature, air velocity and radiant temperature were predicted, and these were then used to calculate internal resultant temperatures.

On average the difference between monitored internal resultant temperatures and those predicted using *Flovent* was just 1.4^{o}c. It was found however that generally *Flovent* only predicted half the internal stratification which had been monitored within the spaces investigated. Whilst at night or during periods with little solar radiation this problem did not significantly affect the overall accuracy of the simulations, during periods of strong internal stratification it could result in model errors of up to 4.5^{o}c.

These errors may have been caused in part by the oversimplified nature of the solar model within *Flovent*, however as the predicted radiant stratification was generally more than twice the predicted stratification of internal air, it seemed more likely that there was a problem within the fluid flow model itself.

It was considered that this problem originated from a number of oversimplifications in the technique use to specify the boundary enclosing the simulated space. These oversimplifications resulted a number of fundamental difficulties that will be discussed further in the next section of this chapter.

The comparative accuracy of this approach is difficult to assess because of the lack of conclusive validation presented by previous researchers. For example comparison between the monitored and predicted data generated by Wu et al. led them to suggest that '*...model correlations to each period were within 3% of standard error*'[21], whilst Piksaikina stated that, '*...discrepancies between the experimental data and the predicted ones for the inside air temperature constituted 5- 8%..'* [22]. What precisely either of these statements refers to is not made clear by the published text.

Other researchers describe good correlation between monitored data and model predictions despite major oversimplifications in the analytical techniques they adopted. Moseley and Croome for example state that the response factor method predicted internal air temperatures which were all within 2^{o}c of monitored data[23]. However no attempt was made to simulate internal thermal gradients within the space investigated despite the fact that stratification of up to 7^{o}c had been monitored[24], and it is difficult therefore to see how such accuracy could have been possible.

It has to be considered that the approach adopted for the purposes of this research was significantly more accurate than the techniques used by previous researchers, despite some of their claims to the contrary. Even at their best, previous methods had been based on oversimplified boundary analysis techniques, the stratification of internal air had only been dealt with in a cursory manner, and no attempt had been made at all to simulate radiant stratification.

10:4 OVERALL ASSESSMENT OF THE RESEARCH PRESENTED IN THIS THESIS.

10:4.1 **Introduction.**

It was considered that the investigation presented in this thesis moved forward significantly the body of knowledge relating to the thermal behaviour of spaces enclosed by fabric membranes.

It was apparent however that many of the remaining difficulties resulted from the same fundamental problem that had been encountered by previous researchers. This was that a large number of the monitoring, experimental and analytical techniques adopted had originally been developed for investigating the thermal behaviour of '*conventional*' buildings. Many of the assumptions upon which these techniques were based became inappropriate when applied to spaces enclosed by fabric membranes.

This appears to result from three of the fundamental characteristics of fabric membranes which make such spaces unusual:-

- Fabric membranes tend to be translucent.
- Fabric membranes have insufficient mass to significantly affect their thermal behaviour.
- The geometry of fabric membranes is doubly curved.

The implications of each of these characteristics is discussed below:-

10:4.2 Fabric Membranes Tend to be Translucent.

The translucent nature of fabric membranes means that they tend to diffuse radiation. As a consequence of this, their thermal optical properties cannot be properly investigated using the *specular* techniques appropriate for transparent glass or opaque metals.

The diffuse thermal radiation which fabric membranes transmit or reflect can only be properly quantified hemispherically and this requires the use of Alfred type integrating spheres. Whilst Alfred spheres suitable for measuring solar optical properties are relatively common, long wave infra red integrating spheres tend to be expensive and can be inefficient[25].

It actually only proved possible to measure long wave infra red optical properties at near normal angles of incidence, but this was not considered a serious problem as the membranes investigated transmitted and reflected very little long wave infra red radiation. If membranes are developed however which attempt to fully exploit the potential of long wave infra red radiation exchanges then these properties may need to be determined more accurately. This could be done using an Alfred type sphere whose inside surface is coated with fine powdered gold.

It also became apparent that the angular nature of the solar radiation transmitted by fabric membranes could significantly affect the thermal conditions within the spaces they enclosed. The simplicity of the solar model within *Flovent* however meant that the solar radiation transmitted into the enclosed space had to be considered either entirely direct beam or entirely diffuse. In reality solar radiation within the enclosure was likely to be only partially diffuse, and the resulting variations in internal solar intensities could result in differences in internal resultant temperatures of over 2^{o}c.

In order to properly account for this internal variability, the thermal model would have to be able to determine the diffuse and direct beam intensity of external solar radiation, as well as the diffusivity of the membranes angular solar transmittance. This would require the measurement of very complex membrane optical properties, and the development of a CFD code which incorporates a sophisticated solar model.

10:4.3 Fabric Membranes have Insufficient Mass to Significantly Affect their Thermal Behaviour.

Fabric membranes are so thin relative to their surface area that it is reasonable to assume they have insufficient mass to significantly affect their thermal behaviour. This means that at any instant their thermal behaviour results entirely from their *surface heat transfers*, and their *thermal optical transmission characteristics* at that instant. As both of these parameters are exceptionally sensitive to environmental conditions, so it was found is the thermal behaviour of fabric membranes.

The extent of this sensitivity had not been properly realised when this research was undertaken and as a consequence the environmental conditions which were recorded during the two monitoring programmes had to be supplemented by a number of predicted values. It was apparent that any inaccuracies in these predicted values translated directly into errors in the simulated behaviour.

In order to reduce the potential errors associated with these predicted environmental conditions, it is recommended that future monitoring programmes record two additional parameters, *horizontal diffuse solar radiation* and *sky temperature*. These would eliminate many of the uncertainties within the solar model, and in particular would remove the need to predict *cloud cover*.

The sensitive thermal behaviour of the fabric membranes investigated was also apparent within the spaces which they enclosed. This was reflected both in the technique necessary to monitor their behaviour, and the approach necessary to accurately simulate that behaviour:-

- Surface temperatures within '*conventional*', thermally massive buildings tend to be fairly uniform, and change only slowly during variations in environmental conditions. As a result, air and radiant temperatures at any one location will tend to be fairly similar, temperatures are also likely to be relatively uniform throughout the enclosure and to change only slowly over time. This means that the thermal behaviour of the interior can be measured fairly accurately using just a few, slow response sensors which record components of both internal air and radiant temperatures.

In spaces enclosed by fabric membranes, the variability of the membrane internal surface temperature means that internal temperatures can change noticeably from one location to another and from one moment to the next. Accurately recording such behaviour therefore requires the use of a large number of fast response sensors distributed throughout the enclosure. It is also apparent however that there can be significant differences between the internal air and radiant temperatures recorded at any one location. Ideally therefore, internal air and radiant temperatures should be measured separately rather than using the single resultant temperature adopted for the purposes of this research.

- It is also possible that the changeability of internal conditions within such spaces makes them inappropriate for steady state CFD simulations. There was some likelihood that as *Flovent* attempted to achieve a stable steady state solution, it would diffuse internal air in a way that the changeability of environmental conditions would prevent from happening in reality. In order to avoid this problem in the future, transient analysis may be necessary. This would require the development of a CFD model that allows all run parameters to vary from one moment to the next in order to simulate changing environmental conditions. Currently, *Flovent* is unable to do this.

10:4.4 The Geometry of Fabric Membranes is Doubly Curved.

Much of the existing theory used to simulate thermal behaviour within the built environment assumes that boundary surfaces conform to a Cartesian geometry. For conventional buildings, this may not be an inappropriate assumption, but in order to maintain their structural stability, fabric membranes must be entirely *doubly curved*. This fundamentally non Cartesian geometry becomes a particular problem when attempting to predict *external* and *internal surface convection heat transfers*:-

- *External* surface convection was calculated within the boundary model based purely on a free stream wind velocity and whether the surface azimuth faced windward or leeward. This meant that significant changes in surface geometry could be ignored by the calculation, whilst very subtle azimuth variations could change the membrane orientation classification and so significantly affect the predicted external surface convection heat transfer. It seemed unlikely that such a simple approach could accurately simulate the flow of air over complex, doubly curved fabric membranes.

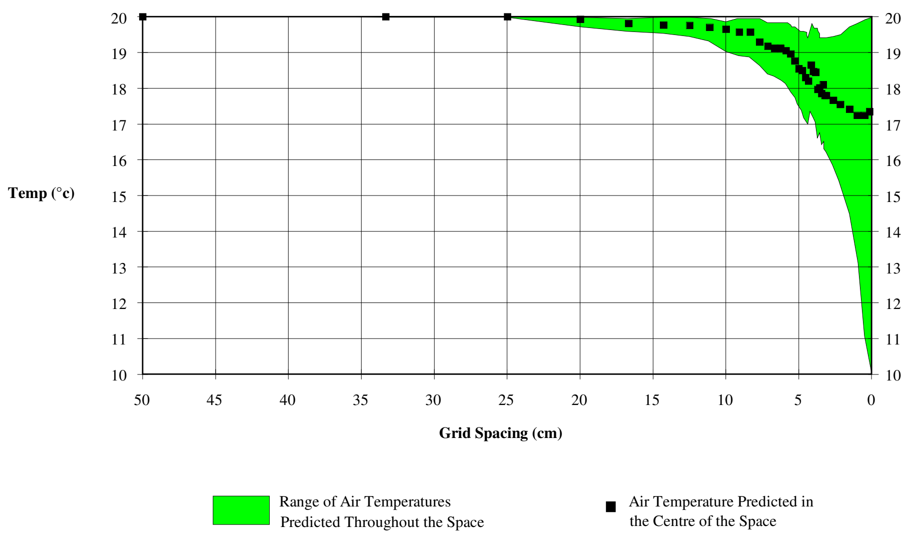
- The study of convection at the *internal* surfaces of many conventional buildings has been simplified by the assumption that surfaces are either vertical or horizontal. Such an approach does not properly describe convection heat transfer at the internal surface of continuos doubly curved fabric membranes. The extrapolation between horizontal and vertical behaviour used in this research to represent inclined surface convection heat transfer has yet to be satisfactorily validated.

It is also apparent that *Flovent* itself can only simulate boundary elements in terms of either horizontal or vertical panels which conform to a Cartesian grid. Representing the geometry of a doubly curved fabric membrane in this way was extremely time consuming and required considerable reinterpretation and simplification. There was some likelihood that this representation of their continuous doubly curved surfaces as a series of discrete steps resulted in the underestimation of internal surface air velocities and so the under prediction of internal surface convection heat transfers.

In order to assess the likely significance of errors associated with these surface air velocities, a series of CFD simulations were carried out based on a simple two dimensional 1m square space.

Three of the boundaries of the space were given a surface temperature of 20^{o}c, whilst the fourth, a vertical boundary was given a temperature of 10^{o}c. This was intended to represent a small space with a cold vertical window on one side. The size of the cells within the space were then varied from 50cm to almost 0cm, and each time the grid size changed, *Flovent* reassessed the internal air temperatures throughout the space. These simulations were carried out in order to discover how much the range of predicted internal air temperatures changed as *Flovent* became more and more able to simulate the fast moving down draft close to the surface of the cold window. The results of these simulations are shown on the graph below.

Figure 10:4.4a Diagram to Show the Affect of Reducing the Grid Spacing Used by Flovent on the Air Temperatures Predicted Within a Small Box.

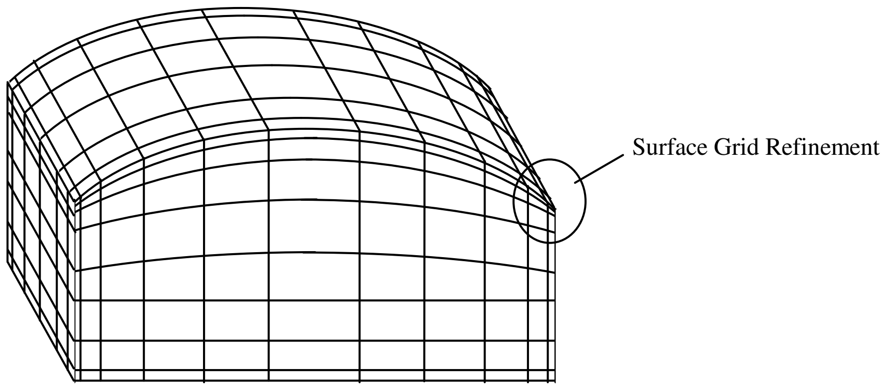


It can be seen that the predicted air temperature in the centre of the space decreased by almost 2.75^{o}c as the grid spacing became smaller. This was as a result of *Flovent* being more able to simulate the fast moving down draft close to the cold surface, resulting in increased convection heat transfer at that surface.

It was seen that the predicted internal air temperature in the centre of the space continued to decrease significantly until a grid spacing of less than 4cm was specified. Obviously specifying such a tight Cartesian grid for a space enclosed by a doubly curved membrane would be computationally impractical (see *Figures 9:7.3a* and *b)*. In order to avoid this problem however it is possible to adopt a Body Fitted Co-ordinates (BFC) grid[26].

This involves distorting a standard Cartesian grid into a doubly curved BFC grid following the exact shape of the membrane boundary. The grid mesh can then be properly refined close to the surface of the membrane without significantly increasing the overall model complexity.

Figure 10:4.4b Diagram to illustrate the Surface Refinement Possible with a Body Fitted Co-ordinate Grid.



Flovent was unable to generate such a BFC grid. Some existing CFD codes are based on BFC grids (*Phoenics*[27]) or even unstructured grids (*Fluent*[28]), but in order to accommodate some of the other developments suggested in this section, it seems likely that a purpose written thermal model may have to be developed.

Despite the difficulties highlighted in this section however, the modelling process adopted for the purposes of this research was considered significantly more appropriate than the approaches adopted by previous researchers, and with experience, it was possible to simulate monitored data fairly accurately. If that monitored data did not exist however, as would be the case if a design investigation were carried out, the situation would become considerably more complex. The reasons for this are discussed in the next section of this chapter.

10:5 FUTURE DEVELOPMENTS.

10:5.1 A Holistic Approach for Investigating the Thermal Behaviour of Spaces Enclosed by Fabric Membranes.

The general lack of existing research encountered during the course of this study, and the obvious complexity of the subject as a whole had suggested that this research could best be dealt with in two parts:-

- An investigation into the thermal behaviour of fabric membranes.
- An investigation into the thermal behaviour of spaces enclosed by fabric membranes.

This separation allowed the techniques used to investigate the thermal behaviour of both parts to be predicted by using monitored data to describe the behaviour of the other part. Such an approach would be impossible however for design investigations as no such monitored data would be available.

If the behaviour of neither the fabric membrane, nor the enclosed space were known, then it would be necessary to make some assumptions about the likely behaviour of one of the systems in order to predict the behaviour of the other. This suggests that design investigations would require an iterative process, where first the behaviour of the enclosed space, was '*guessed*', then the behaviour of the membrane predicted based upon this, then the behaviour of the enclosed space re- assessed, then the membrane, and so on until both parts converged upon a single stable solution.

In effect, it can be seen that the link between the thermal behaviour of the fabric membrane and that of the enclosed space is as dynamic as the behaviour found within either individual system. As the state of the membrane changes, so internal conditions are affected, these in turn influence the state of the membrane and so on. Simulating this situation using the approach described in this thesis could be a time consuming process.

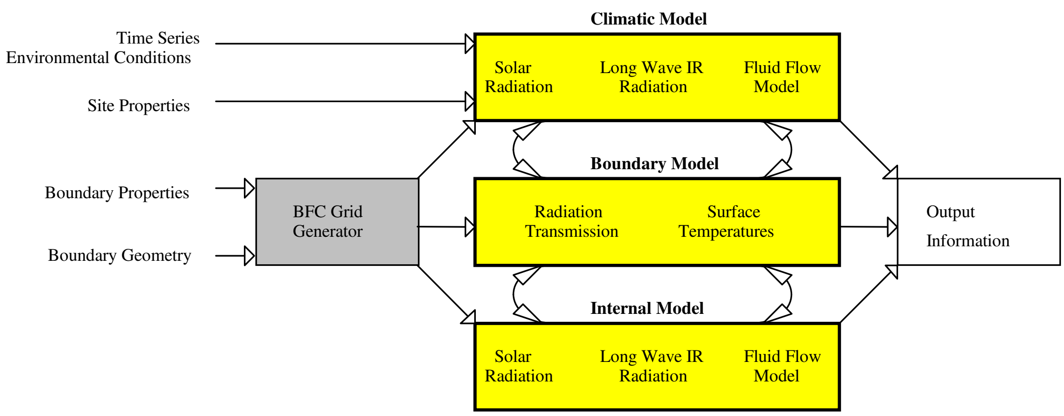
A possible way around this would be to include the boundary model as part of the CFD code itself. This would require the development of a specialist CFD code, as suggested in the previous section of this chapter, but would produce a holistic model which could solve for both the thermal state of the membrane and the enclosed space simultaneously by a process of iteration.

If this development were accompanied by the additional improvements discussed in the rest of this chapter, then a truly powerful design tool would begin to emerge which could be used with some confidence to investigate the thermal behaviour of spaces enclosed by fabric membranes. Some of the more fundamental improvements suggested by this research which could be incorporated into such a model could include:-

- More accurate solar modelling allowing both the intensity and directional composition of solar radiation within the enclosure to be determined.
- Some attempt to simulate external fluid flow based on the orientation of individual membrane panels and the geometry of their surroundings.
- The accommodation of detailed time series data allowing proper transient simulations to be carried out.
- Automated grid specification based on Body Fitted Co-ordinates.

The possible format of such a model is illustrated schematically below:-.

Figure 10:5.1 A Dynamic Tool for Predicting the Thermal Behaviour of Spaces Enclosed by Fabric Membranes.



10:5.2 The Application of a Practical Tool.

CFD models for investigating the variable thermal behaviour of spaces in the built environment are still in their infancy. Whilst considerably more promising than the simplistic analytical techniques otherwise available, as yet they do not seem to provide a practical tool for accurately *predicting* the thermal behaviour spaces enclosed by fabric membranes. At present, the processes which must be undertaken in order to attempt such predictions are cumbersome and time consuming and it could not be expected that designers would be inclined to apply such techniques within the constraints of a tight schedule.

It seems likely that in order to provide a more convenient and reliable tool for this purpose, it will be necessary to develop a purpose written CFD code, tailored to suit the particular needs of the fabric structures industry. This situation is analogous to the unusual structural analysis requirements of the industry which resulted in the development of a large number of complex purpose written form finding codes.

Even with the relatively simple developments described in this chapter such CFD models could become impressive analytical tools which would allow environmental designers to carry out detailed investigations at a number of different levels:-

- To assess the relative thermal performance of various design alternatives.
- To devise basic environmental control strategies.
- To size and specify environmental control equipment.
- To predict energy consumption.
- To develop system control programmes to maximise building management efficiency.

The current complexity and expense of such investigations however means that in the majority of cases designers are likely to continue to attempt environmental assessments either using very simple and inappropriate calculations, or based on past experience. The success of those designs for which more rigorous analysis is considered necessary may provoke further research.

It is hoped that in the future detailed investigations into the thermal behaviour of spaces enclosed by fabric membranes may become as natural a part of the design process as complex structural investigations already are.

10:6. CONCLUSION.

In this chapter the investigation into the thermal behaviour of spaces enclosed by fabric membranes described in this thesis was compared to the work of previous researchers. Some of the difficulties still remaining with this work were discussed, and a number of developments necessary to overcome these difficulties were suggested.

In particular, it was apparent that the behaviour of such spaces is inexorably dynamic, and that whilst the separating the overall thermal investigation into the *fabric membrane* and the *enclosed space* was a valid approach for the purposes of this research, in reality no such distinction can be made. It was proposed that practical design investigations would require the development of a truly dynamic and holistic CFD model encompassing the behaviour of both the fabric membrane and the enclosed space.

Despite the range of difficulties identified however, it was considered that the approach adopted for the purposes of this research was significantly more accurate and appropriate than the techniques used by previous researchers. Such approaches had typically been based upon the use of shading coefficients and U- values, only very simple attempts had been made to simulate the stratification of internal air and the significance of internal radiant gradients had not been recognised at all.

In the next chapter, the overall conclusions of the research presented in this thesis are briefly summarised.

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