3: THE EXISTING BODY OF KNOWLEDGE.

3:1. INTRODUCTION.

In the previous chapter, the historical evolution of fabric structures and the fabric structures industry was described, and their characteristic features were highlighted.

It was proposed that the performance requirements being made of modern fabric structures are becoming more complex, and that at the same time the variety of membrane types with which to satisfy those requirements is increasing. It seems however that whilst designers have been able to keep up with the structural implications of this changing situation, environmental issues, continue to be dealt with in a cursory manner which is increasingly unable to satisfy clients requirements.

A number of simple qualitative studies into the environmental behaviour of fabric structures were undertaken by previous researchers in the 1960's and 70's [1][2][3], but this did little to enable designers to approach environmental analysis with the same degree of confidence with which structure investigations were possible. Designers and manufacturers alike began to realise that if membrane enclosed spaces were to achieve the same level of environmental performance as more conventional buildings, it would be necessary to develop analytical techniques which could be used to assess the likely performance of various design alternatives.

In this chapter, those attempts of previous researchers to investigate the environmental and specifically the thermal behaviour of spaces enclosed by fabric membranes using quantitative techniques is critically reviewed. This review was undertaken in order to provide a clear impression of the current state of development of the subject, and to highlight those areas which required further research.

3:2. THE EXISTING BODY OF KNOWLEDGE RELATING TO THE THERMAL BEHAVIOUR OF FABRIC MEMBRANES.

3:2.1 Steady State Analysis of the Thermal Behaviour of Fabric Membranes.

Early qualitative investigations into the environmental behaviour of spaces enclosed by fabric membranes had made it increasingly clear that if such spaces were to be designed competitively it would be necessary to develop a technique with which their thermal behaviour could be predicted. This would allow designers to determine the most efficient way of maintaining occupant comfort, and to predict how much energy such an approach would consume.

Early attempts at quantitative investigations assumed that the enclosed space behaved as a single homogenous system. This meant that internal conditions could be predicted based on a simple estimation of the total heat transfer into or out of the space through the fabric membrane envelope. Initially, attempts to quantify this boundary heat transfer involved the adoption of simple steady state techniques developed for the analysis of more conventional structures. Such techniques tended to be based on the use of *U-values*.

U-values represent the amount of heat in watts per meter squared which will conduct from one side of a building material to the other as a result of a temperature difference of one degree centigrade across that material. This simple performance description was developed as a means of approximating the rate of heat loss or gain through conventional building envelopes as a result of a difference between the internal and external air temperatures. Generally the lower the U-value of the building envelope, the greater the thermal resistance of its construction and so the less energy will be required to maintain a given temperature within the enclosed space. Part L of the British Building Regulations recommends that the U-value of the external walls of standard dwellings should be less than $0.45\mathrm{W/m^{2\,o}c}$[4].

In the early 1970's, Larsson monitored the heat losses of five air supported fabric structures, each enclosed by a different membrane envelope configuration[5]. The recorded heat losses suggested that a U-value of $5.5\mathrm{W/m^{2\,o}c}$ was typical for a single membrane building envelopes. This compared very unfavourably with the performance of more conventional building materials, and in 1979 an internal report was prepared by Du Pont to determine whether it was theoretically possible to achieve a U-value of $1\mathrm{W/m^{2\,o}c}$ with a membrane envelope whilst maintaining a translucency of 2 to 4% [6]. The U-value calculations carried out for this purpose were based on the standard equation below:-

$$U = \frac{1}{\frac{1}{h_o} + \frac{g}{C_{core}} + \frac{1}{h_i}}$$

Where h_o and h_i describe the thermal conductivity of the internal and external surfaces of the membrane, and C_{core} represents the thermal conductivity of the membrane core, thickness g. For double layer membrane envelopes a more complex equation was developed:-

$$U = \frac{1}{\frac{1}{h_i} + \frac{g_2}{C_{core2}} + R_s + \frac{g_1}{C_{core1}} + \frac{1}{h_o}}$$

where R_S represents the thermal resistance of the air space between the outer membrane (1) and inner membrane (2).

The core resistance of the membranes were determined experimentally, and film resistances h_o and h_i were estimated based on ASHRAE standard summer and winter conditions (summer h_o=22.7 W/m^{2o}c, winter h_o=34.1W/m^{2o}c, summer h_i=6.1W/m^{2o}c, winter $h_{i=}$9.3W/m^{2o}c [7]).

This produced two sets of U-values which were considered to be in close agreement with independently obtained laboratory results. It was concluded however that not even a triple membrane envelope could achieve a U-value of 1W/m^{2o}c. The addition of 50mm glass wool insulation would produce a U-value of 0.6W/m^{2o}c, but this did not allow the required translucency of 2%.

During the course of these investigations however, it became increasingly apparent that the thermal performance of translucent fabric membranes could not be judged based on U-values alone. In his report for Du Pont, Solenberger suggested that it was also necessary to evaluate solar heat gains.

This he attempted to account for using the concept of the *solar heat gain coefficient* (F) such that:-

$$F = \tau + (\alpha \times U / h_o)$$

where τ represents the solar transmittance of the membrane, and $(\alpha \times U / h_o)$ is indicative of the inward flow of heat resulting from the solar absorptance (α) of the membrane. This allowed the total amount heat entering a space per unit area of a fabric membrane as a result of solar radiation to be calculated:-

$$Q_{sol} = F \times I$$

where I represents the intensity of incident solar radiation.

By combining these two concepts, the U-value and the solar heat gain coefficient, the net heat transfer between an enclosed space and the external environment per unit area of its membrane boundary could be calculated:-

$$Q_{mem} = (F \times I) + U (t_o - t_i)$$

This basic steady state approach for calculating the heat transfer across fabric membranes, was quickly accepted by membrane manufacturers as a means of quantifying the relative thermal performance of their products.

Today, most membrane manufacturers tend to describe the thermal performance characteristics of their products in terms of U-values and a property indicative of solar heat gain known as the *shading coefficient.* Shading coefficients represent the solar heat gain through fabric membranes relative to the known solar heat gain through glass.

Solar heat gain factors describe the solar heat gain through a single sheet of 3mm double strength clear plate glass under different conditions. Tables exist which catalogue solar heat gain factors on average days throughout the year and at different angles of incidence, and conversions can be applied to these in order to predict solar heat gain factors under non average conditions[8]. The solar behaviour of materials other than 3mm glass can then be predicted based on shading coefficients which describe the total solar heat gain through that material compared to glass. For a given material under known conditions therefore:-

Solar heat gain = shading coefficient (SC) × solar heat gain factor (SHGF) [9]

Shading coefficients can be measured using an illuminated hot box under simulated *summer* and *winter* conditions, and from these values, solar heat gain under a range of different conditions may be predicted.

Membrane manufacturers now tend to calculate the U-values of their products based on an updated version of the technique adopted by Solenberger such that:-

$$U = \frac{1}{R} = \frac{1}{R_{si} + R_c + R_{so}}$$

$$\text{where} \quad R_{so} = \frac{1}{(\varepsilon_o \times h_{ro}) + h_{co}} \quad \text{and} \quad R_{si} = \frac{1}{(\varepsilon_i \times h_{ri}) + h_{ci}}$$ [10]

where h_{ro} and h_{co} are the external surface radiation and convection heat transfer coefficients respectively, h_{ri} and h_{ci} are the internal surface radiation and convection heat transfer coefficients, and ε_i and ε_o represent the inside and outside surface emissivities of the membrane.

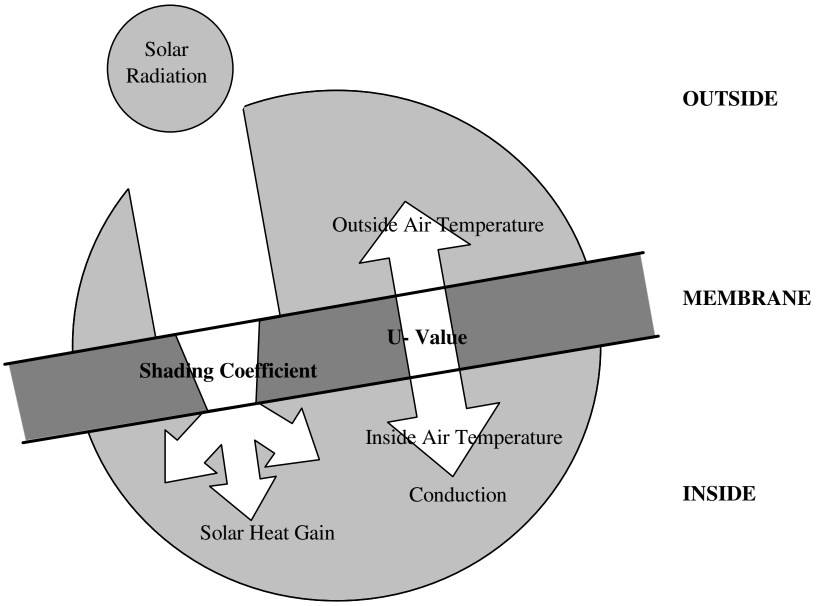
In practice either the membrane core conductivity is determined experimentally using a thermoconductometer, and then the overall U-value is calculated by assuming standard internal and external surface resistances, or the overall U-value is determined experimentally using a '*hot box*'. Because of the significance of surface resistances, two values are often provided by membrane manufacturers, one for standard winter conditions, and another for standard summer conditions[11].

Combining these two concepts the U-value (U) and shading coefficient (SC), should allow the steady state heat transfer across a fabric membrane of area A to be calculated. Assuming that internal conditions are uniform, the total heat transfer across a fabric membrane building envelope may be considered to be indicative of the overall thermal performance of that building.

$$Q_{mem} = A\,((SC \times SHGF) + (U(t_o - t_i))) \qquad [12]$$

Where t_o represents the external air temperature, t_i the internal air temperature and SHGF the solar heat gain factor under the conditions being investigated.

Figure 3:2.1 Schematic Illustration of the Standard Method For Calculating the Heat Transfer Across Fabric Membrane Building Envelopes.



Some additional information is occasionally available from membrane manufacturers and this can include average transmittance of visible light, average solar transmittance, solar reflectance and solar absorptance and emissivity. Unfortunately it is often unclear how these '*average*' properties have been measured, or exactly what they represent.

3:2.2 Evaluation of Steady State Analysis Techniques.

U-values assume that the heat conducted across a building envelope is proportional to the difference in the temperatures of the air on either side of it, and this relationship is calculated as the reciprocal of the sum of the *core resistance* and the two *surface resistances*.

For many conventional building materials, this is not an inaccurate representation. In order for the external walls of a conventional dwelling to conform to the British Building Regulations, the thermal resistance of their core material must account for at least 94% of the total boundary resistance[13]. This means that the fact that surface resistances are dependant on a great number of variable environmental parameters other than air temperature is of little consequence, and so within the limited range of conditions found in the built environment it is generally acceptable to assume that U-values are constant.

Under standard winter conditions, the thermal resistance of the core material of a thin fabric membrane can account for as little as 1.2% of the total boundary resistance[14]. This means that its overall thermal resistance is almost entirely dependant on the heat transfers which occur at its surfaces. These surface heat transfers can only properly be described in terms of the difference between the temperature of the membrane surfaces and the environmental conditions either side of them. This means that air to air U-values which ignore the temperature of the membrane itself are an entirely inappropriate method for quantifying their thermal behaviour.

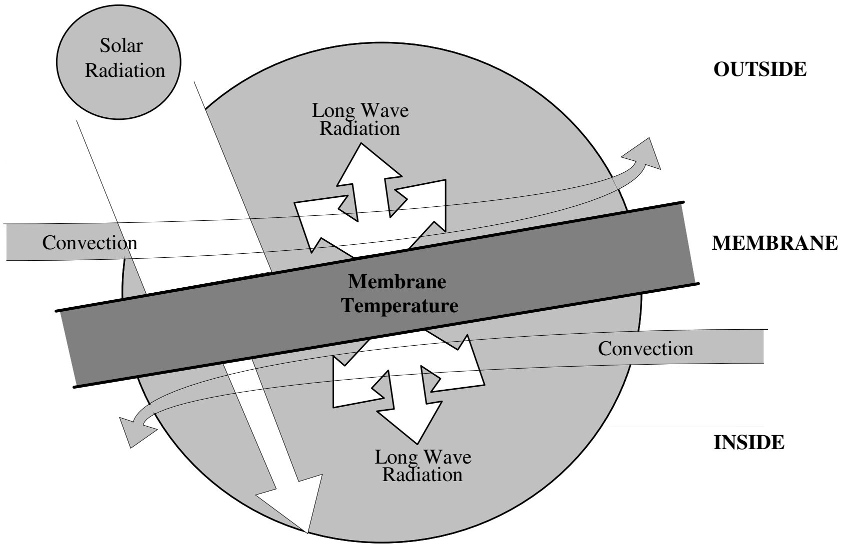
Similarly shading coefficients assume that the amount of heat entering a space as a result of solar radiation striking its envelope is linearly related to the intensity of that solar radiation. Whilst in terms of directly transmitted solar radiation this may not be an inaccurate assumption, the proportion of absorbed solar radiation which will be subsequently radiated into the enclosed space is dependent on the difference between the temperature of the membrane surfaces and the environmental conditions on either side of them, and not just the solar intensity.

It can be seen therefore that both thermal transmission through fabric membranes and solar heat gain across them are dependant upon the relationship between external environment and the membrane and the relationship between internal environment and the membrane, not the relationship between internal and external conditions.

The relationship between the state of the membrane and the heat exchanges with its surroundings is not constant. For example as a membrane becomes hotter by absorbing solar radiation, so it will lose more heat by long wave radiation and surface convection, reducing the rate at which its temperature increases. This suggests that the characteristic thermal behaviour of fabric membranes could only ever be properly predicted by using dynamic analysis techniques based on the temperature of the membrane itself.

This situation is illustrated schematically by *Figure 3:2.2*, overleaf.

Figure 3:2.2 Diagram to Illustrate the Dynamic Thermal Behaviour of Fabric Membranes.



3:2.3 Dynamic Analysis of the Thermal Behaviour of Fabric Membranes.

In 1984, a paper was published by Moseley and Croome in which various methods for predicting the temperatures within lightweight structures were reviewed[15]. They suggested that steady state boundary analysis techniques produced *'...at best, conservative estimates of energy loads'* [16] and suggested that in order to accurately predict the temperature within spaces enclosed by fabric membranes, it would be necessary to adopt a dynamic approach. For this purpose, they attempted to use three dynamic analysis techniques in order to predict the temperature within an air supported fabric structure which had been built specifically for their research.

Moseley and Croome chose *the finite difference method*, *the response factor method* and *the admittance method* for this purpose. These methods were used to determine the heat transfer across the core material of the fabric membranes investigated, and then using standard internal surface heat transfer coefficients the amount of heat exchanged with the interior was calculated.

As with steady state techniques however, these methods were originally developed for investigating the thermal behaviour of more conventional building materials, and the manner in which they were re applied to the analysis of fabric membranes was not entirely appropriate.

These techniques tended to be based on complex dynamic analysis of the heat transfer across the boundary material itself, but dealt with surface heat transfers in only a cursory manner. This meant that whilst Moseley and Croome carried out detailed simulation of the transient flow of heat across the membrane core itself, they specified climatic conditions using a single value, the *sol-air* temperature, and the simplifications associated with the calculation of internal surface heat transfers were described as a '*problem*'.

It was seen from the previous section of this chapter that such an emphasis was entirely inappropriate when applied to large surface area low mass fabric membranes.

The *finite difference* or *heat balance* method was also adopted by both Hart et al.[17][18] in order to assess the relative energy performance of a range of fabric membranes. This approach was based on the division of the membrane *core* into a series of discrete homogenous volumes for each of which the basic assumption is that:-

heat in - heat out = heat stored

In order to carry out detailed energy analysis Hart et al. then selected an existing thermal model and used finite difference analysis to produce the input information necessary to specify the problem. Unfortunately this required that the dynamic boundary analysis was used to predict U-values and shading coefficients, the only input information which the thermal model would accept.

In 1985, a paper was presented by Sinofsky at the ASHRAE Annual Conference in Waikiki[19]. Again Sinofsky adopted the finite difference approach to the dynamic analysis of the thermal behaviour of fabric structures, however, Sinofsky based his analysis on fairly detailed information regarding the thermal properties of fabric membranes, including their angular solar optical properties and surface emissivities. This allowed surface heat transfers to be investigated in more detail than in the work of previous researchers.

The methods by Sinofsky measured the material properties which he used for this purpose however were not entirely satisfactory, and as with the work of Hart et al., Sinofsky was forced to use his dynamic analysis technique in order to calculate steady state U-values and shading coefficients in order to carry out energy analysis using an existing thermal model.

Future work was recommended by Sinofsky which was intended to replace shading coefficients with real solar heat gain calculations, and to allow other environmental heat transfer mechanisms such as long wave infra red radiation and convection to be properly calculated. It appears however that this work was not carried out.

3:3. THE EXISTING BODY OF KNOWLEDGE RELATING TO THE THERMAL BEHAVIOUR OF SPACES ENCLOSED BY FABRIC MEMBRANES.

3:3.1 Early Investigations into the Thermal Performance of Spaces Enclosed by Fabric Membranes.

The three groups of researchers described in the previous section; *Moseley and Croome* (1984), *Hart et al.* (1984) *and Sinofsky* (1985) all used their simple boundary models to produce information with which they could attempt to predict the overall thermal behaviour of spaces enclosed by fabric membranes.

Moseley and Croome used the three boundary analysis techniques described to produce information which could be input into three existing thermal models. The finite difference approach was used to specify the boundary conditions for an investigation using the ESP model, the response factor method was used with a temperature prediction model developed by Grainland (UK) Ltd and the admittance method was used to predict internal conditions based on algorithms taken from the CIBSE Guide[20]. Each of these techniques had originally been developed for the analysis of more conventional, thermally massive buildings, and as a consequence they assumed that internal conditions were entirely uniform.

Little specific detail exists regarding the actual techniques used by Moseley and Croome, however the response factor method in particular was considered to be very accurate and predicted temperatures were claimed to be within 2^{o}c of monitored data.

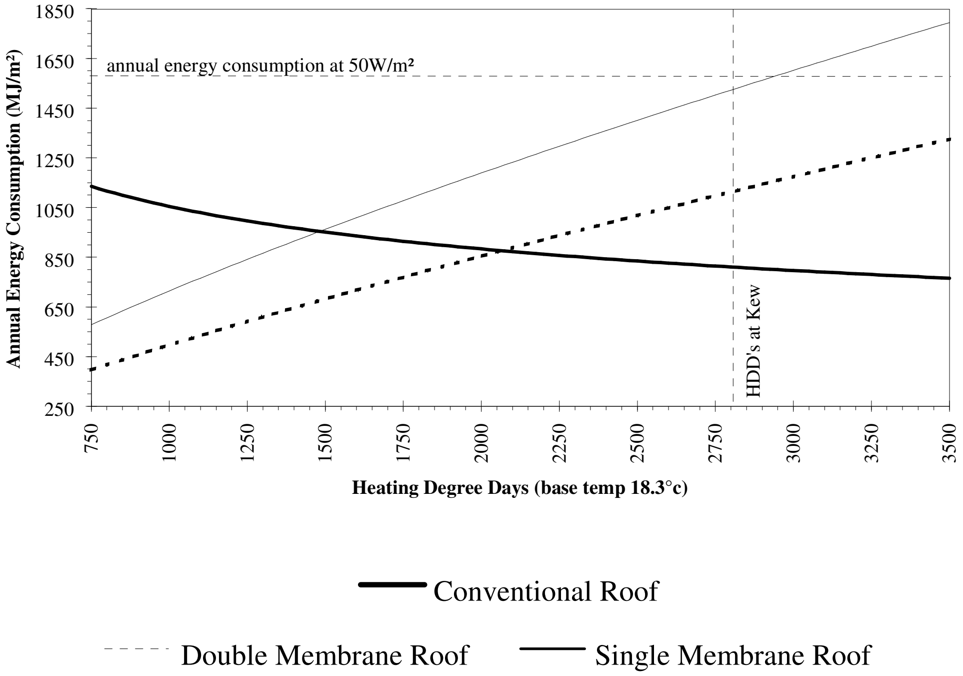
Hart et al. used a modified version of the American energy analysis model DOE-2.1 in order to assess the environmental performance fabric roofed spaces. This again was a computer programme which was designed for investigating the energy consumption of conventional, thermally massive enclosures, and so as with the work of Moseley and Croome, internal conditions were assumed to be entirely uniform.

Hart et al. carried out three sets of simulations using DOE-2.1. These simulations were intended to predict the energy consumption of a standard design shopping arcade under the climatic conditions found within 19 contrasting cities around the USA. The design was simulated first with a single membrane roof, then with a double membrane and finally with a conventional roof. The information upon which these simulations were based was supplemented by data monitored at the Bullocks Department Store in San Jose, California, a fabric roofed building similar to that being modelled[21].

The membrane was treated as a large translucent window, and thermal calculations relating to it were based on the use of shading coefficients and U-values which had been determined by the finite difference approach previously described. The DOE model was only set up to deal with discrete rhomboid surfaces, and so the fabric roof was represented as rectangular based truncated pyramid. The thermal properties of the conventional roof were detailed so as to meet ASHRAE energy consumption standards.

The extrapolated trend of the results obtained by this method are illustrated below:-

Figure 3:3.1 Diagram to Show the Relationship Between Climatic Conditions and the Annual Energy Consumption Predicted by Hart et al. (artificial lighting 29.1W/m^2).



They concluded that in all areas, a space enclosed by a double layer fabric roof would be more energy efficient than one enclosed by a single layer roof. Comparison with conventional structures was complicated by the need to specify the level of artificial lighting required within the spaces, however, generally it was considered that single layered fabric roofed buildings would be more efficient than conventional roofs in areas of less than 1677 Heating Degree Days (HDD's).

It is a little difficult to assess the accuracy of these simulations as no validation was presented, and the model codes were not listed. Hart et al. themselves however suggested that '*...more field data and experimental data be obtained...to substantiate the fabric structures version of DOE-2*'[22].

Sinofsky carried out a similar investigation into the thermal performance of retail spaces, again using a modified version of DOE-2. He also proposed that energy competitiveness was based on the trade off between heating / cooling and lighting, and that the position of the balance depended on the local climate. Sinofsky suggested that in climates with less than 2500 HDD's, membrane enclosed retail spaces would use no more energy than similar conventional structures and that energy equivalence codes could be met in all of the climates investigated if a small amount of translucent insulation was included.

In order to simplify analysis however, all of these researchers had accepted the basic assumption that the thermal conditions found within spaces enclosed by fabric membranes could be considered to be uniform. This proved to be a little over simplistic.

3:3.2 The Observed Thermal Behaviour of Spaces Enclosed by Fabric Membranes.

During the mid nineteen seventies, Piksaikina carried out a number of field surveys in order to investigate the actual thermal behaviour found within membrane enclosures[23]. It was observed that such spaces were very sensitive to changes in climatic conditions and that they experienced extreme temperature swings, particularly as a result of changes in solar intensity. More importantly however, it was found that during hot weather, internal air temperatures close to the membrane could be up to 7^{o}c hotter than those nearer the floor.

In an attempt to investigate the potential of this thermal stratification as a means for providing environmental control, Wu et al. carried out field monitoring in the Bullock Department Store, San Jose in California, and in the air supported Unidome at the University of Northern Iowa, both of which had double membrane envelopes[24]. Stratification of up to 14^{o}c was recorded inside the air supported Unidome, and Wu et al. proposed that left undisturbed, such thermal gradients could be exploited in order to prevent extreme temperatures from penetrating into the low level zone occupied by people. Little stratification was found within the Bullock Department Store, but it was considered that this resulted from the inflation fans disturbing the '*natural*' distribution of internal air.

Wu et al. recognised that predicting the extent of internal stratification would require an understanding of the variable thermal behaviour of the entire enclosed space, not just the boundary heat transfers. They suggested that such behaviour could not be properly represented by conventional analysis techniques which assumed that internal conditions were uniform.

Hart et al. agreed that thermal stratification could have a significant affect on the thermal performance of spaces enclosed by fabric membranes[25]. They suggested that undisturbed stratification could reduce cooling loads, and that the stratified area high above the occupied zone could be used as a heat sink into which excess heat from internal sources could be vented.

Sinofsky proposed that the unusually extreme thermal stratification found within membrane enclosed spaces resulted primarily from the low thermal resistance of fabric membranes, but that this was compounded by the fact that such spaces were often very tall. He agreed with previous researchers that this phenomena could be exploited to reduce summer cooling loads, and also suggested that destratification fans could be used to increase thermal efficiency in cold climates by recirculating hot air into the occupied zone.

Sinofsky admitted however that '*To the author's knowledge, stratification in large spaces of complex geometry has yet to be predicted quantitatively.*'[26] and warned that designers should be aware of the modelling errors that this omission would produce.

3:3.3 Recent Attempts to Model the Thermal Behaviour of Spaces Enclosed by Fabric Membranes.

Following their programme of field monitoring, Wu et al. made an attempt to simulate the behaviour they had observed in the air supported Unidome by using an adapted version of the BSCI model developed by the University of Michigan[27]. This involved adding algorithms to the basic BSCI model to account for the affects of thermal stratification. These algorithms were based on empirical analysis of the observed behaviour.

As none of the equations or properties information used by the model were published by Wu et al; is difficult to judge the legitimacy of this approach. The fact that the algorithms added to the BSCI model were empirical in nature and were based on very little data however must raise serious doubts about the general applicability of the technique.

In 1980 a paper was published describing research by Bazjanac et al. which was carried out in order to investigate the energy consumption of the Stephen C. O'Connell Centre at the University of Florida[28]. This research again used the DOE model, however whilst the researchers recognised that DOE could not accurately model thermal stratification itself, an attempt was made to mimic the effect by specifying the enclosed space in terms of three freely interactive horizontal layers with a notional thermal resistance between them. This was intended to allow thermal gradients to accumulate vertically within the simulated space.

Again, this paper listed none of the equations developed, and no validation of the approach was presented, however this was the first and only significant attempt to model the thermal behaviour of spaces enclosed by fabric membranes in a way which realistically represented their actual behaviour. If this method had been extended, and the relationship between interacting zones clarified, it was possible that it could have provided a practical approach for simulating the non uniform thermal conditions.

Moseley and Croome suggested that in order to properly model the thermal gradients found within spaces enclosed by fabric membranes it would be necessary to divide up the enclosure into a nodal network containing a large number of interacting zones and to solve for behaviour at each node using finite difference techniques based on the theory of fluid flow[29]. It appears however that such an approach was not attempted.

3:3.4 Evaluation of the Existing Body of Knowledge.

The relative immaturity of this subject is clearly illustrated by the time scale of the papers reviewed in this chapter. The first paper describing a serious attempt to quantify the thermal behaviour of spaces enclosed by fabric membranes was published in 1977, and the most recent paper, describing Sinofsky's research was published just eight years later in 1985. Whilst a number of attempts have been made to predict the likely behaviour of such spaces since then, these have tended to relate to individual design projects and have been considerably less detailed than the research reviewed here.

There was a general tendency for the researchers discussed to continue to use the basic assumptions of conventional heat transfer theory despite the fact that monitored data suggested that these were inappropriate for representing the thermal behaviour of spaces enclosed by fabric membranes. U-values and shading coefficients were used to describe the dynamic thermal behaviour of fabric membranes, and the resulting behaviour of the enclosed space was generally treated as being entirely uniform.

As membrane temperature of over 40°c had been recorded[30], and internal thermal stratification of 14°c had been observed[31], the close correlation between predicted behaviour and monitored data claimed by several researchers who had ignored these phenomena is difficult to explain.

The lack of existing research which was carried out in a way appropriate for investigating the thermal behaviour of spaces enclosed by fabric membranes, suggested that there was a considerable amount of fundamental research still to be done in this area. A sound theoretical base was required from which thermal investigations could be carried out with a known degree of confidence in order that spaces enclosed by fabric membranes might be designed to be more environmentally competitive in an increasingly demanding market.

At a basic level, there was a need to establish which of the properties of fabric membranes significantly affect their thermal behaviour and how that behaviour might best be represented. At the more complex end of the problem, an attempt to identify how the thermal stratification found within spaces enclosed by such membranes might best be simulated was necessary. It also seemed desirable to obtain a comprehensive set of data describing the characteristic thermal behaviour of such spaces against which the accuracy of thermal modelling techniques might be properly assessed.

These were quite fundamental and wide ranging objectives, however the development of an analytical methodology which was actually appropriate to the thermal behaviour of spaces enclosed by fabric membranes seemed to be long overdue.

3:4. CONCLUSION.

This chapter provided an overview of the existing body of knowledge relating to the thermal behaviour of spaces enclosed by fabric membranes. Whilst a significant amount of research has already been done in this area, much of it appears to be greatly oversimplified. There seems to have been a general tendency to adopt conventional analytical techniques which originally developed for the analysis of more thermally massive buildings, but little regard was given for whether these were appropriate for describing the behaviour of spaces enclosed by thin fabric membranes.

Previous researchers described how thin fabric membranes could become very hot when exposed to bright sunshine, and how strong thermal stratification could build up within spaces enclosed by such membranes. It became apparent that this behaviour could only be properly investigated using dynamic and holistic modelling techniques based on appropriate properties information and detailed spatial representation, however it appears that no such investigations were attempted.

In the next chapter a simple pilot study is described which was carried out in order to return to the fundamentals of this subject and gain a basic insight into the characteristic thermal behaviour of spaces enclosed by fabric membranes. A detailed methodology which was adopted for the rest of the research presented in this thesis is then described.

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