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Thermal Comfort of Spectators in Stadia Built in Hot Climates

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Abstract:

There is very little research that could be found on how best to determine the appropriate comfort design conditions for semi-outdoor stadia in hot climates. This paper provides a definition of acceptable target comfort criteria and discusses the implementation of a comfort cooling strategy on a sample section of a stadium to be built in a hot climate.

Different comfort assessment methodologies were used at different stages of the design. These ranged from a simplified zone-based analytical approach during the concept design to develop the building envelope, to an in-depth application and development of the cooling strategy, followed by detailed assessments of the spectators' near-field conditions during the detailed design.

A strategic approach was adopted to deliver the project in a holistic way, that involved architects, structural and building engineers, as well as other specialists. A key part of this strategy was to combine both analytical and engineering design skills to deliver a seamless process for designing a world-class stadium from inception to delivery of construction information.

The semi-outdoor nature of the stadium and the likely comfort expectations of spectators during sports events have been considered. Comfort criteria were studied and this led to adopting comfort standards that are less onerous than those used in office buildings, which have historically benefited from published research. This approach, combined with conceiving and providing an efficient air delivery system for the spectators, contributed to significant energy savings and reduced construction costs.

Dynamic thermal modeling and computational fluid dynamics tools were used in combination to determine the required thermal performance of the roof used in the case study. Also to arrive at the optimum cooling system design criteria, in terms of the air flow rates and temperatures that are necessary to achieve the target comfort conditions. Results obtained from the detailed thermal and air flow analysis indicated that the comfort targets were been achieved for the sample case study, which covered a representative section of the stadium. Benefits were gained from collaborative research and laboratory tests undertaken with a leading UK University. This approach corroborated key analytical data used in the design of the mechanical air supply system.

Keywords: Thermal comfort, dynamic thermal modeling, stadia, mechanical and environmental design, hot climates, computational fluid dynamics, energy, sustainability.

1. Introduction

Thermal comfort is influenced by a combination of physical factors, such as air temperature, mean radiant temperature, air speed, humidity, metabolic rate and clothing levels. The latter two factors are independent of the environmental conditions, but are influenced by the human physiology and the personal choice of clothing. Conversely, the building characteristics and the performance of the mechanical cooling system are driven by the first four factors.

Published surveys of building occupants indicate that the above physical factors are not the only factors that determine thermal comfort. A more suitable approach involves using the adaptive comfort theory in buildings, as it deals with thermal comfort, local weather patterns, local culture and the expectations of the occupants. Even if the physical factors which influence thermal comfort may be similar in different types of buildings, such as theatres, offices or stadia, the perception of comfort may be quite different.

A stadium is a unique type of building that is designed to host sports and cultural events, which bring large number of spectators in one space for long periods of time.

This paper provides a definition of acceptable target comfort criteria and discusses the implementation of a comfort cooling strategy on a sample section of a stadium in a hot climate. Appropriate comfort conditions within the stadium bowl are defined, in relation to the semi-outdoor and psychological state of mind of spectators during sporting events. These factors are very likely to make a difference in the comfort expectations and perceptions of spectators.

Analysis has indicated that, in a hot climate, a very good thermal performance for the stadium roof is essential. This to minimize both the direct solar radiation falling on the spectators' area and the thermal heat gain arising from the hot inner surface of the roof and its effect on the mean radiant temperature.

It was essential to provide comfort cooling in order to respond to the client's requirement to extend the use of the stadium during the relatively long period of hot climatic conditions. The mechanical air cooling system described in this article creates a comfortable microclimate around the spectators' by delivering cool air through the outlets beneath the seats. This approach has the key benefit of cooling only the spectators' zone rather than the whole stadium volume. An additional benefit of the under-seat air cooling system is to offer spectators a degree of control or adaptability over their comfort by moving their legs in relation to the air stream.

The analysis discussed in this article is based on a series of parametric studies. A number of numerical tools, such as dynamic thermal models (DTM) and computational fluid dynamics (CFD) were used in combination, in order to determine the required thermal performance for the roof and also to inform the supply air conditions (air flow rates and temperatures) that are necessary to achieve the target comfort conditions.

The results obtained from the detailed thermal and air flow analysis indicated that comfort targets have been achieved for the sample case study of the stadium. The levels of localised air draughts around the air outlets are not considered to have an adverse effect on comfort.

The above analytical and engineering design approach resulted in significant energy savings and reduced operating construction costs,

2. Background: Thermal Comfort

Thermal comfort is a measure of occupants' satisfaction within a specific thermal environment. This notion is used to predict how comfortable an indoor / semi-outdoor environment is perceived by its occupants and becomes an acceptable and important driver in building design. The level of thermal comfort deteriorates from the optimum, i.e. the proportion of occupants dissatisfied by a thermal environment will increase, depending on how much the conditions vary from the perceived most acceptable conditions.

The definition of thermal comfort and the boundaries of comfort zone have been introduced in the early part of the 20th century. However, thermal comfort is not a new concept that was forced upon people as a result of recent developments in architecture and building engineering design. Thousands of years ago, ancient cultures considered the use of factors such as thermal mass, ventilation and solar orientation, as a fundamental part of constructing residential buildings. There are pre-modern historic references that go back to the Greek philosopher Socrates (469 BC – 399 BC) - *"Now, supposing a house to have a southern aspect, sunshine during winter will steal in under the verandah, but in summer, when the sun traverses a path right over our heads, the roof will afford an agreeable shade, will it not?".*

In parallel with the developments in heating (late 18th century) and cooling (early 20th century) technologies, engineers started to focus their research on the control of the thermal environment. World Wars accelerated the pace of research studies and more disciplines, such as physiology, climatology and geography, started to get interested and involved in the concept of thermal sensation.

Heat dissipation from the human body is mostly affected by six variables: air temperature, radiation, air movement, humidity, clothing insulation and metabolic rate (activity). Clothing and metabolic rate are considered as personal factors, whilst the other four indicators are referred as environmental or climatic factors.

Air temperature (dry bulb) is the most significant factor that determines the convective heat exchange between the body and the air surrounding it. Air movement is another major variable which influences the convective heat transfer, by reducing the surface resistance of the body and increasing the evaporation rate from the body. Relative humidity (RH) is the ratio between the amount of water in the air and the maximum amount of water vapour that the air can hold, and this determines the evaporation rate. However, studies have showed that relative humidity has comparatively little impact on thermal sensation unless it is too high or too low, i.e. out of the normal range of 40-70%.

Radiation heat exchange between the human body and the environment depends on the mean radiant temperature, which is a function of the view factors of each surrounding surface as seen by a person, amongst other things.

Clothing provides a barrier to heat transfer between the body and the surrounding environment. If clothing is not suitable for the surrounding thermal environment, the body may experience thermal stress, even if the environment is not "too hot" or "too cold".

The inherent biological processes within the body lead to heat production. The rate of heat produced by the human body, called the metabolic rate, depends mainly on the physical activities carried out. Some other physiological variables contributing to the determination of thermal comfort differ, these depend on age, gender, body proportion (mass to surface), state of health and consumed food and drinks.

There are also psychological variables which affect thermal comfort. Research has showed that human perception of thermal environment or judgement of thermal conditions, relate to the thermal comfort expectation and past experience of thermal comfort.

There are three main approaches to define thermal comfort: heat balance approach, physiological approach and psychological approach. The heat balance approach assumes that the environment is thermally comfortable *"when heat flows to and from the human body are balanced and skin temperature and sweat rate are within a comfort range"*. The physiological approach defines the thermal comfort as *"minimum rate of nervous signals from the thermal receptors in the skin and in the hypothalamus"*. British standard BS EN ISO 7730 and ASHRAE refers to the psychological definition of thermal comfort as *"the condition of mind which expresses the satisfaction with thermal environment"* (Höppe – 2001, Auliciemsand Szokolay – 1997).

Many different models have been developed by researchers to assess thermal comfort. The fundamental work based on heat balance approach was undertaken by P. O. Fanger. His model uses the physics of steady state heat transfer between the body and its environment, based on the above six variables and combined with an empirical thermal sensation to define the terms *predicted mean vote* (PMV) and *predicted percentage dissatisfied* (PPD). Auliciems and Szokolay's "Thermal Comfort" article gives an excellent review of various empirical and analytical indices of thermal comfort, including Fanger's PMV, (Auliciems and Szokolay, 1997).

Fanger's study became a milestone in thermal comfort studies, however it is not considered applicable to every environment that a person can experience. Many researchers have discussed its limitations and the validity of PMV in various conditions.

Field surveys, especially in hot climates, showed significant differences with the PMV results (Humphreys and Nicol, 2002). In surveys taking place in hot climates, people were not experiencing discomfort at temperatures which are classified as "severe" according to the heat balance model. These studies led to the conclusion that a purely physical determination of thermal comfort falls short in explaining the thermal comfort responses in field surveys that took place in hot climates. People in hot climates were found to be more tolerant than the PMV model predicts, possibly due to adaptation.

The above issues have initiated discussions about people's natural tendency to adapt to thermal stimuli. Periodic exposure to extreme climates may result in a complex set of physiological and psychological changes. Metabolic rates could be altered by the scheduling of daily activities. For instance, during the siesta period the metabolic rates are reduced during the hottest hours of the day. Energy intake in the form of food and drinks can be reduced or increased by dietary changes, etc.

Researchers have attempted to find a correlation between the temperature range that is considered comfortable (comfort zone) and the general trend in the local climate. Based on available filed survey data in 1976, Humphrey found a correlation between the monthly outdoor mean temperatures (T_m) and the temperature at which the reported discomfort was minimal, "*neutral* or *comfort temperature*" (T_n):

$$T_n = 11.9 + 0.534\ T_m \qquad (1)$$

Equations (2) to (6) show, in chronological order, various formulae of the neutral temperature from similar studies (Auliciems - 1981, Griffiths - 1990, Nicol and Roaf – 1996, de Dear et al – 1997, Humphrey and Nicol - 2000).

$$T_n = 17.6 + 0.31\ T_m \qquad (2)$$

$$T_n = 12.1 + 0.534\ T_m \qquad (3)$$

$$T_n = 17.0 + 0.38\ T_m \qquad (4)$$

$$T_n = 17.8 + 0.31\ T_m \qquad (5)$$

$$T_n = 13.5 + 0.54\ T_m \qquad (6)$$

Humphreys and Nicol suggested that "*in a situation where there was no possibility of changing clothing or activity and where air movement cannot be used, the comfort zone may be as narrow as ±2ºC*". Auliciems suggests that the temperature range of ±2.5ºC around the neutral temperature can be taken as comfort zone for 90% acceptability, (Auliciems and Szokolay, 1997). Table-1 summarizes the recommended ranges of comfort zones for "free-running" and mechanically cooled or heated buildings, according to Auliciems and Szokolay:

Table 1: Recommended comfort zones for "free-running" buildings and mechanically cooled buildings [Auliciems and Szokolay]

Building type	Formulation of T_n	90% acceptable comfort zone	80% acceptable comfort zone
Free running	$T_n = 17.8 + 0.31\ T_m$	±2.5ºC	±3.5ºC
Buildings with HVAC	$T_n = 21.5 + 0.11\ T_m$	±1.2ºC	±2.0ºC

Surveys of outdoor spaces also confirm that a purely physiological approach is not sufficient to characterize levels of thermal comfort. A research study (Nikolopoulo, 1999) provides some quantitative data, which can be expected to apply to "covered open spaces" (Figure-1). It is clear that whilst Fanger's prediction shows only a 10 to 40% level of satisfaction (the red bars), a much higher level of satisfaction will be experienced by people if they were sat in covered open spaces. There is however a small difference between tested subjects, who chose to be there, and those who had to be there.
More recent studies expand the research from steady state approach to transient variation of perceived thermal comfort. Höppe (2001) shows how people respond to environments where the air temperature is of the order of 30°C, and the mean radiant temperature is 60°C. He suggests that this would only be sensed as severe discomfort after a period exceeding 30 minutes of exposure.

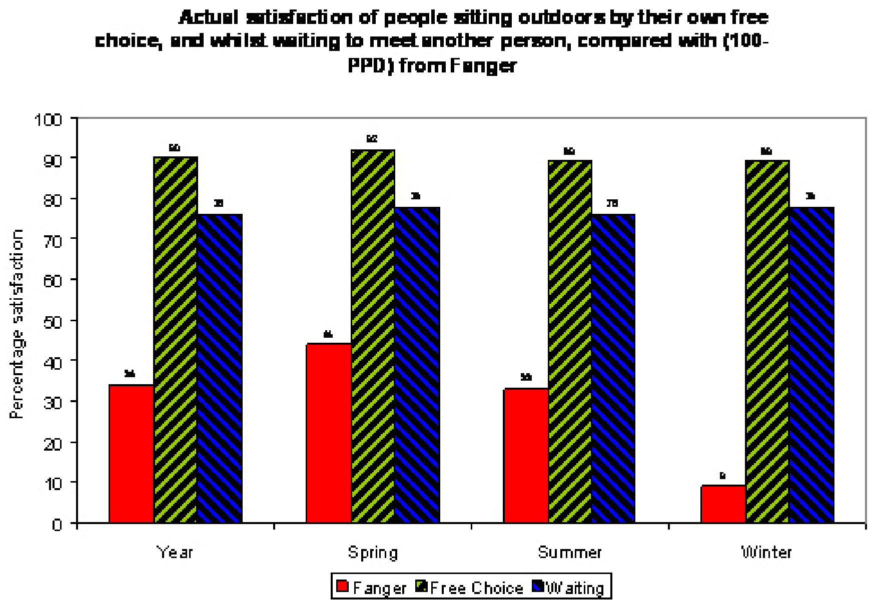

Figure 1: Actual satisfaction compared to Fanger's comfort index PPD

Unfortunately research in this area is in its infancy and so there are no established assessment procedures. However, it can be stated with some confidence that if a space feels like being external, people will accept a much greater range of conditions than they would tolerate in an enclosed office.

3. Methodology

3.1 Analytical approach

The methodology selected to assess the variables affecting thermal comfort involved the modeling of the stadium environment, using the relevant climatic conditions and occupancy levels. The simulation was undertaken by combining a dynamic thermal model (DTM) with a computational fluid dynamics (CFD) model - Arup's in-house DTM software, ROOM, in combination with ANSYS CFX.

The results available from these simulations were developed and led to an appropriate methodology for the calculation and interpretation processes that were necessary to assess spectator comfort conditions in a semi-outdoor environment in a hot climate.

DTM and CFD are complimentary analytical tools for assessing building energy use and indoor environmental conditions. Coarse coupling of DTM and CFD is a commonly used approach for assessing the thermal performance of buildings. DTM tools have been traditionally used to resolve the radiant field (short-wave and long-wave) and thermal capacitance of materials in hourly intervals over a month or year, but with limited detail on air movement and temperatures in a single or small number of zones. CFD has been traditionally used to calculate detailed air movement and temperatures, including heat transfer at the surfaces at a chosen design time. The coarse coupling is derived from fixing the DTM-predicted surface temperatures in the CFD model for the chosen design. The CFD model is then run as a "convection only" model with the radiant field already resolved.

It is possible to extend a CFD model to resolve the heat transfer in materials (conjugate heat transfer method), however, this approach is computationally very intensive and expensive to operate and therefore impractical for the majority of applications.

The comfort interpretation methodology was extended using a formulation of CFD and DTM results. Key components for spectator comfort were the DTM-predicted surface temperatures (the roof had a large influence on spectator MRT in the "far-field") and the CFD-predicted air movement and (dry-bulb) temperatures around the body ("near-field").

3.2 Laboratory tests approach

The development of the "near-field" methodology used in the simulations was helped by gaining a better understanding of the variation of conditions over the body, through specified experiments, that were privately funded and carried out in collaboration with Loughborough University. A mannequin based study was completed in a similar environment similar to the stadium and with a similar mechanical air cooling system.

Heat fluxes for different parts of the body were generated (Figure 2) in order to maintain a constant skin temperature and this provided a gauge for the single point data that was generated within the simulations. Further confidence and corroboration was provided through a separate CFD model of the test chamber, using measured boundary conditions as fixed inputs to the CFD model. This validation exercise provided further insight into an appropriate interpretation of simulation results. It is worth noting that a numerical mannequin comfort assessment approach, commonly used in automobile comfort studies, is not practical for crowd studies such as in stadia.

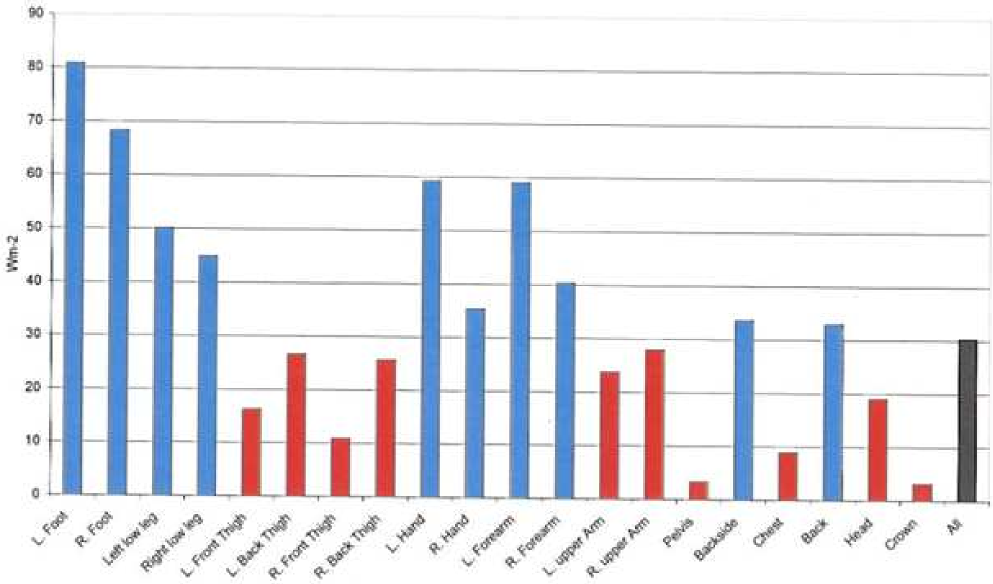

Figure 2: Sample relative heat fluxes generated by mannequin experiments

4. Case Study – Representative section of stadium in a hot climate environment

4.1. Local climatic conditions and comfort zone range

Representative Middle Eastern climate data was used for the case study.

Table-2 illustrates the monthly mean outdoor temperatures and the corresponding temperature ranges for 90% acceptable comfort zones for buildings with HVAC systems and "free- running" buildings, based on Auliciems' recommendations (see Table-1 for the correlations).

It was shown that for the hottest month of the year, that the acceptable comfort zone range is 26.7-30.7ºC for free running buildings, and 24.2-26.6ºC for buildings served by HVAC systems.

The combined effect of spectators sitting in the semi-outdoor environment of a stadium and watching a sport event generates an acceptance of a much wider range of conditions than tolerated in an office environment. Given this situation, a target of 27ºC operative temperature was set against peak climatic conditions utilising a high performing roof (effective control of "far-field" conditions) and under-seat air cooling system (close control of "near-field" conditions).

Table 2: Representative Middle East climate data –Monthly mean dry-bulb temperatures and corresponding comfort temperatures for buildings with HVAC systems and "free-running" buildings

Month	Monthly Mean Temperature (ºC)	Temperature range for 90% acceptable comfort zone (Auliciems)	
		Free running buildings	Buildings with HVAC
January	18.2	21.4 - 25.4	22.3 - 24.7
February	20.3	22.1 - 26.1	22.5 - 24.9
March	22.5	22.8 - 26.8	22.8 - 25.2
April	27.0	24.2 - 28.2	23.3 - 25.7
May	31.1	25.4 - 29.4	23.7 - 26.1
June	33.0	26.0 - 30.0	23.9 - 26.3
July	34.9	26.6 - 30.6	24.1 - 26.5
August	35.3	26.7 - 30.7	24.2 - 26.6
September	33.3	26.1 - 30.1	24.0 - 26.4
October	28.9	24.7 - 28.7	23.5 - 25.9
November	24.5	23.4 - 27.4	23.0 - 25.4
December	20.4	22.1 - 26.1	22.5 - 24.9

4.2. Strategic approach to design

The overall design objective was to allow sport events to be held, over the longest possible time of the year, by offering spectators and players a thermally comfortable environment. An efficient air cooling system was designed to ensure the comfort of spectators during summer events and made effective by combining with a high performing roof.

At the concept design stage, the DTM was used to primarily drive large scale design variations in the performance of the building envelope and the materials selection, through a series of parametric studies. The comfort target was deemed applicable to the whole spectators' zone, to help guide the design at an early stage. CFD was used to explore different approaches to the delivery of air through outlets beneath the seats, (e.g. multi "holes" versus single "hole" outlets).

During the scheme design, the overall thermal performance of the stadium bowl and envelope was refined using DTM and CFD in combination. This was performed using the same comfort target but now deemed applicable to the "back of neck" region, in order to help drive the envelope design. In addition, this application of the comfort target was used to drive the air cooling strategy, with the CFD providing a better understanding of the likely air movements and air dry-bulb temperature distribution around the spectators, as well as testing for the most appropriate air flow rates and supply air temperatures.

At the detailed design stage, the thermal performance of the stadium bowl, envelope and mechanical cooling system was further optimized using the same comfort target applied to region directly around the body for a "typical" spectator. CFD was able to provide "averaged" conditions for air speed, dry bulb temperature and mean radiant temperature (the required inputs for the operative temperature assessment), as well as an indication of the spatial variations over a spectator's body.

4.3 Energy, sustainability and interpretation of results

The combined effect of applying less onerous, but appropriate comfort criteria and the use of an inherently efficient mechanical air cooling system, has produced valuable benefits. These include reduced capital costs, energy savings, and enhanced sustainability credentials. The impact of such benefits is significant due to the size of the stadium.

In terms of energy use and sustainability, a like for like comparison indicated that an overhead system has an estimated energy consumption of up to two and a half times that of an under-seat system.

An under-seat mechanical air cooling system was selected to create a comfortable microclimate only in the zone occupied by spectators. This is achieved by supplying moderately cool air around the seating zone, instead of cooling the whole stadium volume, Figure 3.

The proposed under-seat air supply system delivers cool air to each seat, via holes formed in the vertical section of the terrace concrete structure. Each spectator benefits from a dedicated air outlet beneath the seat, which delivers air at an appropriate air speed and temperature. Air is primarily delivered in a horizontal direction around the legs area, but further cooling to the spectators' neck area is available from a similar air outlet that serves the seat behind, Figure 4.

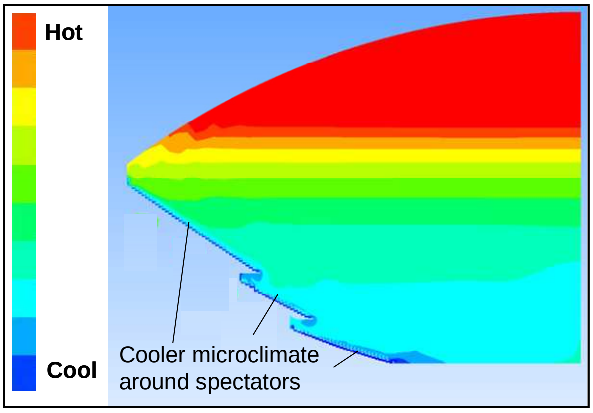

Figure 3: Under-seat air cooling system creating a local microclimate around spectator zone

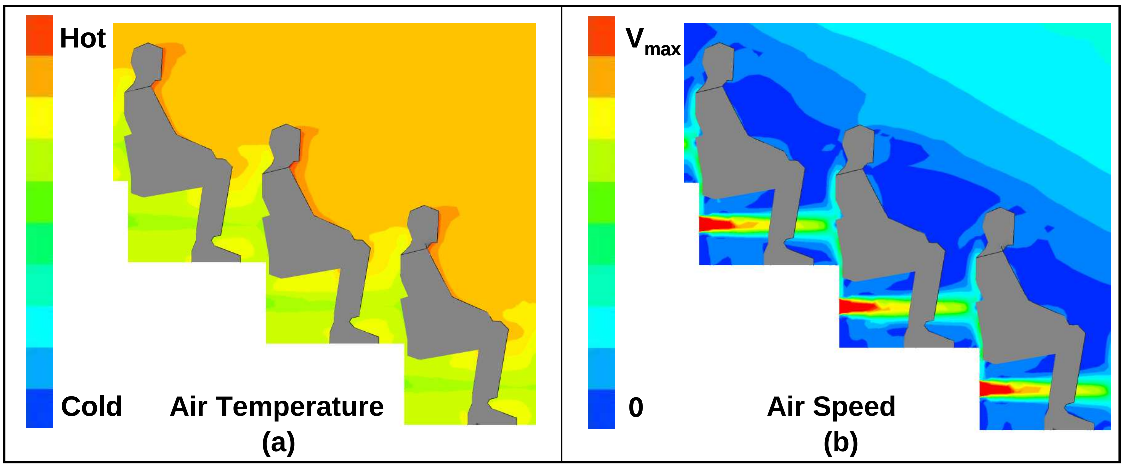

Figure 4: CFD predictions of (a) air (dry bulb) temperature and (b) air speed

The above plots show air temperature and air speed data presented on a section through a detailed geometric representation of the spectators' area. However, this approach is computationally limiting, if a large spectator zone requires examination to accurately predict conditions experienced by spectators during an event. A lower resolution "person" model was therefore used in a model of a "half slice" of the stadium, which is 12-seat wide (Figure 5). Operative temperatures were plotted on the body surface of a representative spectator within the seating tier (circled in yellow, Figure 5). This data, together with other environmental variables plotted in a similar way, gave the ability to generate surface-averaged data to input into a comfort index.

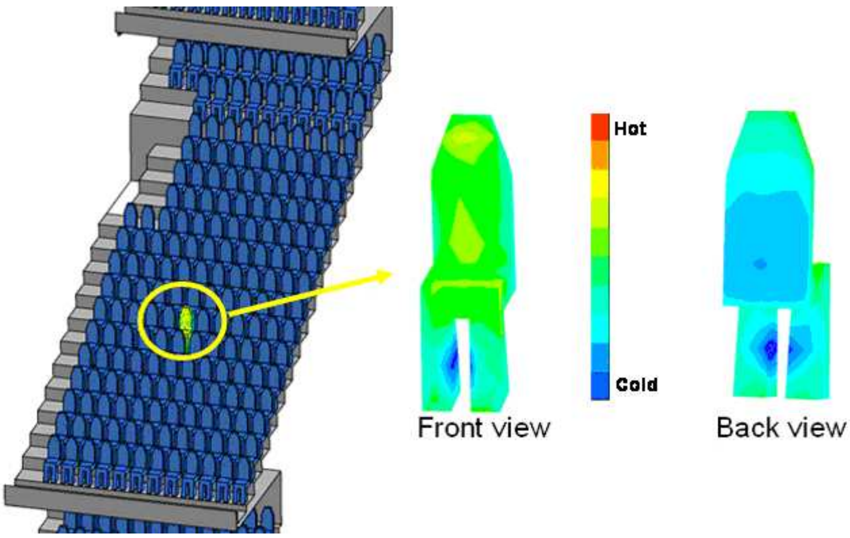

Figure 5: CFD predictions of operative temperature "next to the body"

4.4 Comparison with alternative concepts of air delivery
As part of a design development exercise the under-seat system was compared against an overhead system, designed to give the same mean air temperature within the occupied zone (Figure 6).

An inherent advantage of a well designed under-seat air supply system is the uniformity of environmental conditions generated within the occupied zone, coupled with an efficient delivery of the cooled air. Many stadia with mechanical cooling systems feature an overhead air supply system, which results in a much greater mixing with the bowl air volume, and significant variations of conditions experienced by spectators within the occupied zone. This greater variation in conditions within the seating zone (Figure 6) provides an additional challenge to the assessment and interpretation methodology in case of an overhead air supply system.

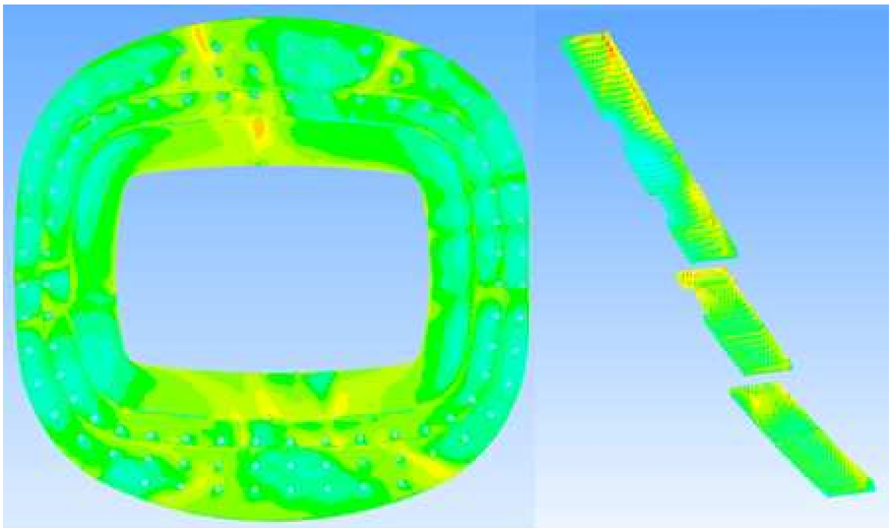

Figure 6: CFD predictions of air temperature variations in an overhead air supply system

Results obtained from the combined DTM and CFD analyses of the case study stadium indicate that an operative temperature of about 27°C is an appropriate target. This is based on conditions during the hottest time of the year with an outdoor temperature of 43ºC, an air dry-bulb temperature in the order of 22°C and a mean radiant temperature in the order of 32°C. These conditions were met by the under-seat air supply system.

4.5. Spectators adaptation within the stadium micro-climate

It is interesting to note that one of the first adaptive and natural reactions of people when exposed to hot thermal environments is to use their hands as a fan, to create an air movement around themselves. This action increases the convective heat loss between the body and the air, as well as increasing the evaporation of sweat from the skin hence cooling the body.

The proposed under-seat air cooling system creates a livelier environment around the spectators in terms of air movement, under hot climatic conditions. Such a lively environment leads to increased comfort levels, as the air temperature adjacent to the body is less than the body/skin surface temperature, and hence it is able to remove the heat away from the body more effectively.

The adopted environmental design approach makes allowances for the fact that comfort levels perceived by a particular person are not a constant "value", because of varying personal tolerances, clothing levels and metabolic rates. However, spectators have some degree of control over their comfort by moving their legs in relation to the air stream. It therefore recognized that spectators will adapt by, for example, changing the position of their legs towards or away from the moving air stream between their legs. This simple method of self regulation is totally driven by personal preferences.

A centralized form of control through a BEMS system and operator control is also utilised to vary the supply air quantities and temperatures, to respond to varying external and internal conditions.

4.6. Roof thermal performance

A fundamental requirement for providing a thermally comfortable environment is to shade the spectator area from direct solar radiation. Fully sheltered seating zones are therefore provided by closing the roof during daytime events in the summer. Although, the roof contains some translucent elements to allow daylight, the materials used in the remainder of its construction do not result in significant direct solar radiation. All incident solar radiation is largely diffused by the high performance translucent elements. The short wave solar transmission is fully diffused and spread throughout the tiers and pitch zones.

The roof is designed to act as a primary thermal barrier by preventing excessive heat build-up prior to events during peak summer days. Another enhancement in its thermal performance is achieved by providing a roof that is quite reflective and heavily insulated to minimize the surface temperatures of the inner parts of the roof. This approach prevents the indirect heating-up of all the other internal surfaces via surface-to-surface or long-wave heat exchange.

4.7. Crowd heat gains and "near-field" mean radiant temperature

Traditionally, the convective component of a person's heat gain may be considered within a CFD model, as its influence helps to drive the air movement in the form of thermal plumes. This component can therefore be introduced into the CFD model as a heat flux, over an individual's body surface or within an occupied zone. The radiant heat component from a crowd provides an additional complexity, in terms of the overall balance of resulting surface temperatures and also the mean radiant temperature experienced by a typical spectator.

It may be assumed that there is negligible long-wave heat exchange between spectators sitting next to each other (near-field) and those sitting in tiers on other side of the stadium (far-field), as they have similar skin temperatures. In a DTM analysis, the crowd surface temperature may therefore be assumed to be uniform, thus providing an appropriate balance for the other surfaces.

The higher resolution data gained from the CFD analysis allows the proper assessment of both the near- and far-field long-wave exchange within the spectator zones, together with accounting for other influences such as a cooler floor surface, the pitch zone and the hot roof areas. The influence of a typical stadium seat can be combined into the derivation of a single mean radiant temperature (MRT) value assigned to the spectator, although its true impact on comfort is more difficult to gauge. Consideration of the "equivalence" of this MRT as a defined measure requires further examination, but is considered the key driver to generate appropriate values for use within the design process.

4.8. Influence of air speed on comfort

A parametric study was carried out to examine the influence of air speed on comfort. This study took into consideration the roof thermal properties, the air inlet temperatures and the air flow rates delivered to the under-seat air outlets. Such influences were analysed to determine the optimum combination of these parameters, in order to achieve the target operative temperature of 27°C. As part of this process, the potential risk of air draughts or increased air speeds in the spectators' zone was examined.

CIBSE Guide A, Figure 1.1 (reproduced below, shown as Figure 7) illustrates the graph for relative air speeds, which indicates that the "still air" operative temperature should be adjusted to account for the effect of air draughts, in order to determine an "effective operative temperature". For example, a relative air speed on this graph of 1.0m/s would result in a "correction" in operative temperature of about 2.5°C. The net effect of this correction in a warm environment would be to improve conditions by moving the experienced conditions in the stadium down towards a more comfortable band.

However, there is uncertainty as to how this correction should be applied to single point comfort evaluation methods, as mean values for air speed are considerably lower than peak values. The higher air speeds are applied to a very limited area of the body (back of exposed leg when positioned in the air stream). For example, a semi-outdoor sporting environment will inherently result in less complaints of discomfort, when compared to equivalent office conditions, for which the majority of design guidance was generated and applied. Spectator adaptation is also expected, with many people wishing to take advantage of the moving air stream to improve comfort levels further, if and when this is required.

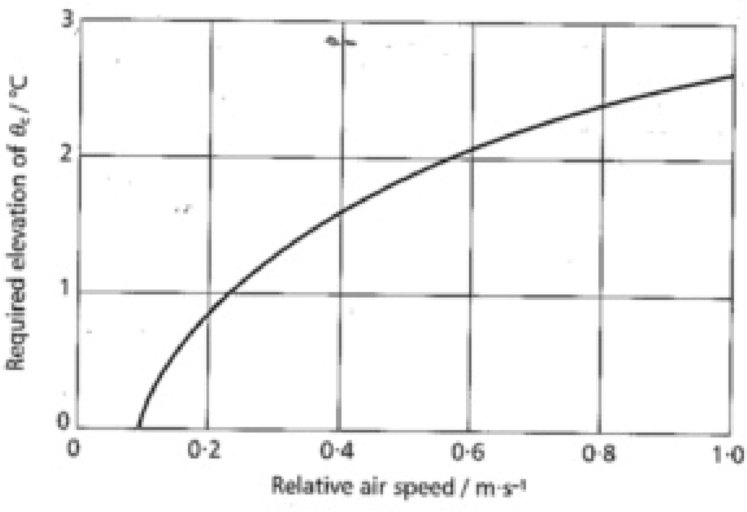

Figure 1.1 Correction to operative temperature (θ_c) to take account of air movement

Figure 7: CIBSE Guide A, Figure 1.1

5. Conclusion

The spectators' comfort in a semi-outdoor hot climate is positively influenced by three main factors: shading from direct solar radiation and reduced air temperature provided by mechanical air cooling coupled with good air movement.

The spectators' perception of comfort depends on many factors. These include their level of activity (sitting during a game) and the type clothes they wear. Also on the temperature of the external environment they come from, the climate they are accustomed to, and the type of venue they attend (sports stadium in this case).

The environmental strategy for providing comfort to spectators relies upon:

- ensuring that the spectators seats are protected from the direct sun,
- minimising the inside surface temperature of the surrounding roof envelope, by using materials with superior thermal performance, resulting in lower mean radiant temperatures,
- providing a mechanical air cooling system to generate the feeling of a light cool breeze in the seating area, and not the whole stadium volume.

Another key consideration is that different people will perceive various levels of comfort within the same environment of the stadium. The air stream generated beneath the spectators' individual seats provides the major source of overall feeling of comfort. This method of air supply allows each spectator to control their own comfort levels, to some degree, by moving their legs away or into the air stream. Inevitably, there will be a variation in the comfort levels perceived by different spectators, however, it can be concluded, with some degree of confidence that if a space feels like “an outdoor environment”, people will accept a much wider range of conditions than they would tolerate in an enclosed space such as an office.

The target for the maximum design comfort (operative) air temperature was set at 27°C, under peak climatic conditions, based on a correlation of monthly mean air temperatures. Our studies have shown that the cooling air system achieves this target in an economical and efficient way.

The above target was also used to inform the selection of materials for the stadium’s envelope and the design of the air distribution and cooling systems.

Different strategies for comfort assessment are appropriate for different stages of the design process, depending on the type of analysis tools used and the resolution of output data. At one level it is important to use an appropriate methodology at an early design stage to allow the design to progress in the correct direction, but at another level, it is important during detailed design to have an in-depth understanding of the analysis output, with the appropriate analytical and engineering skills to interpret the results and apply the desired solutions.

Dynamic thermal modeling and computational fluid dynamics tools were used in combination to determine the required thermal performance of the roof used in the case study. Also to arrive at the optimum cooling system design criteria, in terms of the air flow rates and temperatures that are necessary to achieve the target comfort conditions. Results obtained from the detailed thermal and air flow analysis indicated that the comfort targets were been achieved for the sample case study, which covered a representative section of the stadium. Benefits were gained from collaborative research and laboratory tests undertaken with a leading UK University. This approach corroborated key analytical data used in the design of the mechanical air supply system.

There is a need to further develop the single value approach to comfort assessments, using more complex tools that inherently generate larger data sets. An important element in the design process is to develop a simple gauge, which can be explained to client and architect alike, in order to smoothly progress a design along from concept through to detailed design.

The mechanical air cooling system proved to be capable of not only meeting the target comfort criteria, but also in delivering lower construction costs and energy savings, coupled with enhanced environmental credentials

A fundamental aspect of dealing with the case study project was to combine both analytical and engineering design skills to deliver a seamless process for designing the stadium from inception to delivery of the details needed for construction. This approach, combined with conceiving and providing an efficient air delivery system for the spectators, contributed to significant energy savings and reduced construction costs.

6. Confidentiality

Confidentiality agreements and copyrights prevent the authors from declaring the name and location of the stadium used in the case study outlined in this paper.

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8. Authors of this paper

The authors of this paper at Arup in London have worked together throughout the design and delivery phases of several world-class stadia.

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