Thermal Comfort Modelling of an Open Space (Sport Stadium)

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Abstract

Indoor thermal comfort - the condition of mind which expresses satisfaction with the thermal environment, has gained in importance, due to the rapid urbanisation in the developing countries and the fact that some aspects of the thermal environment such as air temperature, radiant heat, humidity and air movement may contribute to the symptoms of sick building syndrome. Lot of research has been done on the indoor comfort but indoor models can not be employed to assess outdoor comfort conditions because outdoor environmental conditions are altogether different. Outdoor thermal comfort is therefore lacking in the research and models for its prediction.

Some recent work was done for the prediction of outdoor thermal comfort in the RUROS (Rediscovering Urban Realm of open spaces) project. A comfort indicator named as ASV (Actual Sensation Vote) was developed, but it has the limitation of considering meteorological data from a near by climate station, not from a specific site under study. Another outdoor comfort indicator has been developed by Givoni and Noguchi [3], named as Thermal Sensation (TS). This comfort indicator in-conjunction with the ESP-r (Building simulation tool) has been employed to assess outdoor comfort conditions.

The aim of this project is use the ESP-r Building Simulation tool to assess outdoor comfort in an open sport stadium during typical winter and summer weeks.

Information required for the assessment of comfort by Thermal sensation (TS) is obtained from this simulation, which is then imported into an Excel spread sheet and the Thermal Sensation (TS) has been calculated for all the simulation periods.

The outcomes of research work revealed that the sport stadium was uncomfortable for base cases of winter and summer. The introduction of shading has improved the thermal comfort conditions in summer. Winter comfort conditions can be obtained by installing the radiant panels under the seats of the stadium. Moreover, it has been proved that adaptation plays an important role to achieve comfort conditions outdoors.

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1 Introduction

1.1 Introduction

Due to rapid urbanization and global warming, the issues of outdoor air quality and thermal comfort conditions have gained a great attention. The importance of thermal comfort in a daily life can not be denied, whether it is related to indoors such as in an office or outdoors in an open space (sport stadium). It certainly has a profound effect on the mental satisfaction of people. Lot of research has been done to find the indoor thermal comfort. However, the outdoor environmental aspects are lacking in research regarding thermal comfort models. Keeping in view the importance and need for research in outdoor thermal comfort, ASHRAE 55 had introduced a standard that can be used as guidance during the design stage to obtain a comfortable environment, not only in residential or commercial buildings, but also for the occupied spaces for transport (cars, trains, planes and ships).

Outdoor environmental conditions (e.g. in a sport stadium) are different from indoor conditions. There are several parameters differing from indoor conditions. The sport's stadium orientation and climatic conditions (ambient air temperature, Mean radiation temperature, Wind speed and direction) cause difficulty in analysing the situation and acquiring useful results.

Recently, a research work has been done on the outdoor thermal comfort with the project named RUROS (Rediscovering the Urban Realm and Open Spaces) by the European Union in 1998-2002. They conducted surveys in 14 cities across Europe and then found a Thermal Comfort index named as the Actual Thermal Sensation Vote (ASV). This model uses Meteorological data from the near by station. Another useful study aiming to assess the outdoor thermal comfort was done by Givone & Noguchi [3]. They introduced another outdoor thermal comfort indicator, named as Thermal sensation (TS). Before this, many models were developed by Fanger [23], but they were all for indoor conditions and can not be employed outdoors due to the variation in personal and environmental factors variations outdoor.

1.2 Appropriate Outdoor thermal comfort indicator

A review of the outdoor thermal comfort indicators for the purpose of this thesis revealed that two are widely used with high accuracy in predicting the outdoor comfort conditions. Outdoor environmental conditions are altogether different from indoors and hence, indoor comfort models cannot be employed to assess outdoor comfort conditions.

The first outdoor comfort indicator is “Actual Sensation Vote (ASV)” and the second is “Thermal Sensation (TS)”. ASV can be used for open spaces like parks, streets etc because it takes environmental data from a meteorological station to assess the thermal comfort. In the context of this research, about studies regarding comfort conditions in a sport's stadium, ASV can not predict comfort conditions with accuracy because it takes environmental data from a near by meteorological station not a specific site under study. So the appropriate outdoor indicator for a sport's stadium is thermal sensation (TS) which considers the environmental parameters of that specific place of research and hence gives more accurate results. According to the comparison study of different outdoor comfort models [27] TS gives results up to 78% accuracy. Keeping in view the accuracy and its use of local environmental parameters, thermal sensation (TS) has been employed to assess the outdoor thermal comfort conditions in this project.

1.3 Application of Thermal Sensation Indicator

In order to assess the outdoor comfort conditions of a sport stadium by the TS indicator some pre-assessment information is required. This involves the values of the parameters that are required to calculate the comfort conditions with the TS model. The ESP-r Building simulation tool has been employed to model the sports stadium and find out the pre-requisites required for the assessment of TS indicator.

1.4 Objectives of the Study

The objectives of this study were twofold. First was to perform thermal comfort modelling of an open space (part of a football stadium) to find out the comfort conditions under its full occupancy. The second was to give suggestions to a designer on how one could modify the design to make the stadium comfortable.

Besides these objectives it was the ambition of the author to learn the thermal comfort modelling techniques and tools that are widely used by the industry.

1.5 Problem Definition

The aims of this thesis are as follows:

1. To identify what has been done so far in assessing the thermal comfort conditions indoor and outdoor.
2. To carry out the thermal comfort modelling of an open stadium in the UK climatic conditions.
3. To identify the optimum environmental parameters in which spectators can find comfort.

1.6 Project organisation

Chapter 2: Thermal comfort and Research Issues: This chapter gives the details of factors affecting the thermal comfort of humans. It further contains the research issues which are important for the assessment of indoor and outdoor thermal comfort.

Chapter 3: Review of indoor comfort models: This chapter consists of a review of indoor comfort models. It elaborates the widely used Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) comfort model by P O Fanger and many others.

Chapter 4: Review of outdoor comfort models: This chapter is devoted to review outdoor thermal comfort indicators. As these are very few with good acceptability, attention has been given to Actual Sensation Vote (ASV) by Marialena [20] to find the comfort conditions in the open urban spaces. It further describes the research methodology of Thermal Sensation (TS) done by Givone & Noguchi [3] to discover outdoor thermal sensation and thermal comfort. This is the comfort indicator being used to assess the thermal comfort of foot ball stadium in UK climate conditions

Chapter 5: Research Methodology for case study: This chapter includes the details of how sports stadium modelling is done and the simulation software that is being employed. Moreover, there is a discussion on the basic requirements for the simulation of outdoor comfort in any building design tool.

Chapter 6: Modelling of the sports stadium: This chapter comprises of the details of sport stadium modelling in ESP-r. It further discusses the summer and winter cases that have been considered for this research work. It describes the different stages of the modelling work and options available to modify the stadium design to get the required comfort conditions out doors.

Chapter 7: Results and Discussion: This chapter is the most important part of this research work. It includes the result analysis of the modelling work. It further describes the modelling results and discussion about the thermal comfort and sensation in an open sport stadium. It also gives the details of parameters which have predominant affect on the thermal sensation of spectators inside the stadium

Chapter 8: Conclusion and Future Work: This chapter comprises conclusions and further recommendations to achieve the best possible comfort conditions at reasonable energy cost.

2 Thermal Comfort and Research Issues

2.1 Definition

Thermal comfort can be defined through three different approaches that are:

1. Psychological
2. Thermo physiological
3. Heat balance of Human Body

The psychological: British standard BS EN ISO 7730 and ASHRAE defines thermal comfort as following:

"It is the *condition of mind which expresses the satisfaction with thermal environment"*. [1] [9]

It is very hard to deal with human thermal comfort due to its subjective character, which reflects a wide inter-individual variation. Psychological factors are very important especially outdoors.

The thermo physiological approach is based on the firing of the thermal receptors in the skin and in the hypothalamus. Here the thermal comfort is defined as "*minimum rate of nervous signals from these receptors"* [9]

According to heat balance approach, thermal comfort is defined, "*when heat flows to and from the human body are balanced and skin temperature and sweat rate are within a comfort range."* [9]

Keeping in view the definitions above, we need to take into account a variety of parameters which include environmental and personal factors when deciding what will make the people to feel comfortable. The combination of these factors makes up what is known as the human thermal environment.

The only option that can be accepted realistically is to achieve a thermal environment that satisfies the majority of people in it. Health & safety executive (HSE) considers 80% of occupants as a reasonable limit for the minimum number of people who feel comfortable in a given thermal environment. So thermal comfort is not only measured by the air temperature, but by the number of occupants complaining of thermal discomfort. There are many other factors which contribute to thermal comfort along with air/mean radiant temperature. [1]

2.2 Importance of Thermal comfort

Due to the psychological nature of thermal comfort, it may affect the overall morale of occupants in a building or place. In a working environment, occupants' complaints may increase and they may refuse to work in a particular uncomfortable environment. Some aspects of the thermal environment that include air temperature, radiant heat, humidity and air movement may also contribute to the symptoms of sick building syndrome. In places of leisure, the visitors may be reduced due to discomfort in the thermal environment which can affect the business very seriously. In a stadium environment, where people go mainly for enjoyment, the issue of thermal comfort has vital importance as it can affect the number of spectators very diversely. Whilst watching a match in such stadiums, the expectations of spectators are very high and they desire a thermally comfortable environment. [1]

2.3 Factors which affect the thermal comfort

The most commonly used indicator of thermal comfort is air temperature because it is the most easy to use and people can rate it with out any difficulty. Although it has vital importance, however, it is not the only parameter that can be used to define thermal comfort very accurately. Air temperature should always be considered in relation to other environmental and personal factors. The following are the six environmental and personal parameters that contribute to the thermal comfort condition in a particular place. These may be independent to each other but they have collectively a great impact. They included following:

2.3.1 Environmental factors

1. Air temperature
2. Mean radiant temperature
3. Air velocity
4. Relative humidity

2.3.2 Personal factors

1. Clothing insulation
2. Metabolic rate

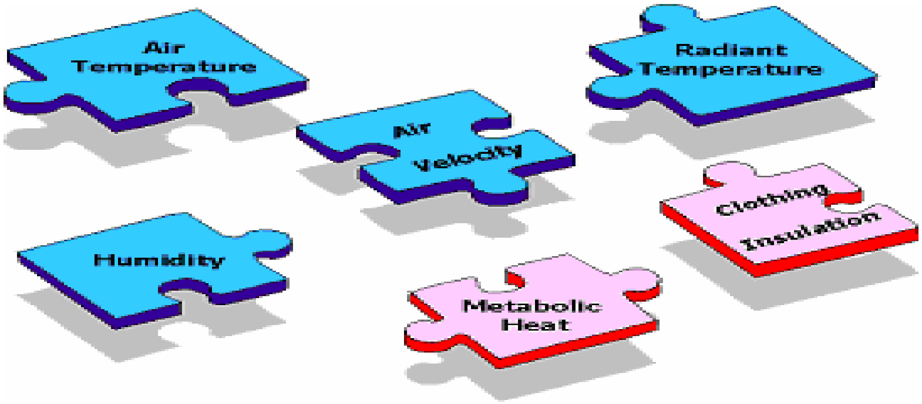

Figure 1: Chart of Factors Affecting thermal comfort of human [1]

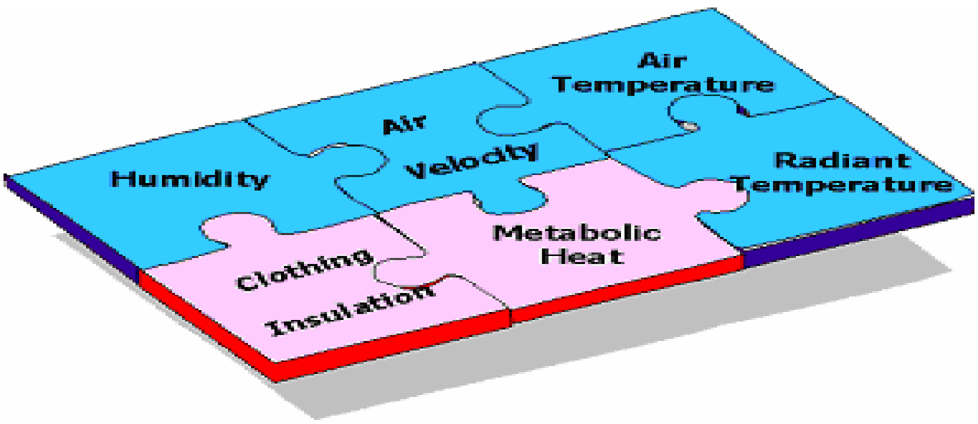

Figure 2: Charts representing the factors affecting the thermal comfort collectively [1]

1-Air Temperature (DBT):

Dry bulb temperature is one of the most important factors and it is the temperature of the air around us. The human body's primary response is towards the change in temperature and it is the temperature that we want to keep within the comfort conditions while designing structures for buildings and other habitations. It is defined in degree Celsius (C). [1, 2]

2- Mean Radiant Temperature:

The other important factor in defining the thermal comfort is the mean radiant temperature or thermal radiations. Radiation falling on the surface of human body causes the same affect as warm air because it activates the same sensory organs. When these radiations fall on the intervening surfaces, such as clothes, the radiant heat is absorbed and then conducted through intermediate material to skin. [1, 2]

Equivalent Mean Radiant And Air Temperature for feeling of 21.21^oC (70F)																
MRT ^oC	18.3	18.9	19.4	20	20.6	21	21.7	22.2	23	23.3	23.9	24.4	25	25.6	26	26.7
Air T^oC	25	24.2	23.4	22.7	21.9	21	20.3	19.6	19	18	17.2	16.4	15.7	14.9	14	13.3

Table 1: Equivalent Mean radiant temperature and air temperature for feeling at 21.21^oC [1]

Table 1 represents the combination of mean radiant temperature and air temperature (dry-bulb temperature) that will give a thermal sensation of 21.11 ^oC. Mean radiant temperature is the mean of thermal radiation readings from all materials around us which includes walls, floors, and other human bodies etc. There may be a difference in the MRT and air temperature.

3- Air Velocity (v): It is the air movement across the occupants or subjects in a particular environment. Air velocity is also an important parameter for thermal comfort as people are sensitive to it. It can produce different thermal effects at different air temperatures, which are given below:

When temperature of the moving air is less than the skin temperature, the convective heat losses are increased. The air movement accelerates the evaporation by physiological cooling. Its affect increases when the humidity level is lower than 30% and there will be unrestricted evaporation even with still air. When the humidity level is high as 85% then air movement cannot increase evaporation because the air is already highly saturated.

Air movements induce skin evaporation more significantly in the medium range of humidity's (40%-50%).The physical activity increases the air movement, so air velocity should be corrected by considering the person's level of physical activity.[1,2]

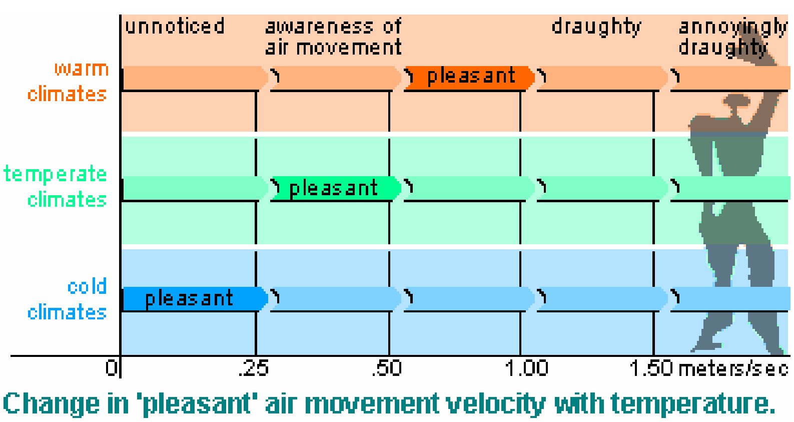

Figure 3: Affect of change in air velocity on the thermal comfort [1]

4-Relative Humidity:

When water is heated up, the vapour generated will go into the surrounding environment; the resulting amount of water in the air will provide humidity.

"Relative humidity is the ratio between actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature."[1]

The humidity has very little impact on the thermal sensation unless it is very low or very high. Relative humidity in the range of 40% and 70% does not have any significant impact on the thermal comfort. The relative humidity actually determines the evaporation rate. The moisture from the skin dries more quickly in the dry than in a humid atmosphere. At high temperatures heat is mostly dissipated through evaporation from the skin surface, but at 100% saturated air (humidity) there will be no cooling by evaporation. [1, 2]

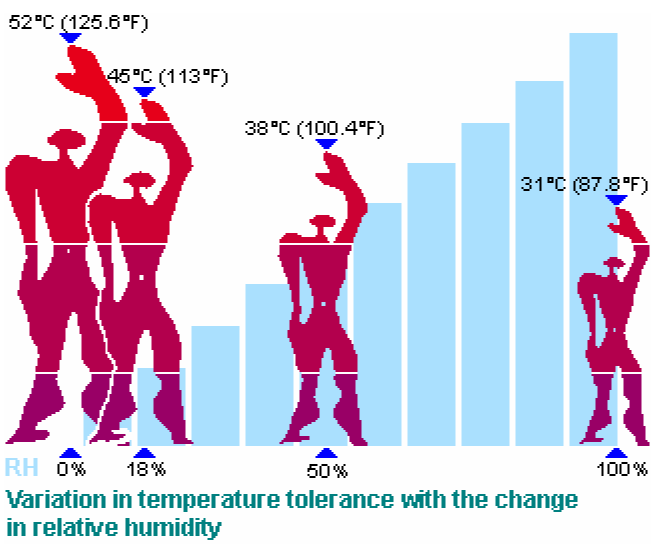

Figure 4: Variation in temperature tolerance with the change in relative humidity [1]

5- Clothing Insulation (CLO):

Clothing due to its nature provides a barrier to heat dissipation from body to the environment. Thermal comfort is very much dependent on the insulating effect of clothing on the wearer. Sometimes wearing too much clothing and or protective equipment (PPE) may cause thermal stress even if the environment is not very cold or hot. If clothing does not provide enough insulation then the wearer may be at risk in the very cold conditions.

Calculation of the heat transmission from the clothing is very difficult so a unit known as "*clo"* is introduced to represent the insulation capability of clothing. This corresponds to the average U-values of 6.5 W/m^2 ^oC over the whole of the body surface. Under still air condition, when the occupant is engaged in sedentary activity the 7 ^oC change in temperature can be compensated by 1 clo variation. Under windy conditions or some one is engaged with heavier work this effect is more pronounced. [1, 2]

Garment Insulation Value(Clo)

Description	**CLO**	**Description**	**CLO**
Underwear		**Trousers and Coveralls**	
Men's Briefs	0.04	Walking short	0.15
Panties	0.03	Trousers	0.24
Bra	0.01	Sweat pants	0.3
T-shirt	0.08	**Suits Jackets and vests(lined)**	
Full slip	0.16	single breasted, thin-thick	0.36-0.44
Long underwear top	0.2	Double breasted, thin-thick	0.42-0.48
Long underwear bottom	0.15		
Foot wear		**Dresses and Knees Length skirts**	
Ankles-high Athletic socks	0.02	Skirts, Thin-thick	
Calf-length socks	0.03	Long sleeve dressshirt,thin-thick	
Panty Hose	0.02	Sleeveless, scoop-neck thin-thick	
Sandals/Thongs	0.02	**Sweaters**	
Boots	0.1	Sleeveless, thin-thick	0.13-0.22
Shirt and Blouses		Long-sleeve thin-thick	0.25-0.36
Sleeveless, scoop-neck blouse	0.12	**Sleepwear's and Robes**	
Short sleeve, dress shirt	0.19	Long -sleeve,longgown -thick	0.46
Long sleeve, dress shirt	0.25	Long-sleeve pyjamas thick	0.57
Long sleeve, flannel shirt	0.34	short-sleeve Pyjamas thin	0.42
Long sleeve, sweat shirt	0.34		

Table 2: Details of different garment's clo value. [2]

6- Metabolic Rate/Activity (MET):

It describes the "heat that is produced inside our body as we carry out physical activities." [1]. It has great importance for thermal risk assessment. Our body is constantly producing heat but at different rates. More heat is produced during the physical activities as compared with at rest. The main principle involved here is the metabolic rate. These are the biological processes within the body which lead to heat production. [1]

Activity	**W/m^2**	**Met**
Reclining	46	0.8
Seated relaxed	58	1
Sedentary activity (office, dwelling,	70	1.2
School, laboratory)	70	1.2
Car driving	80	1.4
Graphic profession - Book Binder	85	1.5
Standing, light activity (shopping, laboratory, light industry)	93	1.6
Teacher	95	1.6
Domestic work -shaving, washing and dressing	100	1.7
Walking on the level, 2 km/h	110	1.9
Standing, medium activity (shop assistant, Domestic work)	116	2
Building industry - Brick laying (Block of 15.3 kg)	125	2.2
Washing dishes standing	145	2.5
Domestic work - raking leaves on the lawn	170	2.9
Domestic work - washing by hand and ironing (120-220 W)	170	2.9
Iron and steel - ramming the mould with a pneumatic hammer	175	3
Building industry -forming the mould	180	3.1
Walking on the level, 5 km/h	200	3.4
Forestry -cutting across the grain with a One-man power saw	205	3.5

Volleyball	232	4
Callisthenics	261	4.5
Building industry - loading a wheelbarrow with stones and mortar	275	4.7
Bicycling	290	5
Golf	290	5
Softball	290	5
Gymnastics	319	5.5
Aerobic Dancing	348	6
Basketball	348	6
Swimming	348	6
Sports - Ice skating, 18 km/h	360	6.2
Agriculture - digging with a spade (24lifts/min.)	380	6.5
Skiing on level, good snow, 9 km/h	405	7
Backpacking	405	7
Skating ice or roller	405	7
Tennis	405	7
Handball	464	8
Hockey	464	8
Racquetball	464	8
Cross County Skiing	464	8
Soccer	464	8
Running 12 min/mile	500	8.5
Forestry - working with an axe (weight 2 kg. 33 blows/min.)	500	8.5
Sports - Running in 15 km/h	550	

Table 3: Activities levels and their MET values [2]

2.4 Some Other Factors

The most important parameters that affect the thermal comfort have been described above but there are also some subjective non quantifiable factors that can be considered during the designing stage to get some additional benefits.

1 Acclimatization
2 Age and sex
3 Body build
4 Conditions of health
5 Food and drinks
6 Other factors (Presence of draughts, cold and warm floors) [2]

2.5 Indoor and Outdoor Thermal Comfort

According to a survey, in an industrialised country, people spend more time indoors as compared with outdoor. The results of the survey done by *Leech et al* [9], shows that people spend 90% indoor, 10% outdoor in summer and 3-4 % in winter time. These are the results under the severe weather conditions (too hot or too cold). This means that the comfort models based on the steady state conditions are appropriate for indoor due to long stay indoors but, these steady state conditions are hardly reached outdoor due to very short time spent outdoors (mostly less than one hour). A lot of work has been done on the thermal comfort of people indoor but very little is done on outdoor. *Potter and de Dear* [9] asked a question:

"*Why do holiday makers deliberately seek out thermal environments, that would rate 'off the scale' if they were encountered indoors?"*

They did research on this issue and found out the answer. They found that according to predicted mean vote the thermal neutrality was at 24.1^{o}C but in reality the values for outdoor spaces was 27 ^{o}C. Keeping in view this situation it is evident that the conditions outdoor are different and hence the indoor thermal models can't be used outdoor. [9]

2.6 Different approaches to define thermal comfort

There are three principle approaches to define thermal comfort:

1 Psychological
2 Thermo physiological
3 Heat balance of Human Body

2.6.1 Psychological Aspects

These factors are important both indoors and outdoors. Rohles [9] reports in his paper called "Temperature and Temperament: a psychologist looks at thermal comfort".

During his studies he proves that just by adding wood-panels, carpets and comfortable furniture with out changing thermal parameters in a chamber, made occupants more comfortable even at a higher temperature.

In winter people prefer warm temperatures over cold temperatures but in summer the situation is opposite. It is due to the fact people considered it as kind of luxury to have warm thermal conditions in cold winter.

More than 250 people were interviewed in an outdoor study, on a sunny street and park lawn. If assessed by the PMV-index the values were more than +3(hot) yet most of the people were feeling comfortable. In more details they told the reason for this was:

1 The weather day before was unseasonably cold
2 They had a time off and enjoyed easy living

In another study on an Italian beach, it was found that many people exposed themselves voluntarily to objectively very adverse conditions with physiological equivalent temperature higher than $40^{o}C$.

These studies highlight the importance of psychological aspects in terms of subjective assessments of thermal comfort, especially outdoors. There is not only this factor which distinguishes between thermal comforts indoors and outdoors, there are some other quantifiable parameters as well. [9]

2.6.2 Thermo Physiological Aspects:

There are many divergences between indoor and outdoor models which includes

1 Clothing
2 Activity levels
3 Time spent in this environment
4 Solar radiation
5 Wind speed

The important factor of these is the time ranges spent indoor and outdoor environments. Exposure to outdoor climate in most of the cases is in the range of minutes, while indoor exposure is in the range of several hours. Steady state conditions are reached in the air conditioned indoor environments but outdoors thermal steady state is rarely reached. So steady state models can't give the realistic results.

The slow changes of the thermal state of the body in the cold climatic condition are due to a reduction of peripheral blood flow as a consequence of vasoconstriction. But in hot condition vasodilatation increase this flow between skin and core. So the thermal adaptation of the body is much faster in summer as compared with winter. [9]

3 Review of Indoor Thermal Comfort Models

3.1 Assessing Thermal Comfort

There are many models developed by people to assess the thermal comfort indoor but for outdoor conditions their list is very short. The fundamental work was done by P O Fanger [23]; His model is based on the heat balance conditions of the human body.

However, there are many other Indoor comfort models available, these can be classified into following groups:

1 Theoretical Models
2 Adaptive models
3 Empirical Models

3.2 Theoretical Models

3.2.1 Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD)

Fanger's model of thermal comfort was a ground breaking contribution to the theory and the measurement of a highly important parameter for building construction planning. This model sets the correspondence between the characteristics of individuals (Activity level and thermal resistance of clothing) and their thermal environment (Air temperature, mean radiant temperature, relative air velocity, water vapour pressure in the ambient temperature), and thermal sensation (thermal vote). [4]

The term predicted mean vote (PMV) is the mean vote expected to arise from averaging the thermal sensation vote of large group of people in a given environment. The basic of PMV includes the physics of heat transfer combined with an empirical sensation.

The thermal strain which is established by the PMV is based on the steady- state of heat transfer between the body and the environment. The term PPD represents the predicted percentage of people dissatisfied at each PMV. The index chart which is -3, -2, -1, 0, +1,+2,+3 for the PMV has direct impact on the PPD. As PMV changes away from zero, in either the positive or negative direction, the value of PPD increased.

The base of PMV equation for thermal comfort is a steady state model. It is an empirical equation for predicting the mean vote on an ordinal category rating scale of thermal comfort of a population of people. The equation used a steady state heat transfer from human body, which postulates a link between the deviation from the minimum load on the heat balance effectors mechanisms that includes sweating, vaso-dilation, vaso-constriction and thermal comfort vote. These conclude that the greater the load, the more the comfort vote deviates from zero. To develop a curve and get average results enough people were exposed to different environments at varying time span. Predicted Mean Vote (PMV), as the integrated partial derivative is now known, is the most widely used thermal comfort index today.

Due to some limitations the ISO (Internal standards organisation) standard 7730(ISO1984), "Moderate Thermal Environment-determination of the PMV and PPD indices and specification of the conditions for thermal comfort" used limits on PMV as an explicit definition of the comfort zone.

The PMV equation applies to the human exposed for a long period to constant conditions at a constant metabolic rate. The heat balance equation is based on the conservation of energy.

The equation is in the following form:

$$H - E_d - E_{sw} - E_{re} - L = R + C$$

Equation 1: Heat balance Equation used by Fanger

Where:

H -- Represents the internal heat production

E_d -- Heat loss due to water vapour diffusion the skin

E_{sw} -- Heat loss due to sweating

E_{re} -- Latent heat loss due to respiration

L -- Dry respiration heat loss

R -- Heat loss by the radiation from the surface of the clothed body

C -- Heat loss by convection from the surface of the clothed body

The equation is expanded by putting the value of each of the variables with the functions that are derivable from the basics laws of physics. The components of this equation are measurable except the convective heat transfer coefficient and clothing surface temperature which are the functions of each other.

To solve this problem initial value of the clothing temperature is assumed and convective heat transfer coefficient is computed. Using this value, new clothing temperature values are found through iteration.

When the body is not in heat balance conditions, the equation can be written as:

$$L = H - E_d - E_{sw} - L - R - C$$

Equation 2: Heat balance equation when body is under thermal load

L ----- represent thermal load on the body of subject.

To calculate "L", it is require to define thermal strain or sensation Y, as some unknown function of "L" and metabolic rate. The mean votes are used from the climate chamber experiments to write Y as a function of air temperature at different levels of activities while holding all variables constant except air temperature and metabolic rate. Now substitute the L for air temperature that was determined above from the heat balance equation. Evaluate the partial derivative of Y with respect to "L" while keeping Y=0 and plot the points obtained versus metabolic rate. An exponential curve is obtained that fits to the points and integrated with respect to "L" other wise known as "PMV"

So in the equation can be written as:

$$PMV = \exp^{[met]*L}$$

Equation 3: Derived PMV equation by Fanger

Where $L = f\left(P_a, T_a, T_{mrt}, T_{cl}\right)$

The PMV is scaled to predict the thermal sensation votes on a seven points, these points are:

Hot (+3)

Warm (+2)

Slightly warm (+1)

Neutral (0)

Slightly cool (-1)

Cool (-2)

Cold (-3) [23]

3.2.2 Limitation of Fanger's Model (PMV, PPD)

The quantification of the model has been tackled by the Fanger through a conditional regression approach. To start with, the link between air temperature and his measurement of individual satisfaction, the predicted mean vote (PMV), is set by regression this variable on the former. To be meaningful, this regression should be based on data generated through an experiment that keeps all the climatic variables constant that can have an impact on thermal comfort, as well as the thermal resistance of the clothing and the activity level. The regression is repeated for different observed activity levels and the results are combined to establish a unique relationship between the PMV and those parameters of comfort. Clearly, this statistical approach is limited in scope as it relies upon data generated in very strict experimental conditions.

More specifically, all individuals must experience same climatic conditions, the same met level, clothing and only one parameter of comfort may vary at a time. This homogeneity is necessary to establish an invariant relationship between the mean vote and air temperature. It is also necessary to keep the dispersion of vote as small as possible. If dispersion is high then mean vote would be meaningless and relationship between PMV and PPD will be very difficult to find out. So it is costly and a difficult way to quantify the model.

Taking a mean activity level in Fanger's model results in loss of information and hence of precision when estimating the model. The number of activity levels can not be too large as the first stage of Fanger's procedure has to be repeated for each activity level.

The local climatic conditions in a room are not the same everywhere because there was always inhomogenieties, even in the climatic chamber.

Fanger's results depend on the choice of coding (for votes). Changing the coding gives a different mean vote and as results the parameters of regression have no physical meanings.

The choice of a linear regression between the mean vote and the ambient temperature introduces two implicit assumptions concerning thermal sensation of people. These are *symmetry of the sensation* and *consistency of the amplitudes* between the appraisals.

Fanger's methodology calculates PPD after PMV but it can be calculated directly if a qualitative response model is built.

PMV can be beyond the value of 3 so the model is restricted to situations near the neutral. [4, 24]

3.2.3 ASHRAE's Standard Effective Temperature (SET*)

SET is a comfort index that was developed based upon a dynamic two-node model of the human temperature regulation. A transient energy balance states that the rate of heat storage is equal to the net heat gain minus the heat loss. The thermal model is described by two coupled heat balance equations, one applied to each compartment:

$$S_{cr} = M - W - (C_{res} + E_{res}) - (t_{cr} - t_{sk})(5.28 + 1.163(skbf))N$$

Equation 4: Equation of rate of heat storage in core node in SET* Model

$$S_{sk} = (t_{cr} - t_{sk})(5.28 + 1.163(skbf)) - (C + R + E_{sk})$$

Equation 5: Rate of skin node heat storage in SET* model

Where:

S_{cr} is the rate of heat storage in the core node (W/m^2); S_{sk} the rate of heat storage in the skin node (W/m^2) ; C_{res} the rate of convective heat loss through respiration (W/m^2); E_{es} the rate of evaporative heat loss from respiration (W/m^2); t_{cr} the temperature of core node; t_{sk} the temperature of skin node; $skbf$ the peripheral blood flow (*L*/*h* m^2); *C* the sensible heat loss from skin through convection (W/m^2); *R* the sensible heat loss from skin by radiation (W/m^2); E_{sk} the total evaporative heat loss from the skin (W/m^2).The rate of heat storage in the body equals to the rate of increase in internal energy. The rate of storage can be written separately for each compartment in terms of thermal capacity and time rate of change of temperature in each compartment:

$$S_{cr} = (1-\alpha)mC_p, b(dt_{cr}/d\theta)/AD$$

Equation 6: Rate of heat storage in terms of thermal capacity and time rate

$$S_{sk} = \alpha mC_p, b(dt_{sk}/d\theta)/AD$$

Equation 7: Rate of heat storage in skin node in terms of thermal capacity and time rate

Where α is the fraction of the body mass in skin compartment; *m* is the body mass (kg); C_p, b the specific heat capacity of the body (KJ/Kg); θ the times(s); *AD* the Dubois surface area (m^2).

The ASHRAE SET* index is defined as the equivalent temperature of an isothermal environment at 50% RH in which a subject , while wearing clothing standardized for the activity concerned, would have the same heat loss (skin temperature, t_{sk}) the thermoregulatory strain (skin wettedness, w) as in the actual test environment. Isothermal environment is that at sea level where air temperature is equal to the mean radiant temperature, and air velocity is zero. If H_{sk} is defined as the heat loss from skin, which is the thermal load of skin, so we can say:

$$H_{sk} = h_s\left(t_{sk} - SET*\right) + wh_s,e\left(p_{s,sk} - 0.5SET*\right)$$

Equation 8: Equation of thermal load on the skin

Where h_s the standard heat loss coefficient (W/m^2.C); $h_{s,}e$ the standard evaporative heat transfer coefficient (W/m^{2}KPa); w the fraction of the wetted skin surface; $P_{s,sk}$ the water vapour pressure at skin, normally assumed to be that of saturated water vapour at t_{sk} (KPa); *P*SET* the saturated water vapour at SET*(KPa). [19]

3.2.4 Comparison between PMV and SET*

1 The SET* calculations are more complicated and difficult than PMV, because before the calculation of SET* we must first work the physiological parameters of human body using the 2 node model, while this is not necessary for the calculations of PMV.

2 The heat exchange between human body and environment in SET*, s calculation is worked out by the same way as that is used in PMV.

3 SET* has the advantage of allowing thermal comparisons between environments at any combination of the physical input variables.

4 The limitation SET* has is it also requires "standard" people.[19,23]

5 SET* numerically represents the thermal strain experienced by the cylinder relative to a "standard" person in a "standard" environment. SET* has been developed based on the laboratory study with a large number of subjects, empirical functions between two comfort indices , skin temperature and skin wittedness, were then developed. These functions are then used in the 2- node model to produce predicted values of the votes of populations exposed to the same conditions as the cylinder. [23, 19]

3.2.5 Effective Temperature (ET*)

ET* stands for new effective temperature where "effective temperature" is a temperature index that accounts for radiative and latent heat transfers. ET* is based on the heat balance model to predict thermal comfort as it was in the Fanger's PMV model. However, ET* evolves with time rather than being steady- state. The calculations of ET* can be done using a 2-node model that determines the heat flow between the environment, skin and core body areas on a minute by minute basis. The initial conditions for the time scale was taken as "0" and then iteration was carried out until it reached the equilibrium conditions. The typical time scale is 60 minutes to evaluate the model. After calculation, final mean skin temperature and skin wittedness are associated with an effective temperature. The thermal discomfort is then calculated by DISC using the skin temperature and skin wettedness. [23]

3.2.6 Equivalent Temperature

The concept of equivalent temperature was first introduced by Dufton [19] when he studied the heating of buildings. During his studies he developed an integrating thermostat, which would maintain a room at a comfortable temperature, against the variations in air temperature, thermal radiations and air speed. Due to further development in this area of study and interest in panel heating, it was discovered that not only air temperature was an inadequate parameter to describe the thermal comfort.

Dufton then developed a device named as Eupatheostat that simulate a person's dry heat loss. The construction of this device consisted of a vertical cylinder that was heated internally with heaters. Its size was chosen to provide a partition of radiation and convection heat losses that was comparable to a man. This work was extended further as there were some limitations in the concepts of Eupatheostat. Madsen [19] defined the equivalent temperature as "*the uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiations and convections as in an actual environment"*

Mayer [19] did further work and constructed a device named as "artificial skin" that can be used to measure the equivalent temperature. He defined the Equivalent temperature as *"the surface temperature of an imagined room in which surface temperature of a body,* *heated by a definite heat flow density is the same as the actual room (with possible different surface and air temperature and air velocity).”* It is believed that equivalent temperature is the temperature that people can perceive. In summary, Madson's definition seems to be more realistic as compared with Mayer, because the subject in it is the individual, while in Mayer's it is a cylinder.

To have a meaningful understanding of equivalent temperature, we must have knowledge about operative temperature. The concept of operative temperature was introduced by the Gagge et al [19] which is being used as he defined earlier. The operative temperature is defined as “*the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in an actual non uniform environment.”* The fundamental difference between equivalent and operative temperature described by the Madsen for typical indoor climates was *“the operative temperature does not take into account the cooling effect that the air movement has on a heated body like a man, it only take into account the relative influence of parameters- air temperature mean radiant temperature and air velocity on the temperature of an unheated body”*.

Mayer described the difference as is in the ISO 7730 which is that “*The equivalent temperature considers not only the air temperature and the temperature of surrounding surfaces, but also takes into account the influence of the air velocity on the heat balance of a heated body (man)”*.

For the calculation of the equivalent temperature, following two steps are necessary to be considered:

1. Establishing a dry heat loss balance equations between a person and the actual and imaginary environments, respectively.
2. Working out the air and mean radiant temperature of the imaginary environment according to equivalent temperature's definition by Madsen.

Therefore, the equivalent temperature can be calculated after measuring air temperature, mean radiant temperature, and air velocity. [19, 15]

3.2.7 TSENS, DISC

TSENS is the first index that represents the models prediction of vote on a seven-point thermal sensation scale. DISC is second index that is used to predict a vote on a scale of thermal discomfort:

The scale that is produced by the DICS is given below as:

1 Intolerable
2 Very uncomfortable
3 Uncomfortable
4 Slightly uncomfortable
5 Comfortable

After the refinements and many iterations in the 2-node model, the new temperature index that was the most recent iteration, was introduced. This PMV* index incorporates the skin wittedness into the PMV equation using SET* or ET* to characterize the environment. [23]

3.3 Adaptive Models

The Adaptive approach is not based on the heat balance equilibrium between human body and environment but on observations. Depending upon the observations, there are a range of actions which can be performed in order to achieve thermal comfort. In a human body, brain temperature is a sensor to regulate the temperature of the whole body. It acts as a control to maintain the thermal comfort conditions between the body and environment. If changes occur in the environment or somewhere else, the brain equilibrium will deviate from the close limits of thermal comforts, and then action is taken to restore the brain to close limits.

The types of actions that can be taken to restore the thermal comfort by adaptive approach are:

Modifying internal heat generation: That can be achieved unconsciously with the raised muscular tension. The action of shivering in cold conditions can raise the metabolic rate that would produce heat to keep body warm and having siesta in the warm to reduce it.

Modifying the rate of body heat loss: that is achieved unconsciously through vaso regulation or sweating: changing clothes and taking a cooling drink etc.

Modification in thermal environment: This can be achieved through turning on heating or by opening a window etc.

Selecting a different environment: within a room moving to other one where heating is on and to go outside to catch a breeze etc.

The implications of adaptive models are based on the principle that sufficient time is given to the occupants so that they can find the ways to adapt any temperature in an environment without causing any threat of heat stroke or hypothermia. During the adaptive models the discomfort will arise where temperature:

1 Change too fast for adaptation to take place
2 Are outside normally accepted limits
3 Are unexpected
4 Are outside individual control [25]

Therefore, it is evident that adaptive models include in some way the variations in outdoor climate for determining thermal preferences indoors.

3.3.1 Aucliciem's Adaptive Model

Auliciem used the field investigations data of thermal comfort in Australia spanning several climates for his model to find the sensation fits.

The equation used by Auliciem was:

$$T_n = 9.22 + 0.48T_a + 0.14T_{mmo}$$

Equation 9: Aucliciem's comfort model

3.3.2 Humphreys Adaptive Model

Humphrey's equation is more efficient for considerable data for climate- controlled and non-climate controlled buildings:

$$T_n = 23.9 + \frac{0.295\left(T_{mmo} - 22\right)}{e^{-\frac{\left(T_{mmo}-22\right)^2}{24SQRT(2)}}}$$

Equation 10: Combine model of Aucliciem and Humphrey

In both Aucliciem's and Humphrey's models;

T_n -- is the neutral temperature; T_a is the air temperature, and T_{mmo} is the mean monthly outdoor temperature. [23].

We expect the comfort temperature would be close to the average temperature the occupants experienced. Humphreys [25] has shown this to be very close to the real situation by using the results of his field surveys. The results of his surveys are shown in the following graph.

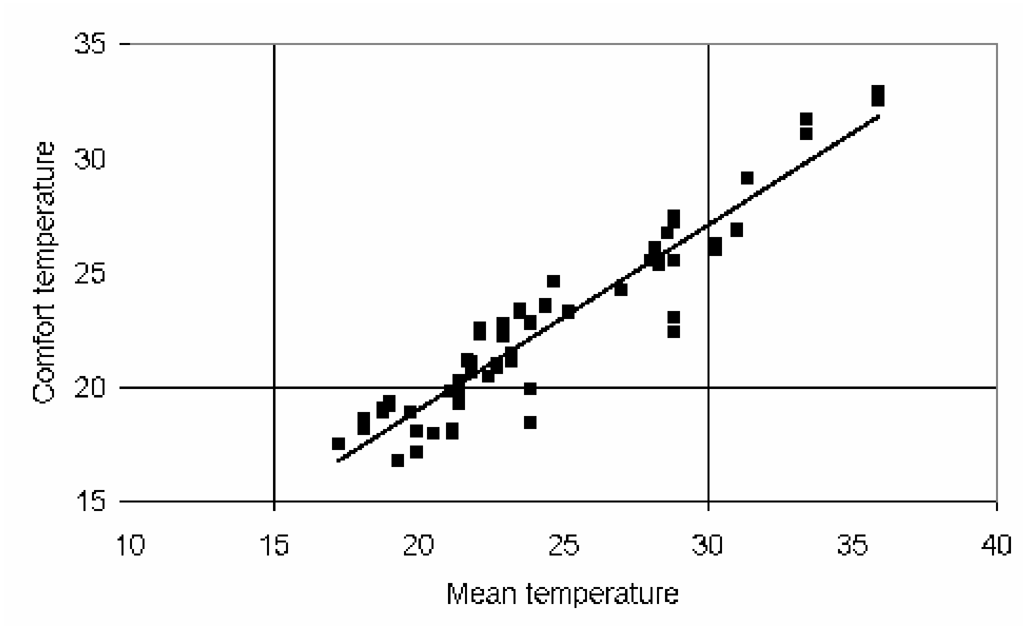

Figure 5: Relationship between comfort temperature (Tc) and Mean experienced temperature(Tm). [25]

To set up an adaptive Thermal comfort model, we need to reflect the interactions between comfort and environment in its formulation. The value of the comfort temperature will vary at the very least with climate and season.

The value of the comfort temperature in free running buildings can be deduced from a graph such as given in the figure 2.9. Humphreys [25] found that the best outdoor temperature predictor for the comfort temperature was the mean of the monthly minimum and the mean of monthly maximum temperatures.

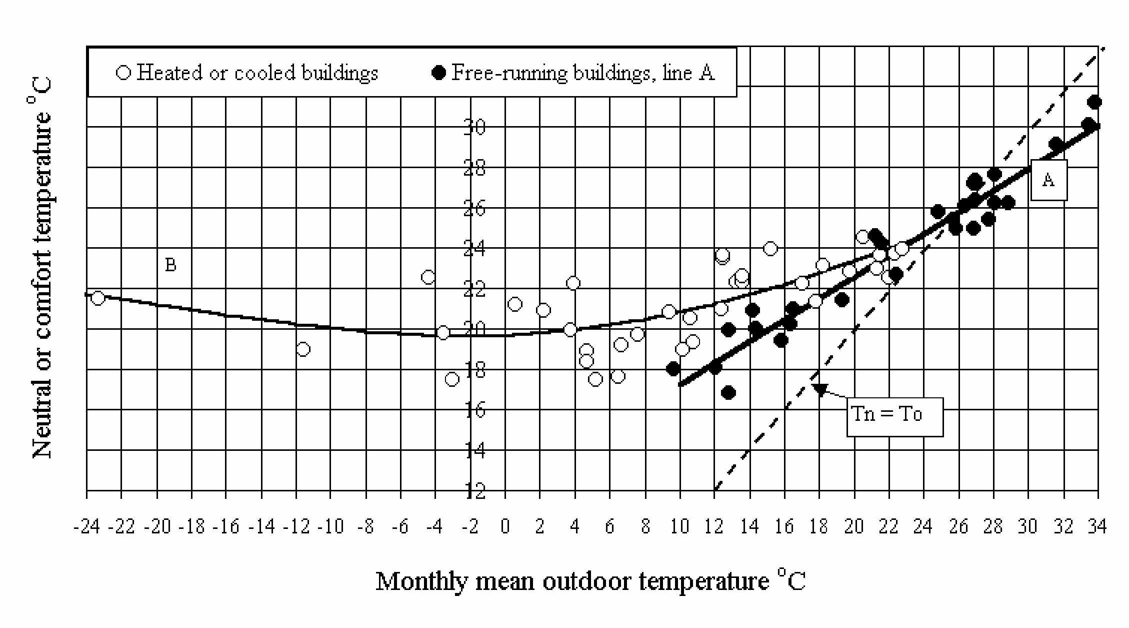

Figure 6: Comfort or Neutral temperature as function of outdoor temperature by Humphreys (1982). [25]

3.4 Empirical Comfort Models

There are many theoretical models (except described already) which are more deterministic and empirical. Some of the empirical models that are being used in the building designs are listed below:

3.4.1 Predicted Percentage Dissatisfied due to Draft (PD)

PD or "predicted percentage dissatisfied due to draft" is the model used to evaluate the thermal discomfort of the group of people due to drafts. This model is based on the air temperature, air velocity, and turbulence intensity.

Keeping in view the energy conservation and energy efficiency draft is always an unwanted entity. The draft risk or PD can be calculated through following equation:

$$PD = 3.413(34 - T_a)(v - 0.05)^{0.622} + 0.369vT_u(34 - T_a)(v - 0.05)^{0622}$$

Equation 11: Draft risk calculation

Where T_u are the turbulence intensity taken as percentage; 0 represents laminar flow and 100% means that the standard deviation of the air velocity over a certain period is of the same order of magnitude as the mean air velocity; v the air velocity in m/sec; and Ta is the air temperature in ^{o}C.

The PD model was developed by two studies [23] in which about 100 people participated. They were exposed to different combinations of air velocity, air temperature and turbulence intensity. For each combination of these three environmental parameters, they were asked whether they felt a draft. PD represents the percent of people who voted that they felt a draft for the selected conditions.

3.4.2 Predicted Percentage Satisfied due to Draft (PS)

PS or "predicted percentage satisfied due to draft" represents the group of people that feel comfortable to a certain level of air velocity. The inputs for PS are the operative temperature and air velocity.

The equation to calculate the PS is given as:

$$PS = 1.13QRT\left(T_{op}\right) - 0.24T_{op} + 2.7SQRT\left(v\right) - 0.99v$$

Equation 12: predicted Percentage satisfied due to draft

T_{op} Is the operative temperature (^{o}C) and v is the air velocity (m/Sec).

This equation evaluates the air velocity that can chosen by a person who is exposed to a certain air temperature when the subject has control over the air velocity source. The **PS** equation predicts the air velocity that will be chosen by a person exposed to a certain air temperature when the person has control of the air velocity source.

The PS equation was established when 50 people were asked to adjust air velocity as they feel comfortable when they were exposed to certain air temperature. PS actually gives the cumulative percent of subjects, choosing a particular air velocity at the specific air temperatures during the experiments.

3.4.3 Thermal Sensation (TS)

TS or "thermal sensation" is model used to evaluate the thermal sensation of a group of people. TS are a linear function of air temperature and partial vapour pressure. The equation used to find out the TS is given below:

$$TS = 0.245T_{a} + 0.248p - 6.475$$

Equation 13: Thermal sensation for a group of people

Where T_a the air temperature ($^{\circ}C$) and P is the partial pressure (KPa).The method to develop this model was very much similar to that used to calculate PMV and PPD by Fanger. [23]

4 Review of out door Thermal Comfort Models

4.1 Why pure Physiological Approach is inadequate for outdoor Thermal comfort Assessment?

The wide range of microclimatic conditions in outdoor spaces strengthens the point that a purely physiological approach is inadequate to characterise the outdoor thermal comfort. However the issue of adaptation becomes increasingly important.

Personal changes, with the seasonal variation of clothing, changing in the metabolic heat with the consumption of cold drinks, changes in the posture and positions become very important parameters to determine the outdoor thermal comfort. The psychological parameters such as personal choice, memory and expectations also play an important role in such conditions.

4.2 Outdoor Thermal Comfort Research Issue

One of the factors, affecting a person's outdoor activities in streets, plazas, the play ground, urban parks etc is thermal comfort. The amount and intensity of such activities is affected by the level of the discomfort experienced by the inhabitants when they are exposed to the climatic conditions in these outdoor spaces. [17]

As an example, on a hot summer day the thermal discomfort of people staying outdoors exposed to the sun may discourage them from utilizing available urban parks, depending on the particular combination of air temperature, the surface temperature of surrounding areas, the wind speed and level of humidity. In such conditions, the availability of shaded outdoor areas may result in greater utilization of the open space by the public.

In the similar way, in a cold region, a given combination of wind speed and air temperature, or the obstruction of the sun in shaded areas, may discourage people from staying outdoors while the provision of sunny areas protected from the prevailing winds may encourage public activities in that outdoor space.

The design details for outdoor spaces can modified the ambient air temperature, solar radiation and wind in a particular location. Such design details may include the provision of shading elements, materials and colours of surrounding hard surfaces, provision and details of planted surfaces, wind breaks and openness to the wind etc. [3]

4.3 Why outdoor Research and Issues are different from indoor?

Research on outdoors comfort involves different conditions and issues, not encountered in studies for indoor comfort. When people stay outdoors, they expect variability in the;

1. Exposure conditions
2. Variation of sun and shade
3. Changes in the wind speed etc

Pedestrians may be exposed to intense solar radiations and to the winds; these factors may modify their response to the temperature and humidity conditions.

4.3.1 Clothing variation:

People staying outdoors usually wear different clothing in different seasons, clothing that are suitable to the prevailing climates. So fixed standard clothing is not applicable to outdoor conditions. In each particular season, the subject should wear clothes which are commonly used in that particular location and season.

The effect of direct exposure to solar radiation is not limited to the thermal sensation. In winter it may produce specific pleasure. On a hot summer day, it may produce specific discomfort, beyond the thermal sensation. In un-shaded areas, pedestrians may also be exposed to surface temperature much higher in summer and lower in winter than the ambient air temperature.

4.3.2 Wind speed:

Outdoor wind speeds are much higher than the wind speeds common indoors. Wind in the summertime up to a certain speed, may be specifically pleasant, while in winter it may be specifically annoying. These factors have to be considered in evaluating the overall subjective responses to the outdoor environment.

4.3.3 Effect of Relative Humidity:

The analysis of the combination of various climatic elements may be more complex in outdoors comfort studies than indoor conditions, because of peculiar interactions between the climatic elements in specific locations and seasons. This factor may present specific problems in developing mathematical models by multiple factor regression.

For instance, in the study done in Japan (1994-1995) [3], the humidity was much lower and the temperature higher during sunny days of the given season than in cloudy days. The subjective feels warmer mainly because of the solar radiation. During the same day the humidity is lower.

4.4 Relative effects of air temperature, solar radiations and wind speed on thermal sensation:

The effects of solar radiation and wind speed can be related to the effect of air temperature by calculating the changes in these factors which will produce the same effect as that of a unit change in air temperature (1^oC).

To get a close combination of the effects of above parameters on the thermal sensation, a predictive formula for the thermal sensation has been developed which takes into account only the effects of air temperature, solar radiation and wind speed. The resulting formula is:

$$TS = 1.2 + 0.1115T_a + 0.0019SR - 0.3185WS$$

Equation 14: Factors affecting Thermal sensation

Where R^2 value of 0.8711

Thus the experimental results of the study in Japan suggest that a change of 59 W/m^2 in solar radiation and a change of 0.35 m/Sec in wind speed had a similar effect to a change of 1^oC in air temperature.

4.5 Comfort and thermal sensation

Thermal comfort level is related to the thermal sensation. However one may feel uncomfortable either when it is too warm, or when it is too cold. Thermal comfort may be a required condition but it is not sufficient, for the environmental positive pleasantness. An alternative way to deal with thermal comfort beyond the sensation of the level of heat or cold, thermal comfort could better be defined just as the absence of any sense of discomfort. So the wording of the 'super comfort' levels could be in levels of pleasantness, or stimulation, rather than thermal comfort. [3]

4.6 Actual Sensation Vote (ASV)

A lot of work has been done to find the thermal comfort conditions indoor but there is very little work done for outdoors. A recent project, RUROS (Rediscovering the Urban Realm and Open Spaces) [20] has researched outdoor thermal comfort. This project was funded by the European Union and it takes four years to complete (1998-2002). This indicated that the environmental parameters are quite similar to those encountered indoor but they are much wider in range and variable. So there are some problems to model outdoor thermal comfort due its

1 variability
2 Temporal and spatial
3 Great ranges of activities people are engaged. [20]

The purpose of this research was to seek the better understanding of the richness of microclimatic characteristics in out door urban spaces, and the comfort implications for the people using them. The hypothesis given by Marialena [20] demonstrates that microclimatic characteristics influence people's behaviour and usage of outdoor spaces. The initial results of his research demonstrate that a purely physiological approach is inadequate to assess the comfort conditions outdoor, and an understanding of the dynamic human parameters is necessary in designing spaces for public use. The thermal environment is indeed of prime importance influencing people's use of these spaces, but physiological adaptation (available choice, environmental simulation, thermal history, memory effect and expectations) is also of great importance in such spaces that present few constraints.

Improved microclimatic conditions have major implications for development of cities. By controlling sources of discomfort, sedentary activities, as well as the use of public transport, cycling and walking, are prompted. Successful areas attract large number of people, which in turn attract businesses, workers, residents, and the area becomes economically profitable. The energy use of the surrounding buildings can also be affected. Finally successful outdoor spaces can benefit the image of city. [18, 20]

4.6.1 Adaptation:

In most of the outdoors thermal comfort studies, a purely physiological model has been used. These involved a mathematical model of the thermoregulatory system employed for calculating thermal satisfaction, depending upon the environmental conditions, activity of people and their clothing level. The field surveys done by Marialena [20] showed that these approaches are inadequate hence the issue of adaptation become very important in outdoors conditions. These include all the actions people do to fit between the environment and their requirements both at physical and psychological levels.

The adaptation in the outdoor environment to keep some one in a comfortable condition is of two types:

4.6.2 Personal changes:

1 Variation of clothing due to seasonal changes

2 Changes in the metabolic heat with the consumption of cold drinks

3 Changes in posture and positions

4.6.3 Personal choice

1 Memory

2 Expectations [20,25]

In the RUROS project for the determination of the outdoor thermal comfort, they did surveys in the 14 cities across the Europe. The people thermal sensation was evaluated on the five points from “very cold” to “very hot”. This index of thermal sensation was defined as Actual Thermal Sensation Vote (ASV). The data they collected from these surveys was analysed and correlation was revealed between the microclimatic parameters and ASV.

4.6.4 ASV Models:

For design point of view, they developed a simple model that can be used to predict the thermal comfort conditions. A linear model was developed by using the publicly available meteorological data from a near by station. ASV predicted from these models can be a platform on which outdoor thermal comfort nomogrames and maps can be constructed. The important consideration done in these models are that they have incorporated the personal parameters, people bring into open spaces and the effect of adaptation physically and psychologically.

4.6.5 City Comfort Index:

Models for different cities have been presented for the calculation of ASV corresponding to different climatic zones. These are based on the hourly metrological data.

The parameters used to find out the ASV from these models are the Air temperature (Tair_met); ^{o}C global solar radiation (Sol_met.W/m2); wind speed (V_met. m/sec) and relative air humidity (RH_met, %).

Athens (GR):

$$ASV = 0.034T_{air\_met} + 0.0001Sol\_met - 0.086V\_met - 0.001RH\_met - 0.412$$

Equation 15: ASV model for Athens

Thessaloniki (GR):

$$ASV = 0.034T_{air\_met} + 0.0013Sol\_met - 0.038V\_met - 0.011RH\_met - 2.197$$

Equation 16: ASV model for Thessaloniki (GR)

Milan (IT):

$$ASV = 0.049T_{air\_met} + 0.0002Sol\_met - 0.006V\_met - 0.002RH\_met - 0.920$$

Equation 17: ASV model for Milan (IT)

Fribourg (CH):

$$ASV = 0.068T_{air\_met} + 0.0006Sol\_met - 0.107V\_met - 0.002RH\_met - 0.69$$

Equation 18: ASV model for Fribourg (CH)

Kassel (D):

$$ASV = 0.043T_{air\_met} + 0.0005Sol\_met - 0.077V\_met - 0.001RH\_met - 0.876$$

Equation 19: ASV model for Kassel (D)

Cambridge (UK):

$$ASV = 0.113T_{air\_met} + 0.0001Sol\_met - 0.05V\_met - 0.003RH\_met - 1.74$$

Equation 20: ASV model for Cambridge (UK)

Sheffield (UK):

$$ASV = 0.07T_{air\_met} + 0.0012Sol\_met - 0.057V\_met - 0.003RH\_met - 0.855$$

Equation 21: ASV model for Sheffield (UK)

These models which have incorporated the "T_{air_met}" and "$V - met$" can be used to obtain the thermal comfort index for a city for different seasons.

It was revealed that very cold conditions are more tolerable during summer and spring as compared with other two seasons for all cities. Hot conditions are considered as comfortable in the autumn and spring.

By using a range of metrological data through out the Europe, a combined ASV model for the Europe was developed:

$$ASV = 0.049T_{air\_met} + 0.001Sol\_met - 0.051V\_met - 0.014RH\_met - 2.079$$

Equation 22: Actual Sensation Model for whole Europe

Solar radiation values of 100, 400, 800 W/m^2 correspond to low insulation that is similar to overcast and late sunny afternoon, average insolation that represents the partly cloud or clear winter day and high insolation that represents the summer clear sky day respectively. The values of relative humidity for dry, average and humid conditions are 20%, 40% and 80%. The wind speeds of 0.1, 1, 3, 5m/sec represents the stale, slight breeze, and strong breeze conditions. Above the wind speeds of 5 m/sec the mechanical effects become more significant than the thermal effects.

Air temperature (°C)	Solar radiation ($W.m^{-2}$)	Relative Humidity (%)	Wind Speed ($m.s^{-1}$)
0	100	20	0.1
5	400	40	1.0
10	800	80	3.0
15			5.0
20			
25			
30			
35			
40			

Figure 7: Meteorological conditions for nomogrames. [20]

4.6.6 Thermal Comfort

Conventional comfort theories rely on steady state conditions where the production of heat is equal to the heat losses to the environment. These models aim to keep the core body temperature at constant value of 37°C. This shows that the environmental conditions which provide thermal satisfaction, depends only upon the activity of subjects and their clothing level, fall within a narrow band.

The theory given by Nicol [26] of “adaptive” actions showed that people take action to improve their comfort conditions by modifying their clothing level and metabolic rate, or by interacting with the buildings.

Baker and Standeven [26]; further give explanation to the adaptive opportunity and separate thermal sensation from thermal satisfaction. He demonstrated that the “adaptive opportunity” (the degree to which people can adapt to their environment) is important for their satisfaction with the space. These theories showed that intrinsic factors like past experience, naturalness, experience and expectations, time of exposure, and the need for environmental simulation are also important for thermal satisfaction. [26]

The research frame work used by Marialena [20] to understand outdoor thermal comfort conditions for the following case is based purely on the physiological model, similar to used for the indoor environment, adapted for the solar radiation parameters.
But the limitations involved here are the lack of understanding of the human parameters in these spaces, and their subjective responses. [26]
In a case study that was done by Marialena to assess the outdoor thermal comfort condition when people are sitting in a resting places. The areas chosen for this research were in the city centre of Cambridge, which have been designed specifically for external public use. They can be identified as urban squares, streets or parks, with strong commercial activities, and very popular in terms of public use. The sites selected for this research were varied in topology, geometry, orientation and intended use. The field studies were taken place in winter, summer and spring of 1997. The total number of interviewees involved in this research was 1431.
As the research done by Marialena [20] is based on the calculation and measuring of outdoor environmental parameters during the periods of interviews, a mini portable met station was placed near to the interviewees. This met station will be used to measure the air temperature, solar radiations, wind speed and humidity of the environment. These were then compared with subjective behaviours and responses to evaluate the thermal comfort conditions people experience. Individual’s characteristics as well as behavioural ones, such as age, sex, race, clothing, posture and activity, were taken into account.

4.6.7 Use of outdoor space

One of the first issues they investigated was whether thermal and, by implication, comfort conditions, affect people’s use of outdoor spaces. The simplest way to examine this was to calculate the number of people using the spaces at various intervals, during the interviewing period and find the mean values for each site. The presence of sunlight and warm conditions are important factors in the use of spaces.

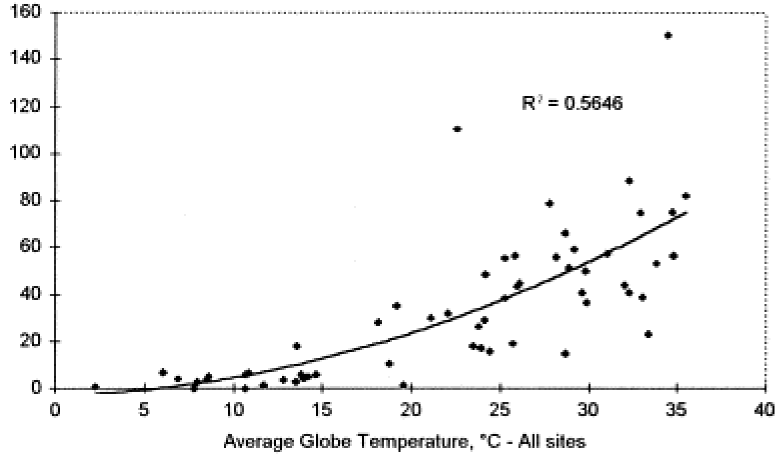

Figure 8: The average number of people increases as the global temperature increased. [26]

The curves of number of people using these urban spaces in the city of Cambridge as the globe temperature increased are given below.

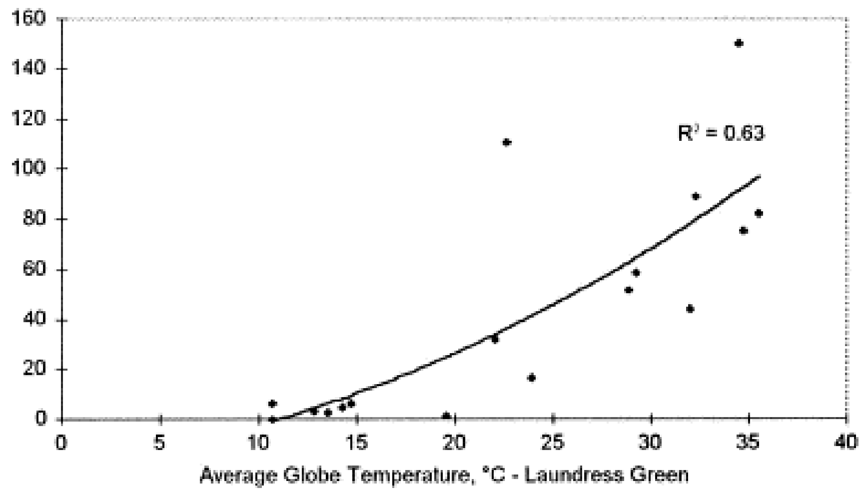

Figure 9: Variation of number of people outdoors, in relation to globe temperature for Laundress green, Cambridge. [26]

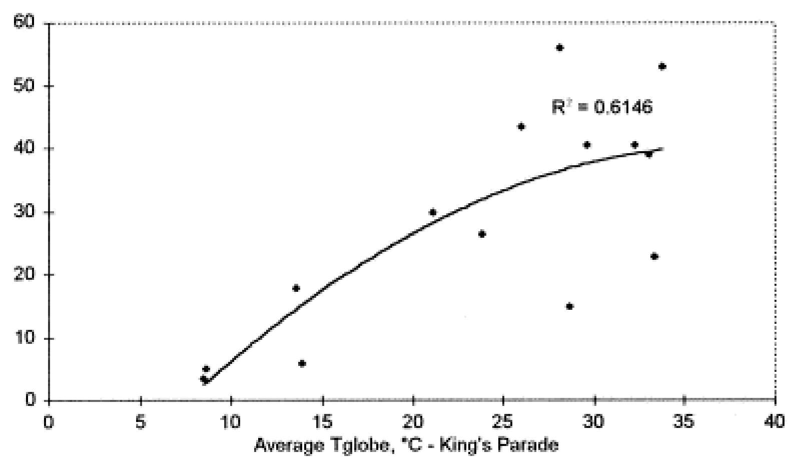

Figure 10: Variation of number of people outdoors, in relation to globe temperature for King's

Parade, Cambridge. [26]

The sites have a variety of spaces with sun and shade, where people have wide range of choices to sit, under different conditions. The situation at site of Kings Parade is different where the curve, stabilises after about 25 °C. The reason behind this fact is that there is no shading available and it remains in the sun in most part of the day. These open spaces are much appreciated during winter but cause problem in summer. So less people will use such spaces, and because there is a general lack of sitting places available in the city centre, people sit but for shorter periods than they do otherwise, e.g. for some rest, to finish off their lunch etc [26].

4.6.8 Thermal Sensation

The interviewees were reporting their thermal sensation and value judgment, on a 5 point scale, from too cold to too hot. The results calculated for Actual sensation vote for the whole year represents that highest frequency of number is for +1 for more than 50 % of the votes. These values remain same for summer and spring but for winter it changed to -1.

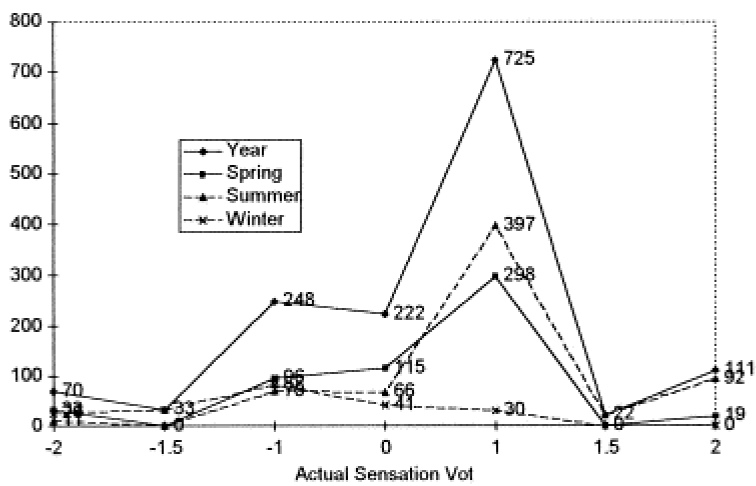

Figure 11: Frequency distribution for the actual sensation vote for the different seasons as well as combined for whole year. [26]

If we don’t take into account the number of people for each season were different, a comparison can be done for each season on equal base. The percentages are presented here to give the real situation of variation of actual sensation votes through out the year.

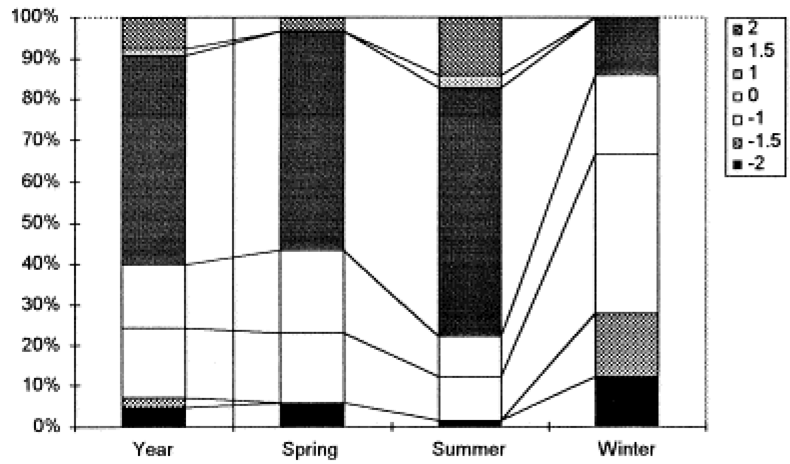

Figure 12: percentage frequency for the Actual Sensation Vote. [26]

The chart represents that the extreme ±2 have very few occurrence for the whole year but these values varies for different seasons. In the summer +2 is higher with 20%, whereas -2 in winters is 12%. It is understandable that there was no vote of +2 in winters because the air temperature is very low, but there was 2% vote -2 in summers. The reason for this may be due to very cold day in summer because of rain and people's perceptions. In spring where the environmental conditions are between summer and winter, the extreme conditions have very few fractions that is about 6% for -2 and 3% for +2.

The people reporting neutrality vote of "0" are very low but the frequency ranging from ±1 are from 10 to 20%. These frequency ranges represents that majority of people are comfortable feeling warm or cool, as opposed to neutral, enjoying the simulation thermal conditions outdoors.[26]

Further study demonstrates the fact that a maximum number of people found outside are in the summer, when the maximum number of thermal votes are falling in the +1 category, suggests that most people enjoy feeling warm. It could be deduced that in warmer climates the situation would be reversed and more people would be found out doors when temperatures would be lower than average and the majority of vote would fall on the cool side, e.g. in the evening when the sun has set.

A comparison between Actual Sensation Vote and theoretical Predicted Mean Vote was done by taking into account the objective and subjective data. This comparison further takes into account the objective environmental parameters recorded for the duration of interview, clothing levels and metabolic rate for each interviewee. The percentage frequency of actual sensation vote and predicted mean vote for all seasons has been showed in the following graph.

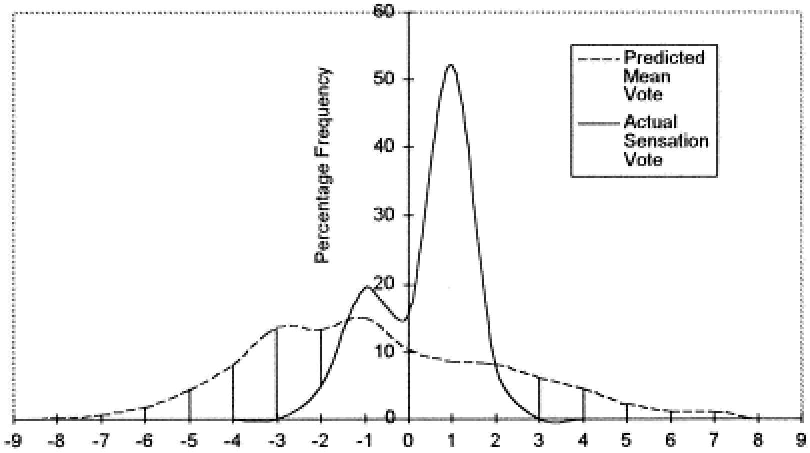

Figure 13: percentage frequency for Actual sensation Vote and Predicted Mean Vote. [26]

The comparison of the two curves shows that a great discrepancy exists between them. The people voted for the cool conditions are 20% and more than 50% for the warm out door environmental conditions for the period of interviewed. But on the other hand for extreme ±2, these values are 10%. The resultant PMV curve is very different and much flatter. The hatched areas representing the difference between the area underneath the PMV lying outside the Actual Sensation Vote (ASV) curve. According to the theoretical comfort conditions, only 35% of the interviewees are within the acceptable thermal conditions. The vast majority of people are present outside the comfort conditions either too hot or too cold because the PMV calculated for the conditions people have experienced lying from -9 to +7.

The predicted percentage dissatisfied of people varies from 56% in spring to 91% in winter, and the yearly average is 66%. This reveal that 944 people out of 1431 are sitting outside should be dissatisfied with their thermal environment. In fact the actual percentage of Dissatisfied (APD) is always around 10%, a figure that is regarded as acceptable, found even in controlled indoor environments.

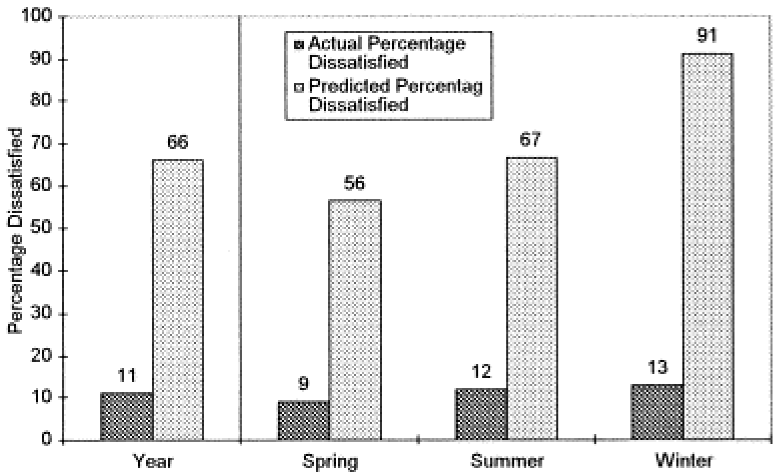

Figure 14: Comparison between Actual Percentage Dissatisfied and Predicted Percentage Dissatisfied. [26]

4.6.9 Comparisons between ASV and PMV

The subjective data collected for ASV during the surveys was then compared with thermal comfort index predicted mean vote (PMV). This index was originally developed for the indoor thermal comfort and cannot be employed for outdoors. PMV was calculated by considering the mean subjective environmental parameters during the surveys, clothing levels and metabolic rate of the interviewee. Comparing the PMV with ASV for each interviewee, great discrepancy was found between these two, as the actual thermal comfort appears to be found at high levels than implied by the mathematical models. [20]

4.6.10 Thermal Neutrality

The term thermal neutrality was first introduced by Humphreys [26] who showed that variation of the neutral temperature is associated with the variation of mean temperature. To calculate thermal neutrality relationship in out door spaces, an average neutral temperature was calculated for each interview day and plotted as a function of the mean meteorological outside temperature for the previous month. Thermal neutrality for outdoor conditions was found to vary from 7.5^{o}C in winter to 27^{o}C in summer; a range of 20^{o}C where as the range Humphreys had in the indoor environment was 13^{o}C.

Seasonal compensation of clothing and small changes to the net metabolic heating can partly justified the extra 7^{o}C by the consumption of cool or hot drinks. Humphreys suggested that the fact neutral temperature lies close to mean air temperature is an indication of influence of the subject's recent experience. His suggestion also apply to out doors conditions because with the memory of the recent conditions being indeed a very critical parameters on the satisfaction with the thermal environment.

Expectations have an important role in two ways. Firstly they may influence person's clothing choice which will affect their actual thermal sensation. Secondly, due to the physiological preparations, it may influence their interpretation of that sensation as dissatisfied. Thermal neutral temperature is always higher than the mean air temperature, showing that people would prefer it were warmer, although they may have partially compensated by clothing etc.

These findings justify the theory of McIntyre [26] that people voting for the neutral temperatures in warm climates prefer to be cool and people in cold climates prefer to be warm.

Following correlation is obtained when neutral temperature is plotted against current meteorological mean air temperature.

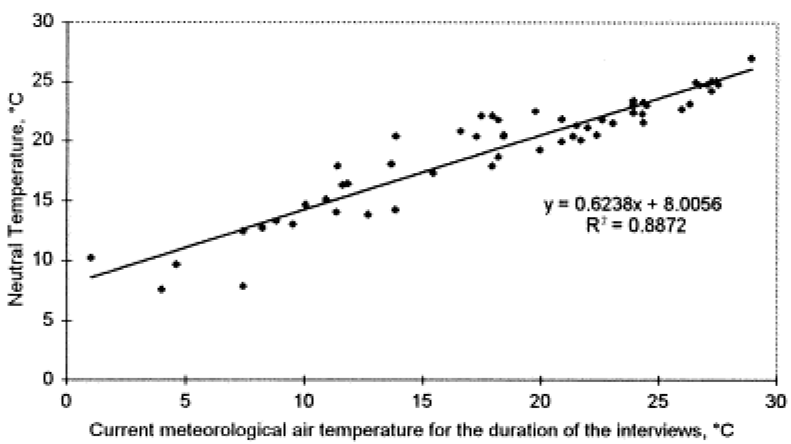

Figure 15: Neutral temperature as function of current meteorological mean air temperature for the duration of the interviews. [26]

This relationship does not represent that there is not memory effect, since there is strong correlation between the hot days and warm months. Current temperature influences the current dress state and other adaptive mechanisms available, e.g. position, posture and consumption of hot and cold drinks to alter the net metabolic heating. [26]

4.7 Thermal Sensation Comfort Model

Thermal comfort of persons staying outdoors is one of the factors influencing outdoors activities in streets, plazas, play grounds and urban parks, etc. The amount and intensity of such activities is affected by the level of the discomfort experienced by the inhabitants when they are exposed to the climatic conditions in these outdoors spaces. [26]

Thus, for example, on a hot summer day the thermal discomfort of the people staying outdoors exposed to the sun may discourage them from utilizing available urban parks, depending on the particular combination of the air temperature, humidity level, surface temperature of the surrounding areas and wind speed. The availability of shaded outdoor areas may result in greater utilization of the open space by the public. In a similar way, in a cold region, a given combination of wind speed and air temperature, or the obstruction of the sun in shaded areas, may discourage people staying outdoors while the provision of the sunny areas protected from the prevailing winds may encourage public activities in that outdoor space.

Thus minimizing outdoor discomfort may enhance the vitality of the location during periods of extreme temperatures (low in winter and/or high in summer).

By the design details of the outdoor spaces, we can modify the actual level of air temperature, solar radiation and wind in a particular location. The details may include one or most of the followings:

1 The provision of the shaded elements
2 Changes in the materials
3 Colours of the surrounding hard surfaces
4 Provision and details of the planted surfaces
5 Wind breaks or openness to wind etc

Thus, the exposure to, or protection from, solar radiation, the temperatures of the surrounding surfaces, and local wind speed, can be modified to a large extent by the choice of different design details. Even the local air temperature can be affected to some degree by the outdoor space design details. Thermal sensation (TS) was established by Givone & Noguchi [3] after experimental surveys in a park of Yokohama, Japan. The Futiji Corporation conducted research, monitoring the thermal sensation and overall comfort of subjects staying outdoors in Japan. The objective of this research was to determine the quantitative effect on the comfort of Japanese persons dressed according to the common practice in the different seasons.

4.7.1 Research Procedure

The research utilized a questionnaire surveys on the subjects sensory response and included physical measurements of outdoor climate data.

The subjects group consisted of six persons, males and females, ranging from the twenties to the fifties. They worked in a group of three pairs; each stayed for 20 minutes in one area and moved to other. This means that after one hour, a pair finishes staying in all the three areas that includes:

1. Exposed to the sun and undisturbed wind
2. Exposed to the sun but reduced wind
3. In shaded area but undisturbed wind

This procedure was repeated seven times in a day. Subjects were asked to sit in their chairs for 15 minutes and filled the questionnaire in the last 5 minutes.

The common clothing that was used in the Japan was selected for three seasons. The values of them are:

Spring and autumn: long sleeve shirt, jacket and trousers (CLO values = 1.1)

Summer: short sleeve T- shirt and trousers (CLO values = 0.65)

Winter**:** long sleeve shirt, knitted jumper, thick jacket and trousers (CLO values = 1.67)

Thermal sensation is the perception of heat or cold, on a scale of one (very cold) to seven (very hot).

The experiments were conducted under controlled solar insulation and wind speed in order to understand how these physical factors influence the thermal sensation and the comfort level of people staying in outdoors spaces. Three groups were made with different exposure conditions and at very small distances between them. The first group was sitting under a large shade tree (TREE), second in an open area exposed to sun (SUN) and third was also in open area exposed to sun but behind a wind break made by transparent polyethylene sheets supported on wood frames (WIND BREAK). The subjects were rotated between the three sites and were asked to fill the questionnaire at the end of each session of 20 minutes.

Due to very small distance between them, it was assumed that the air temperature and humidity were same at a given time. The only difference was the solar radiation and wind speed between the three groups. The measured environmental physical factors were following:

1 Air temperature in the shade (Ta, °C)
2 Horizontal solar radiation (SR, W/m^2)
3 Wind speed (WS, m/Sec)
4 Relative humidity (RH, %)
5 Surrounding ground surface temperature (ST, °C)

4.7.2 TS Model

A multi- factor regression formula for the thermal sensation was generated that depends on five variables:

$$TS = 1.7 + 0.1118T_a + 0.0019SR - 0.322WS - 0.0073RH + 0.0054ST$$

Equation 23: Thermal sensation (TS) out door comfort model

With an R^2 value of 0.8792

Thermal sensation was scaled from 1 (very cold) to 7 (very warm), as well as comfort sensation (very uncomfortable/very comfortable). The value 4 represents the neutrality.

In the formula, the negative sign of humidity showed that it causes the lowering of thermal sensation as it increases. In the study in Japan, the humidity was much lower and the temperature higher during sunny days of a given season than in cloudy days. The subjects feel warmer during the sunny days mainly because of the solar radiation. During the same days the humidity is lower.

The effects of solar radiation and wind speed can be related to the effect of air temperature by calculating the changes in these factors which will produce the same effect as that of a unit change in air temperature (1 °C). The experimental results of this study suggest that a change of 59 W/m^2 in solar radiation, and a change of 0.35 m/Sec in wind speed, had the similar effect to a change of 1 °C in air temperature.

Thermal comfort is related to the thermal sensation. However, one may feel uncomfortable either when it is too warm, or when it is too cold. As an alternative way to deal with thermal comfort beyond the sensation of the level of heat or cold, thermal could better be defined just as the absence of any sense of discomfort.[3,4]

4.8 Classification of Outdoor Thermal Comfort Models

Most research concerning thermal comfort focuses on indoor spaces. However, there are several relevant research studies concerning outdoor spaces, which emphasise the consideration of additional factors, as solar radiation, wind speed, different activities, and sweat rates, among others.

The steady state models like Fanger's comfort model are only appropriate for steady state indoor conditions but these steady state conditions are hardly reached outdoor where the length of outdoor stay is measured in minutes. Here we are concerned about thermal comfort conditions outdoor. We have to search for a model that can predict the outdoor thermal comfort conditions to a satisfactory level.

4.8.1 Predictive Models for Outdoor Thermal Comfort:

Houghton et al. [27], of ASHVE laboratories, proposed the effective temperature (ET), as determined by the dry and wet bulb temperature and wind speed. The Research of Glikman, Smith and Govani [3] showed that ET super estimate humidity. The reference environment started then to be considered with a relative humidity of 50 %

(ET*). The ET* is based on the heat balance model to predict thermal comfort as it was in the PMV by Fanger's model earlier. But this ET* evolves with time rather than being steady- state. The calculations of ET* can be done using 2-node model that determines the heat flow between the environment, skin and core body areas on a minute by minute basis.

The first persons to tackle this issue were "Gold" in 1930,s and "Siple and Passel" in the Antarctic in 1940,s, the creators of the wind chill index. In the absence of any related studies, forty years later "Penwarden (1973)" attempted a more systematic approach for thermal conditions outdoors, by the steady state model, a term for solar radiations.

Vernon & Warner (1932) proposed the corrected effective temperature (CET) substituting dry bulb temperature with globe temperature. This index was adopted by the ASHRAE in 1967, considering for the reference environment at a relative humidity of 50 %(CET*). Gagge (1967) presents new standard effective temperature (SET*) defining it as the air temperature, in a given reference environment, the person has the same skin temperature (tsk) and wetness (w) as in the real environment. So the reference and real environments are equivalent in physiological strain and thermal comfort. The reference environment is defined as: Mean radiant temperature (trm) = air temperature (ta); air speed (Va) = 0.15 m/Sec; relative humidity (ur) = 50%; metabolism (M) = 1.2 met;

clothes insulation (Iclo) = 0.9 clo. SET* is a comfort index that was developed based upon a dynamic two-node model (2NM) of the human temperature regulation. A transient energy balance states that the rate of heat storage is equal to the net heat gain minus the heat loss. In the 1980's a team of researchers at Berkeley (Bosselmann et al, 1984) worked on thermal comfort outdoors, particularly on implications of design solutions for the microclimate of San Francisco, which led to the legislation for solar access and wind protection. Again a mathematical model of the thermoregulatory system was employed for calculating the comfort conditions.

Hoppe [9] defines the physiological equivalent temperature (PET) of a given environment as the equivalent temperature to air temperature in which a reference environment, the thermal balance and the skin and core temperatures are the same, of that found in the given environment. The reference environment is defined as: mean radiant temperature (trm) = air temperature (ta); air speed (Va) = 0.1 m/Sec; vapour pressure (Pv) = 12 hPa (relative humidity (ur) = 50% at ta = 20°C); metabolism (M) = 114W; clothes resistances (Iclo) = 0.9 clo. [27]

4.9 Summary

"One of the more contentious theoretical issues in the applied research area of thermal comfort has been the dialectic between "adaptive" and "static" models. Apart from having disparate methodological bases (the former laboratory-experimental and the later field based), the two approaches have yielded starkly different prescriptions for how the indoor and outdoor climate of a building should be managed. These prescriptions carry implications for the types of permissible building designs, the means by which their thermal environments are controlled, the amounts of energy they consume in the production of habitable indoor and out door climates. Static models have led to indoor climate standards that have been universally applied across all buildings types, are characterised by minimal recognition of outdoor climate context, and are contributing to an increased reliance on mechanical cooling. In contrast, proponents of adaptive models have advocated variable indoor temperature standards that more fully exercise the adaptive capabilities of building occupants. This approach potentially leads to more response environmental control algorithms, enhanced levels of occupant thermal comfort, reduced energy consumption, and the encouragement of climatically responsive building design." [30]

Outdoor spaces present few constraints in calculating and evaluating the outdoor thermal comfort behaviour of occupants. This is due to the variability, temporal, spatial and great range of activities people engage in whilst in an outdoor environment as compared with indoor climate conditions. People sit there by their own free choice. They are there because they want to feel the warm sun rays, fresh air and look at people, while they are out for excitement and enjoying a sport event for example. Therefore, environmental simulation is important to design an open space with high level of thermal comfort and sensation. The degree to which they want to 'charge up' their body with heat and fresh air is important, especially when considered in combination with a person's thermal history. It means that whether they were working in an air conditioned office or in an open space. The affect of memory and expectations can not be denied as it also plays an important role in defining outdoor thermal comfort conditions, both in terms of physical and physiological adaptations. [26]

Purely physiological approach is inadequate in characterising thermal comfort conditions outdoor spaces. In the outdoor research carried out in the RUROS project, it has been justified that there is strong evidence of adaptation taking place, both physically and psychologically. As the indoor thermal comfort models cannot be applied indoor, people had done reasonable work to define the indicators that can be used to assess the outdoor thermal conditions. Those include the work done by Marialena [20] in the RUROS project. He introduced Actual Sensation Vote (ASV) to evaluate the thermal conditions outdoor. The main limitation of this indicator is that it cannot be used for a specific site as it takes the input data from a metrological station. The other indicator is Thermal Sensation (TS) introduced by Givone & Noguchi [3]. He had taken all the environmental parameters for a specific site to assess the thermal comfort conditions outdoor.

Therefore, Thermal sensation (TS) had been selected from a range of outdoor comfort indicators to assess the thermal comfort and sensation conditions for open spaces (sport stadium).

5 Case study research Methodology

5.1 Research Methodology

The research methodology that has been selected to tackle the problem of thermal comfort modelling of an open space like a sports stadium is done with the help of ESP-r (Building simulation tool). Modelling of the sport's stadium has been done in this package and information required for the calculation of outdoor thermal comfort indicator will be taken from its results.

The indicator being employed for the assessment of outdoor thermal comfort is Thermal Sensation (TS) because it can predict the out door thermal conditions very accurately. Information required for the calculation of TS will come from the sport's stadium modelling in ESP-r building simulation software.

The research methodology for the sports stadium comfort analysis consists of two parts;

First: Modelling of a section of the sport's stadium in the ESP-r package. A Simulation is then run for two different seasons of the year namely the typical summer week and typical winter week.

Second: The input parameters for the TS model found from ESP-r modelling are: air temperature, Surface temperature, Relative humidity. These parameters along with solar radiations and wind speed from the ESP-r climate file are imported in excel to calculate the values of Thermal Sensation (TS).

5.2 Purpose of Modelling

A model is a pattern, plan, representation, or description designed to show the structure and workings of an object, system, or concept. [29]

The purpose of this modelling exercise is to find the thermal comfort of spectators in the stadium, in the macroclimatic conditions of a typical UK environment. It is further required to assess the outdoor comfort conditions of occupants in the typical summer and winter week which can only be done by modelling the stadium in building design simulation tool (ESP-r) and find the thermal sensation (TS).

The main purpose of these simulations is to test the suitability of TS to predict thermal comfort in outdoor conditions.

5.3 ESP-r Building Simulation Software

The ESP-r building simulation software has been in constant development within the Energy Systems Research Unit (ESRU) since its first prototype was developed (Clarke 1979). It has evolved in the fully integrated solver – in the pursuit to better represent the interactions of physical processes occurring in the building. It integrates heat transfer processes, inter-zone airflow, intra-zone airflow, electrical power airflow, HVAC plant, moisture flows and natural lightings etc.

ESP-r's "project Manager" provides a central interface from which model creation, simulation and results analysis is controlled. The main components of the project manager are:

1 Database maintenance
2 Geometry construction and surface attribution
3 Pre- simulation tasks such as solar insulation prediction and view factor calculation
4 Heat, air , moisture flow domains
5 Control law generation and attribution
6 Simulation control and initiation
7 Visual results analysis

ESP-r's building thermal model is founded upon a finite – volume heat balance discretisation method. Construction components, surfaces and zones are represented by nodes, for which an energy balance is performed on each. Conduction, convection and radiation exchanges are described relative to other system nodes to generate a series of equations describing energy transfer over space and time. Solar insulation is included in these equations by way of a direct solar tracking processor, which is combined with diffuse distribution. This equations set is then solved simultaneously to provide the thermal state at each node and the energy exchange between them.

ESP-r also employs a partitioned solution approach such that a separate solver treats other solution domains (e.g. air network flow, CFD). Interactions between physical processes in different domains are accounted for by passing information between solvers on time- step basis; known as couple solution evolution. Furthermore this enables an optimised treatment of each domains equation sets which can be very sparse. The cooperative solver approach in ESP-r is thoroughly documented elsewhere (Clarke & Tang) as is ESP-r treatment of physical processes. The remainder of this section will focus on the main choices to be made concerning the sport's stadium thermal comfort modelling in ESP-r.

5.4 Reason to select ESP-r

The simulation software chosen had to be robust enough to handle the complex interaction of thermal comfort within a structure and at the same time accurate enough to correlate the results with reality. It has a capability to easily calculate the temperatures in the different zones as well as the walls of any building model with high degree of accuracy. This is what was required in order to evaluate the thermal comfort conditions of an open space (sport stadium). So it was found that ESP-r is a good option to use and find out the required results.

It has an option that can be used as a thermal comfort tool for such projects. One can easily calculate the required comfort indices (PMV, PPD) by giving the required activity level, air velocity and Clothing level (Clo). But in the context of this research work for outdoor thermal comfort, these comfort parameters are not of primary concern as we need information as input for the Thermal Sensation model (TS).

ESP-r r itself, as mentioned above, has proven to be accurate enough as found in a number of different studies. It has been tested by several organisations external to ESRU and has been found to agree with known analytical and monitoring data sets. ESP-r was participant model in international Energy Agency’s 1, 4 and 10 projects.

It has also been widely tested within the EC, s PASSYS projects. Moreover, it has been declared the European reference model for passive solar architectural designs.

There was lot of local support available for this building simulation tool, which was another solid reason to select it for this research project.

5.5 Types of files in ESP-r

To perform a simulation with ESP-r, following file types may be produced:

1 A mandatory geometry, construction and operational file for each zone

2 A mandatory system configuration file and an optional configuration control file

3 An optional air flow, casual gains, shading/insulation, view factors, surface convection and transparent multi-layered construction file for some or all zones
4 An optional fluid flow network description file, a pressure coefficients file
5 Fluid results and simulation results files

5.6 Energy flow paths and casual effects

Before commencing the development of a model, it is necessary to consider various heat and mass transfer mechanisms and the factors that give rise to them.

5.6.1 Transient conduction

It is the process by which a fluctuation of heat flux at one boundary of a solid material finds its way to another boundary, being diminished in magnitude and shifted in time due to the materials thermal inertia. This lies at the heart of building model. Within the building fabric, transient conduction is a function of the temperature and heat flux excitations at exposed surfaces, the possible generation of heat within the fabric, the temperature and moisture dependent hygro-thermal properties of the individual materials, and the relative positions of these materials.

5.6.2 Surface convection

This is the process by which heat flux is exchanged between a surface (opaque or transparent) and the adjacent air layer. In building modelling it is usual to differentiate between external and internal exposures. In the former case, convection is usually wind induced and considered as forced whereas, with internal surfaces, natural and /or force movement can occur depending on the location of mechanical equipment and the flow field to result.

5.6.3 Internal surface long wave radiation exchange

Surface heat transfer coefficients are treated as combinations of convection and long wave radiation. Inter-surface long wave radiation is a function of the prevailing temperatures, the surface emissivities, and the extent to which the surfaces are in visual contact, referred to as view factor, and the nature of the surface reflection (diffuse, specular or mixed). The flow path will tend to establish surface temperature equilibrium by cooling hot, and heating cold surfaces.

5.6.4 External surface long wave radiation exchange

The exchange of energy by long wave radiations between external (opaque and transparent) surfaces and the sky vault, surroundings and ground can result in a substantial lowering of surface temperatures, especially under clear sky conditions and at night. This can lead to sub-zero surface temperatures, especially with exposed roofs, and can become critical in cases of low insulation level. Conversely, the flow path can result in a net gain of energy, although under most conditions this will be negligible.

5.6.5 Short wave radiation

Some portion of the shortwave energy impinging on an external surface, arriving directly from the sun or diffusely after atmospheric scatter and terrain reflections, depending on subsequent temperature variations affecting transient conditions, finds its way through the fabric where it will contribute to the inside surface heat flux at some later time. It is not uneconomic for exposed surfaces to be as much as 15- 20°C above ambient temperature.

In case of completely transparent structures, the short wave energy impinging on the outermost surface is partially reflected and partially transmitted. Within the glazing layers and substrates of the systems many further reflections take place and some portion of the energy is absorbed within the material to raise its temperature.

Accurate solar irradiation modelling requires methods for the prediction of surface position relative to the solar beam, and the assessment of the moving pattern of insulation of internal and external surfaces.

The thermo-physical properties of interest include short wave absorptivity for opaque elements and absorptivity, transmissivity and reflectivity for transparent elements.

5.6.6 Shading and insulation

These factors control the magnitude and point of application of solar energy and so dictate the overall accuracy of any solar processing algorithm. It is usual to assume that façade shading caused by remote obstructions (such as buildings and trees) will reduce the magnitude of direct insulation, leaving the diffuse beam undiminished. Conversely, shading caused by façade obstructions (such as overhangs and windows recesses) should also be applied to the diffuse beam since the effective solid angle of the external scene, as subtended at the surface in question, is markedly reduced.

At any point in time the short wave radiation directly penetrating an exposed window will be associated with one or more internal surfaces, depending on the prevailing solar angle and the internal building geometry.

5.6.7 Air flow

Within a building there are three predominant air flow paths: infiltration, zone coupled flows and mechanical ventilation. These flow paths give rise to fluid - fluid heat exchanges.

Infiltration is the name given to the leakage of air from outside and can be considered as comprising two components: the unavoidable movement of air through distributed leakage paths such as small cracks around windows and doors and through the fabric itself; and the ingress of air through intentional openings (windows, vents etc) often referred to as natural ventilation.

Zone- coupled air flow is caused by pressure variations and by buoyancy forces resulting from the density differences associated with the temperatures of the coupled air volumes.

Mechanical ventilation is the deliberate supply of air to satisfy a fresh air requirement and, perhaps, heat or cool a space.

5.6.8 Casual gains

These are the gains by the heat effects of lighting installations, occupancy, small power requirement, and IT devices. It is important to process these heat sources in as realistic manner as possible. Typically, this will necessitate the separate processing of the heat (radiant and convective) and moisture emissions, and the provision of a mechanism to allow each casual source to change it values by prescription or via control action.

5.6.9 Heating, ventilating and air conditioning (HVAC) systems

The problem of predicting energy consumption has traditionally been divided into distinct stages:

The first stage is concerned with predicting the energy requirements to satisfy the demands of the building’s activities. This is found by modifying the various instantaneous heat gains and losses as a function of the distributed thermal capacities.

In the second stage, these energy requirements are modified by the operating characteristics of the plant to give the energy actually consumed.

The first stage is concerned with the design of the building to reduce the energy requirements, whilst the second stage is concerned with the design of the installed plant to best match these requirements and minimise consumption.

5.6.10 Control

To direct the path of a simulation, the combined building and plant model is subjected to control action. This involves the establishments of several control loops, each one comprising a sensor (to measure some simulation parameter or aggregate of parameters), actuator (to receive and act upon the controller output signal) and a regulation law (to relate the sensed condition to the actuated state). These control loops are used to regulate HVAC components and manage building side entities, such as solar control devices, in response to departures from desired environmental conditions.

5.6.11 Passive solar elements

Many designers have come to favour the use of the so- called passive solar features. These act to capture and process solar radiations passively and without recourse to mechanical systems. There is a range of possible passive solar elements but each of them imposes some technical complexity for modelling. [28]

6 Modelling of Sport Stadium

6.1 Why a football stadium is considered?

The current theme of this research project is to analyse the thermal comfort conditions for outdoor spaces. After a detailed discussion, a sport's stadium (football) was selected because it represents a useful case of an outdoor space. Moreover, sports stadia are mostly crowded by spectators during match event days and it was interesting to evaluate and predict the outdoor thermal conditions of spectators.

The level of occupancy can be estimated for such places depending upon their capacity which is required to consider the occupants causal gains with accuracy.

6.2 Modelling Approach

The modelling approach selected for this research regarding outdoor thermal comfort is based on the construction of a section of the stadium in the ESP-r geometry and construction option of project manager. The main objective of modelling this stadium in this package is to collect the information that is required to assess the outdoor thermal comfort with the Thermal sensation (TS) model.

ESP-r is a building simulation tool that demands that the building or any design under study to be fully en-closed. As the current study is regarding outdoor thermal comfort of an open stadium, the model has been adapted so that a face of the stadium that is facing west in the model is made of “fictitious” glass to allow solar radiation to pass through unimpeded. Other sides that are open to the environment are north and south faces which are also made fictitious transparent glass materials. In this way, it is now possible to proceed further with modelling in the ESP-r package.

6.3 Stadium Modelling

The stadium modelling has been started from a very simple wire frame model that gives the representation of a part of the stadium... The reason behind this choice was to make the research as simple as possible without losing track of the main objective. Keeping in view this requirement, a portion of 75 meters along the length of the stadium's stairs had been selected for this study.

6.3.1 Climate selection

For researching the sport's stadium's comfort, the UK default climate had been selected. The UK climate is very cold in winter and summer is quite reasonable for outdoor activities.

Summer and winter typical weeks have been selected for simulation because both have severe environmental conditions, hence can affect thermal comfort of spectators. If these extreme weeks are modelled properly then all the rest of year can be assessed on basis of the results. The details of environmental parameters are discussed in the following chapter.

6.3.2 Materials Selection

It's an important part in the modelling of stadium, as materials selection plays an important role in the final results. The selection of materials is based on the following properties that are normally considered.

1 Optical property (opaque/transparent)
2 Thermal conductivity
3 Absorptive properties
4 Emissive properties

After a detailed study about materials available for the construction of the stadiums, the following sections were selected.

The stadium west face is open to environment, (ESP-r requires a closed envelope), and so this face is made up of fictitious glass materials and is transparent. In a base case of the stadium, the roof is considered open to the environment, so it also needs to be made fictitious and transparent. In these conditions solar radiation will enter into the stadium without any obstruction. Along with the field side face, north and south faces are also open to the environment and made of same fictitious materials as that of the field face.

In the other case, the roof is considered to be made up of one layer of steel. This will alter the proportion of incident solar radiation entering the zone.

The seating section of the stadium is made of light aerated concrete that is opaque in optical properties. The layer thickness is 100 mm.

6.3.3 Boundary Conditions

These are exterior for most part of stadium that includes stairs and roof, but are "similar" for, south and north faces because the environmental conditions are similar on both sides of these fictitious walls. During winter simulation, the heating radiators under floor are added to the seating area.   So this surface will act as adiabatic where no heat is assumed to be lost to the outside environment through this wall.

6.4 Operation involved in Stadium

The operations that are required to define in the modelling of stadium as a mandatory file are of two types:

6.4.1 Air flow Scheduling:

The stadium is open to the environment and air can enter into it with out any obstruction and hindrance, so a large air flow rate of 10 ACH (air change per hour) has been given to zone under this study.

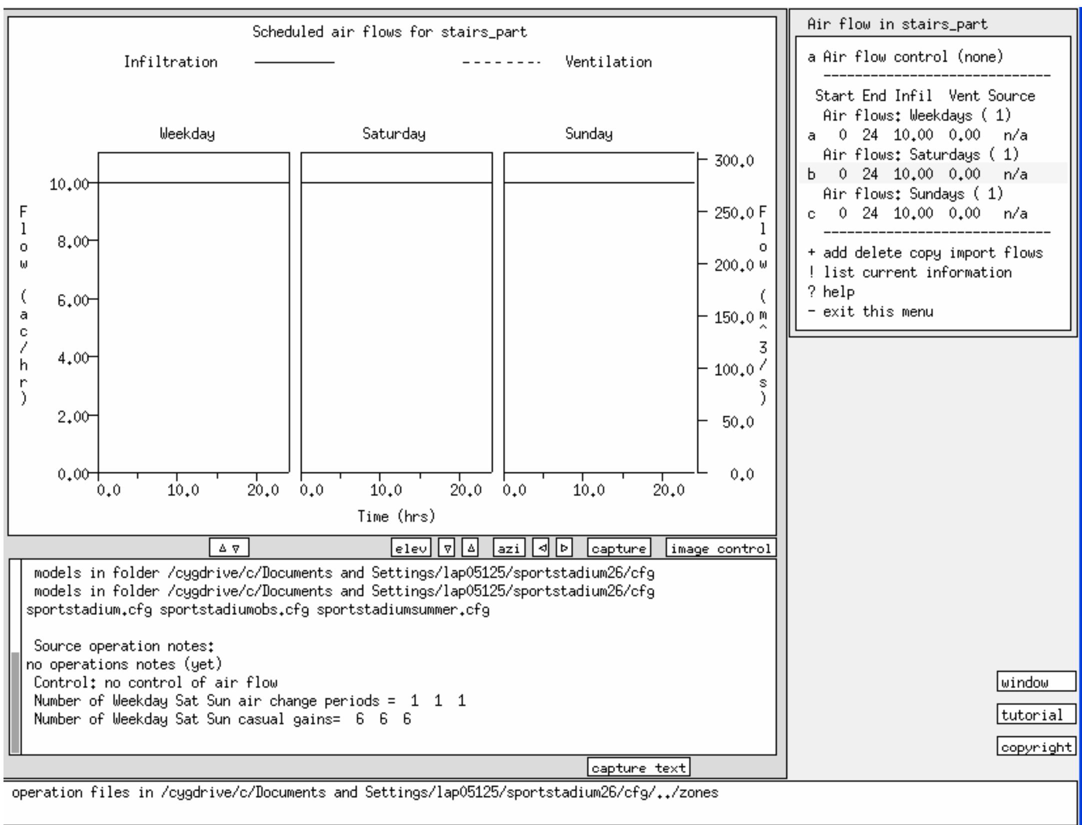

Figure 16: Air infiltration rate through out the simulation week

6.4.2 Casual Gains:

It includes all the sources of heat that can cause to increase the internal temperature of the zone. They are occupants, plant, lightings, and other possible sources. In this case due to high volume of space and openness to environment, lighting and plant will have not any pronounced affect on the internal causal gains. The only parameter considered in the causal gain is occupants. Two sources of heat are being calculated from occupants that are sensible heat and latent heat. The sensible part is taken as 95 W and latent 45 W for one person. The heat transfer from human body is in the form of radiant and convective modes. The radiant factor is 20% and that convective factor contributes to 80% to the total causal gains from occupants. The causal gains are defined according to the occupancy level in stadium at different time of day before and after the match.

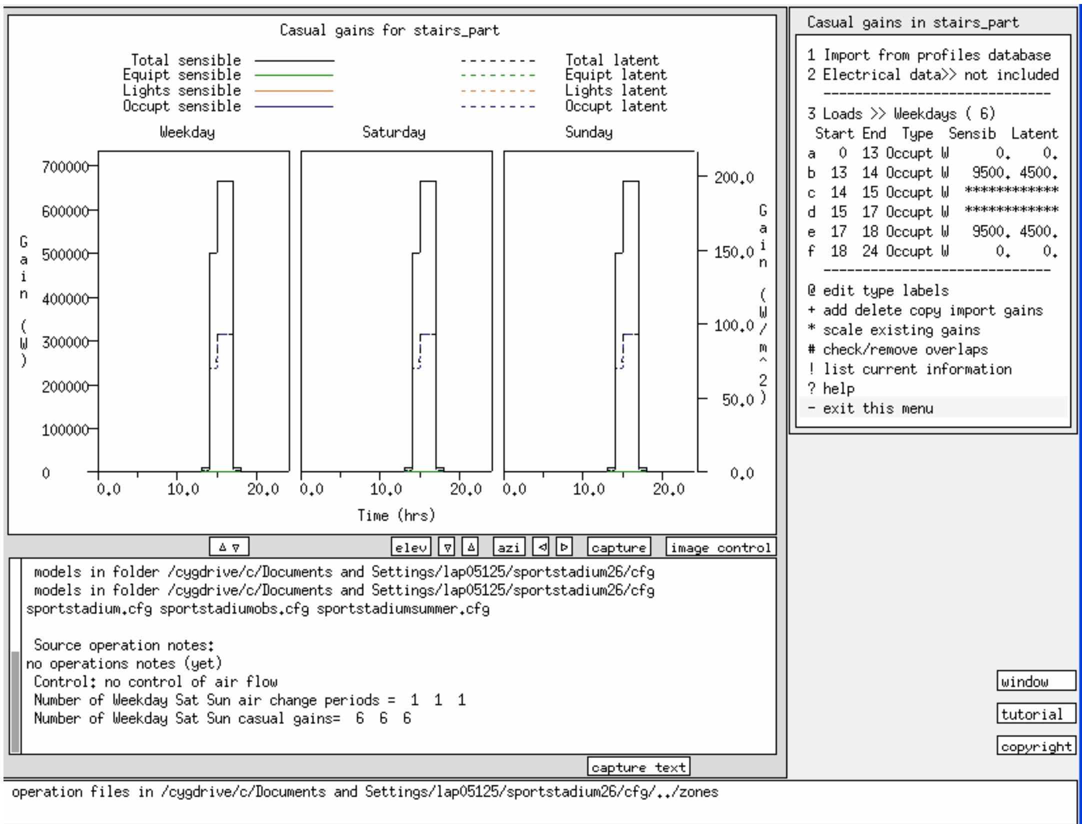

Figure 17: Casual gains distribution due to occupants in the stadium

6.5 Summer Simulation

The results of the summer simulation showed that thermal comfort conditions are poor in the stadium. The main reason for this uncomfortable condition was the solar radiation falling on the spectators. . Although the air temperature of the stadium was within the comfort range, excessive solar radiation destroyed the comfort conditions. The other pronounced affect of the solar radiations is in increased surface temperature. The direct solar along with surface temperature caused the spectator's discomfort.

6.5.1 Mechanism for Comfortable Summer Conditions:

The possible options to improve comfort are: reducing the air temperature, surface temperature and control that of solar radiation.

This option to cool the stadium by introducing cool air into zone is very unreasonable and unviable. The reasons are following:

1. Due to the high volume of stadium, the energy cost of introducing the cold air will be unaffordable.
2. Due to the high volume of conditioned air required, the plant installation and maintenance cost will be too much.
3. Due to the openness of the stadium to the environment, it is illogical to inject cold air because it will go into the open environment and will not have any profound effect on the air temperature.
4. Moreover, this will not cause a decrease in solar radiation and surface temperatures.

Keeping in view these constraints it is not possible to introduce the HVAC plant economically to gain the comfort conditions in the stadium.

The other option is to control the solar radiations to make the stadium comfortable. The solar radiation should be reduced to such a level that it could not make spectators uncomfortable.

The Introduction of shading can reduce excessive the solar radiation. This will also reduce the surface temperature of the area where spectators are being seated. To model this shading blocks are introduced in the model which block direct solar radiations.

6.6 Winter Simulation

Simulation results of the basic model for winter revealed that temperatures of air and surfaces are too low to make the stadium environment comfortable. Moreover, the solar radiation intensity is very low to cause any difference to surface and air temperature.

6.6.1 Mechanisms for comfort winter conditions:

There are two options available to make the stadium comfortable in winter.

Injection of hot air - this option is quite similar to that which has been discussed in the summer simulation. Due to the huge volume of space under study, it will not be economical to install a large enough plant to do this job efficiently.

The other important thing is the spectators are sitting close to a concrete surface; hot air injection will not increase this surface temperature to provide comfortable conditions for them.

Installation of radiant panels close to seating can be a best option in such conditions.

The radiation panels will cause to transfer heat at 95% radiant and 5% convective factor. These radiant panels can be heated through hot water or electrical depending upon the cost effectiveness.

7 Case study: Results and Discussion

The results of the sports stadium modelling and simulation are presented in this chapter. The geometric building model as described in chapter 6 for summer and winter cases will be used with appropriate modifications. The internal conditions and internal heat gains from occupancy will remain constant for all the options of both summer and winter cases, modelled as per the profiles in chapter 6. The air infiltration rate of 10 ACH (air change per hour) will also remain same for all cases. One of the most important assumptions made in the calculation of outdoor thermal Sensation by the TS indicator is that the outdoor air velocity that is being taken as constant throughout the analysis work is 0.1 m/Sec and is very similar to velocity values for indoor buildings.

7.1 Winter Results

The winter simulation has been carried out for a typical winter week (06 - 12 February). Two cases of simulations are undertaken: one is a base case without any heating options and other case is with radiant heating.

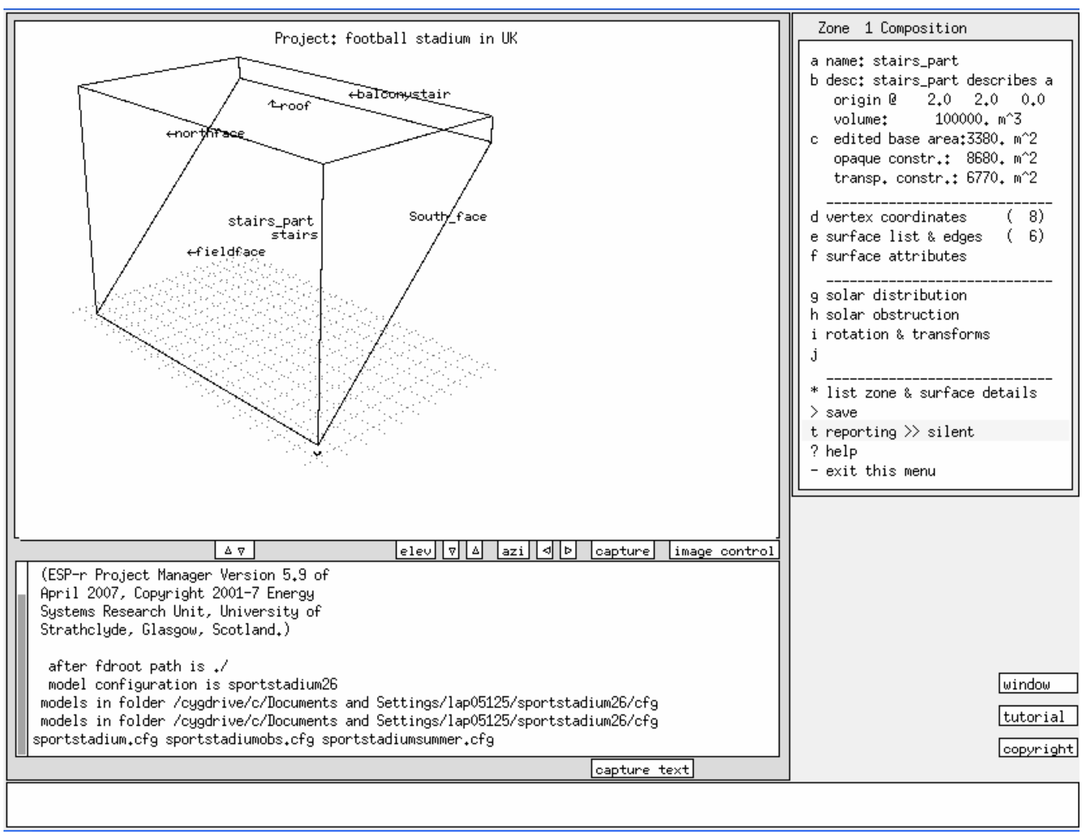

Figure 18: Sport stadium winter case model in ESP-r package

7.1.1 Winter Base Case

A simple sports stadium without a heating option and shading has been modelled to represent the winter base case. The stadium roof as in the other options is made of opaque steel, not open to environment. Three other faces of stadium part are the south face; north face and west face are made of fictitious glass materials. The west face is open to the environment. Typical winter week climatic results are following:

	Air Temp(^{o}C)	Direct Solar Radiation (W/m^2)	Diffuse Solar Radiation (W/m^2)	Relative Humidity(RH)
06-Feb	6.3	0	33.8	84.2
07-Feb	5.7	0	45.2	78.6
08-Feb	5.6	107.4	47.8	56.4
09-Feb	4.2	0	32.6	64.2
10-Feb	4.6	0	33.2	75
11-Feb	5.1	0	34.4	76.6
12-Feb	3.9	300.6	44.4	62
Mean	**5.1**	**58.3**	**38.8**	**71**

Table: 4 Typical Winter week environmental parameters

Simulation results of typical winter week without the heating option are given in the Following graph:

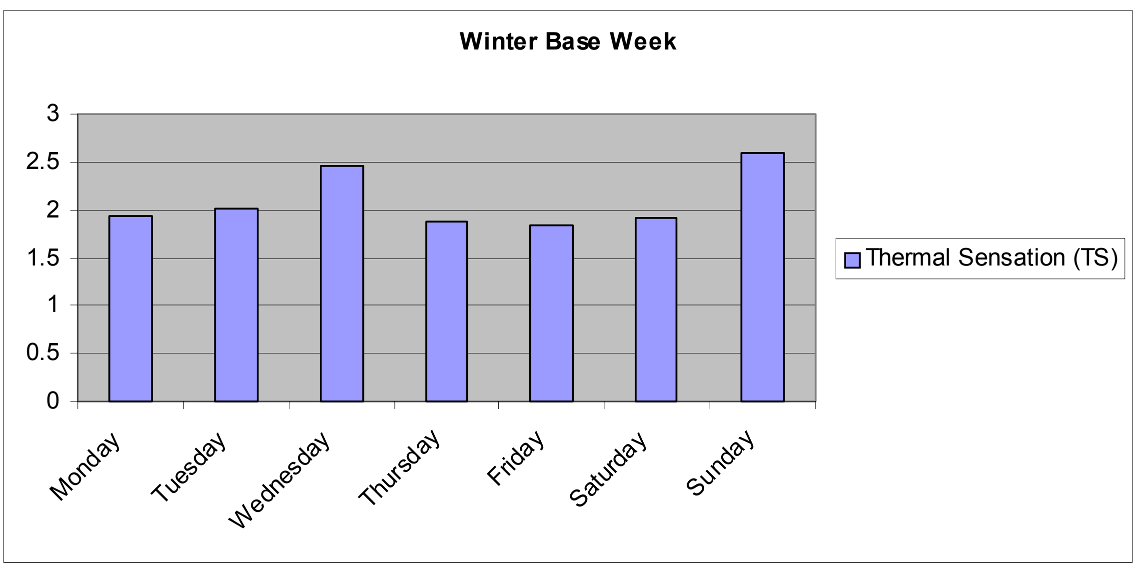

Figure 19: Winter base case simulation results

From this graph, it is evident that the mean values of Thermal Sensation for a typical winter week are near to "2" which means that outdoor thermal conditions are very cold.

The thermal neutral conditions according to Thermal Sensation (TS) indicator are at value of "4". If its value decreases from neutral, the thermal conditions will be shifted towards cold and if it increases greater than neutral, then the outdoor thermal conditions will be shifted towards the warmer side.

The winter week environmental results indicate that mean air temperature is 5.1^{o}C. As the stadium is very big and mostly open to the outside environment, the causal gains of occupants (spectators) have not increased the air temperature to a great extent. So the rise of temperature due to these gains is only near to 1^{o}C .The main environmental parameter that has the most profound affect on the outdoor thermal sensation is the air temperature along with seating surface temperature. As air temperature is very low in winter days, outdoor thermal sensation is uncomfortable.

Close observation of the simulation results indicate that out of the whole week, only Wednesday and Sunday touched the value of "2.5" TS. The seating area surface temperature is affected by the direct incident solar radiations. This temperature is increased as solar radiation increases on Wednesday and Sunday.

	Air Temp(^{o}C)	**Solar Radiation(W/m^{2})**	**Relative Humidity (%)**	**Surface Temperature(^{o}C)**	**Thermal Sensation(TS)**
Monday	6.93	43.2	83.43	5.55	1.94
Tuesday	6.99	54.9	78.76	7.76	2.02
Wednesday	6.99	198.2	56.69	10.68	2.46
Thursday	5.09	42.6	63.4	5.58	1.88
Friday	5.48	43.2	74.54	5.59	1.84
Saturday	6.15	44.8	76.82	7.04	1.91
Sunday	5.4	386	60.45	8.33	2.60

Table: 5 winter base case simulation results

The relative humidity in the range of 40 – 80 % does not have a profound effect on the thermal condition but it contributes to decrease the outdoor thermal comfort when it is too low (dry) or too high (humid). But in the calculations of TS, this contributes always to decrease the thermal comfort independent of its values.

The contribution of air velocity towards Thermal Sensation (TS) is negative and it also caused to decrease the outdoor thermal comfort. In winter, wind decreased more outdoor thermal comfort as compared to summer. Due to very low temperature in winter, high wind will cause the thermal comfort to decrease the inside air temperature of the stadium.

The affects of air velocity have been observed on Wednesday and Sunday in the above discussion.

The results of the winter week simulation reveal that the outdoor thermal conditions are uncomfortable.

7.1.2 Winter Heating Case

The results of the winter base case reveal the stadium is uncomfortable in a typical winter week of simulation. Some actions are available that can be performed to make the stadium comfortable.

Installation of radiant panels is a smart approach but again it can only provide comfortable conditions up to some extent. The radiant panels are installed within the seating surface.

A temperature sensor is installed to detect the db temperature of the stadium zone. A controller is introduced to control the heating power from 10 - 17 hours of each day for the simulation winter week. The heating power plant is adjusted at 300kW and 500kW throughout this control to provide heating to radiant panels. The radiant factor of heat transfer is adjusted at 5% convective and rest of 95% is radiant. Providing radiant heat will provide a major fraction of heat to people sitting in the stadium and will increase their thermal comfort in winter. Simulation results after heating panels are introduced in the stadium stairs are given in the following graph.

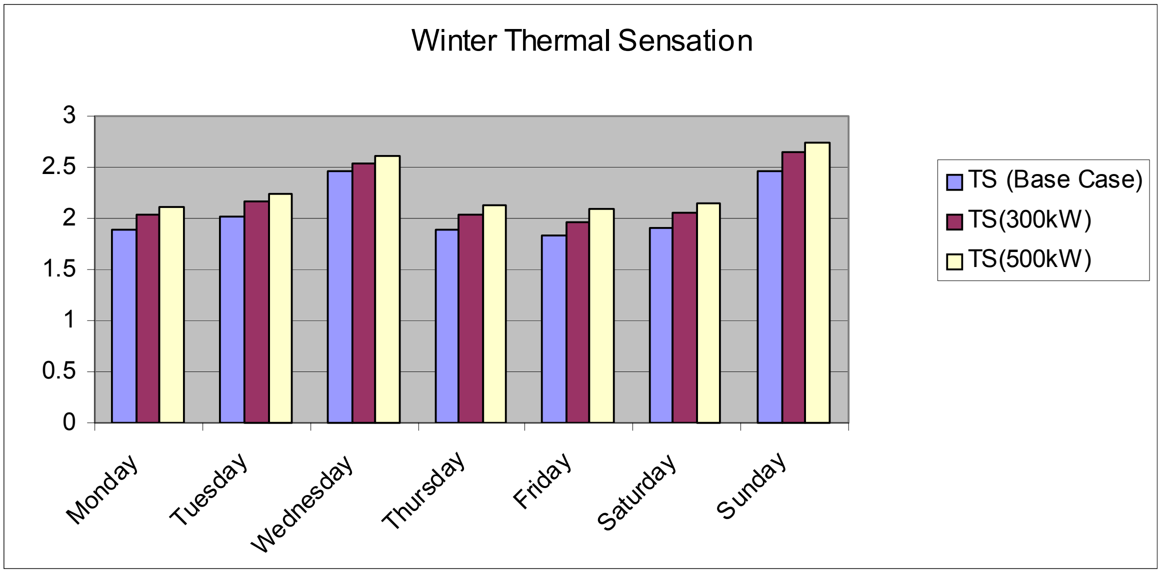

Figure 20: Winter simulation results with installation of heating panels

The introduction of radiant panels with plant working capacity of 300kW and 500kW caused an increase of only a couple of degrees in the air temperature of the stadium. The reason behind this small increment in air temperature is the openness of the stadium to the outdoor environment. The other reason is that the heating increases seating area surface temperature but its effect on the air temperature is very minor. Due to increase in the air temperature, relative humidity level has been dropped which can be noticed form the results table in the appendices.

Air temperature has a major effect on the thermal sensation (TS) but as it has increased only a couple of degrees in this case, that's why TS values are increased only in fractions. According to TS indicator, outdoor thermal conditions are still very cold. The contribution of seating areas surface temperature to raise TS values is present but less than air temperature.

Heating panels in the seating area will provide enough temperature that can keep spectators thermally comfortable. Heat from heating panels will transfer to spectators in the form of radiation but its intensity will be high closer to the seating areas. As distance from seating will increase, the drop in radiation intensity will increase. In this case of heating the seating of a stadium, although the TS values have not increased much, it can still provide reasonable thermal comfort conditions to spectators. These arguments can be justified because radiation intensity nearer to the seating area will be higher than at the middle of stadium.

The radiant heating option of the seating can increase the temperature to a level where it can provide thermal comfort conditions to spectators.

The increase of the stairs surface temperature can be observed in the following graph:

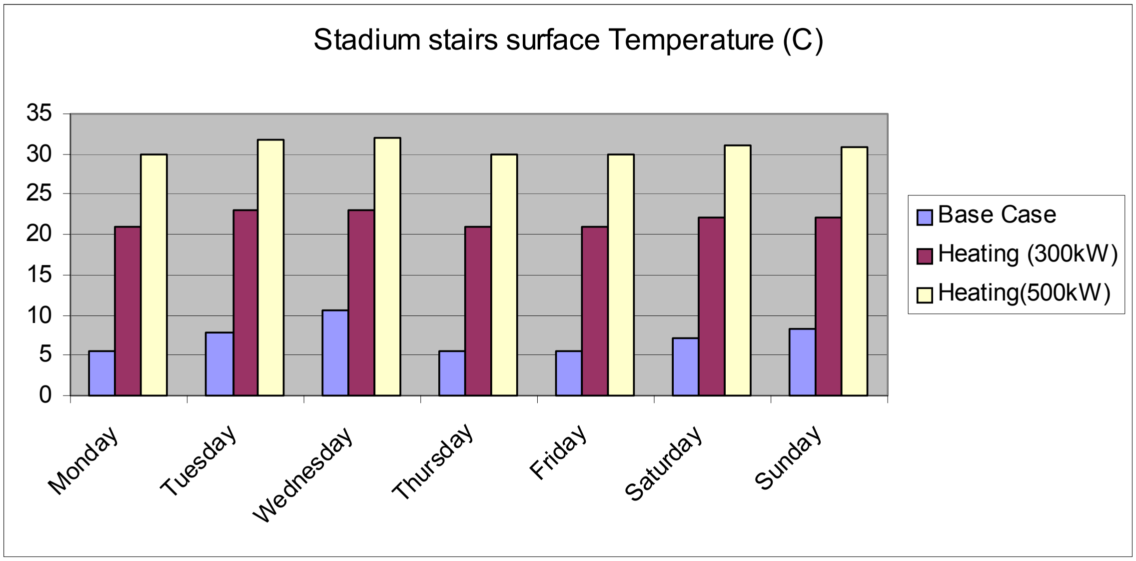

Figure 21: Comparison of Seating surface temperature with installing radiant panels with two different heating capacity heating plant.

It is clear from the above graph that the surface temperature of the seating has been increased to a sufficient degree by introducing radiant panels. The average temperature in the base case was 5^{o}C but it has increased to 23^{o}C (300kW) and 32^{o}C (500kW) during the both heating options during winter.

7.1.3 Heating Cost of Stadium Stairs:

Two heating options are being analysed to make the seating comfortable for spectators. The plant is being operated at heating capacity of 300 kW and 500 kW which has increased the seating temperature to a reasonable degree where spectators will feel comfortable outdoor. If the cost of energy from a power supplier is taken 6p/kWh, approximated cost for the heating of stadium using panels will be £1512/day and £2520/day for the above heating options. So heating the stadium stairs through radiant panels will be an excellent idea along with reasonable heating cost.

To increase the air temperature of stadium, a huge amount of power will be required which will not be feasible economically.

7.2 Summer Results

Summer simulation has been carried out for a typical summer week (3 – 9 July) of the test year. Most of the models parameter will remain same as were in the winter cases. Those include the air infiltration rate, causal gain because of spectators, geometry, construction materials etc. Two cases have been considered in this section. One is base case and other with some modifications in the stadium model to achieve the optimum thermal conditions outdoor. The environmental conditions for a typical summer week are given in the table below:

		Air Temp(^{o}C)	**Direct Solar Radiation(W/m^2)**	**Diffuse Solar Radiation(W/m^2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**
03-Jul	Monday	16.7	375.8	135.4	5.7	45.2
04-Jul	Tuesday	17.2	247	140	4.8	58.4
05-Jul	Wednesday	18.8	229.6	149.6	2.1	55
06-Jul	Thursday	20.2	298.6	134.4	1.9	51.2
07-Jul	Friday	24.4	435.8	133.2	5.9	43.4
08-Jul	Saturday	18.1	415.8	133.6	7.2	45.2
09-Jul	Sunday	20.3	424.2	134	2.6	43.8

Table: 6 summer week environmental conditions.

7.2.1 Summer Base Case:

The same sport stadium model is being used in the base case of the summer simulation as was used in the winter cases. The numbers of spectators remains the same in both the simulation cases of winter and summer. So the part of casual gains due to spectators will be the same in summer. The simulation results of summer base case are following:

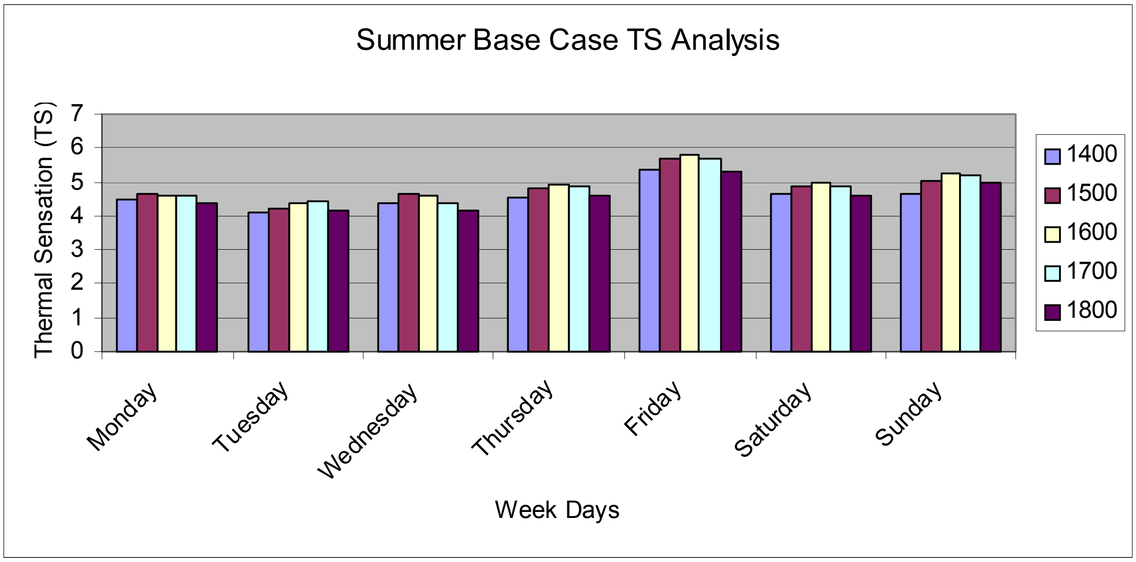

Figure 22: Simulation results of summer base week

	Air Temp(°C)	Solar Radiation (W/m²)	Relative Humidity (%)	Surface Temperature(°C)	Thermal Sensation(TS)
Monday	18.26	558.5	43.56	29.37	4.61
Tuesday	18.36	431.6	54.54	27.4	4.29
Wednesday	20.04	426.4	51.31	28.5	4.49
Thursday	21.65	466	49.11	30.74	4.78
Friday	25.93	569	41.22	35.11	5.53
Saturday	19.46	549.8	43.33	28.01	4.72
Sunday	21.44	558.2	41.59	32.85	4.99

Table: 7 summer base case simulation results

The results of the summer base case showed that air temperature of the stadium is increased by approximately 2°C by the causal gains of spectators. The amount of solar radiation striking the seating is almost same as coming from outside because there is no solar obstruction in this case. The incident direct solar radiation has increases the surface temperature of the seating area to more than 30°C. The calculations of the Thermal Sensation (TS) are between 4.5 and 5.0 which indicate the outdoor thermal conditions are in the range of slightly warm to very warm. TS values on Tuesday are quite near to neutral which mean thermal conditions are very much more suitable for spectators on this day. On the other hand, TS values on Friday are little bit more severe because of high solar radiation which causes the outdoor temperature to increase more than 25°C. As TS is more dependent on air temperature and solar radiation, its values have jumped up more than 5.5 TS. These represent the very warm outdoor thermal conditions.

The summer base case reveals that the outdoor thermal conditions are not entirely comfortable. It varies from slightly warm to very warm through out the simulation week. Some kind of modification in the model is required to get near perfect outdoor thermal conditions.

7.2.2 Shading of stadium:

The summer base case simulation results strengthen the idea of introducing solar shading into the stadium model. The various kinds of solar obstructions were discussed in the last chapter. The more efficient solar obstruction in this case is to introduce shading blocks representing horizontal overhangs which will reduce the incident solar radiation on the spectators. The shading is introduced by extending the roof, providing shading to the stairs most of day. The shaded model of sport stadium is given in the following figure:

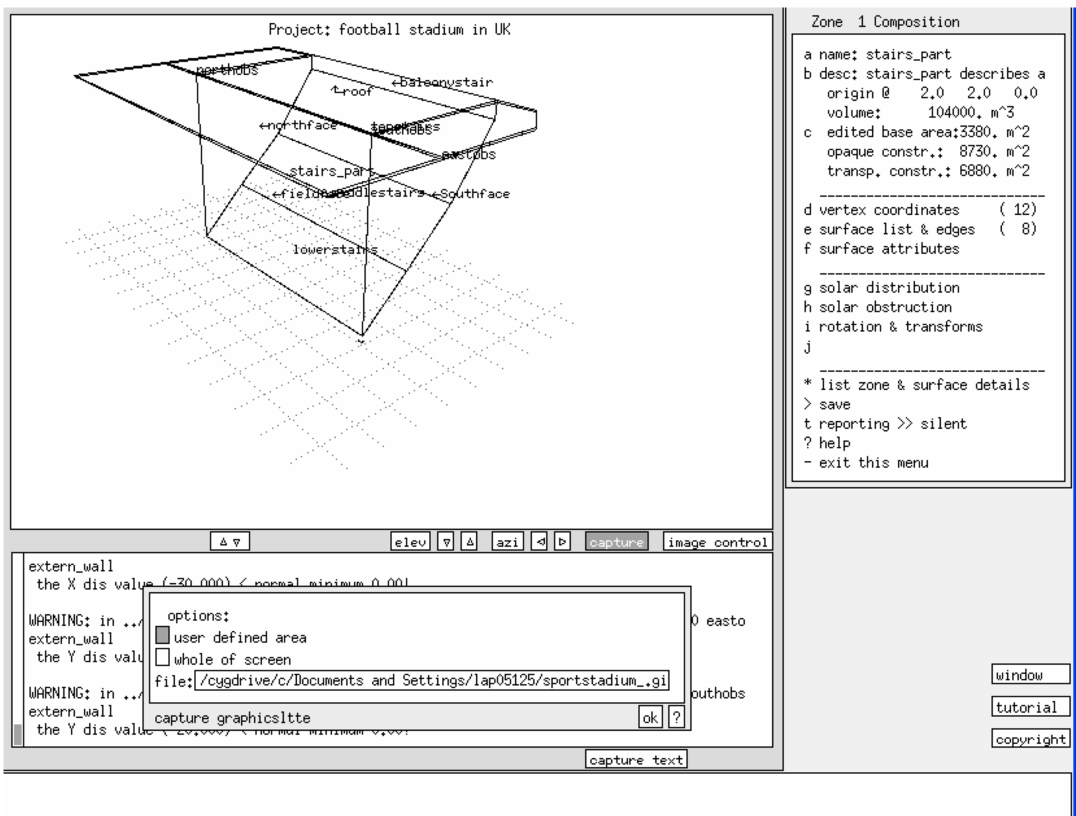

Figure 23: Shaded Model of sport stadium for summer in ESP-r package

Simulation results of the shaded sport stadium are giving the following table.

	Air Temp(^{o}C)	Solar Radiation(W/m^{2})	Relative (%)	Humidity	Surface Temperature(C)	Thermal Sensation(TS)
Monday	18.26	380	43.53		29.23	4.27
Tuesday	18.37	298.25	54.48		27.3	4.03
Wednesday	20.01	289.95	51.25		28.6	4.23
Thursday	21.6	316.88	49.08		30.6	4.49
Friday	25.94	386.92	41.17		34.94	5.19
Saturday	19.46	373.86	43.33		28.01	4.38
Sunday	21.45	379.58	41.57		32.49	4.65

Table: 8 Simulation results of shaded model for summer

It is clear from the results of the shaded sport stadium that only solar radiations are reduced at a reasonable extent but air temperature and stairs surface temperature have dropped approximately by 1^{o}C. Outdoor thermal comfort conditions are affected by solar radiation. Shading has decreased the surface temperature of the stairs only a fraction of 1^{o}C. Due to reduction in incident solar radiations, Thermal Sensation (TS) has dropped to reasonable values. Friday results indicate that it has been decreased from 5.5 to 5.1TS, which gives the affect of shading on TS. In a similar way TS values has decreased throughout the week which has made the stadium quite comfortable. As the values of TS will come closer to '4' outdoor conditions will become more comfortable.

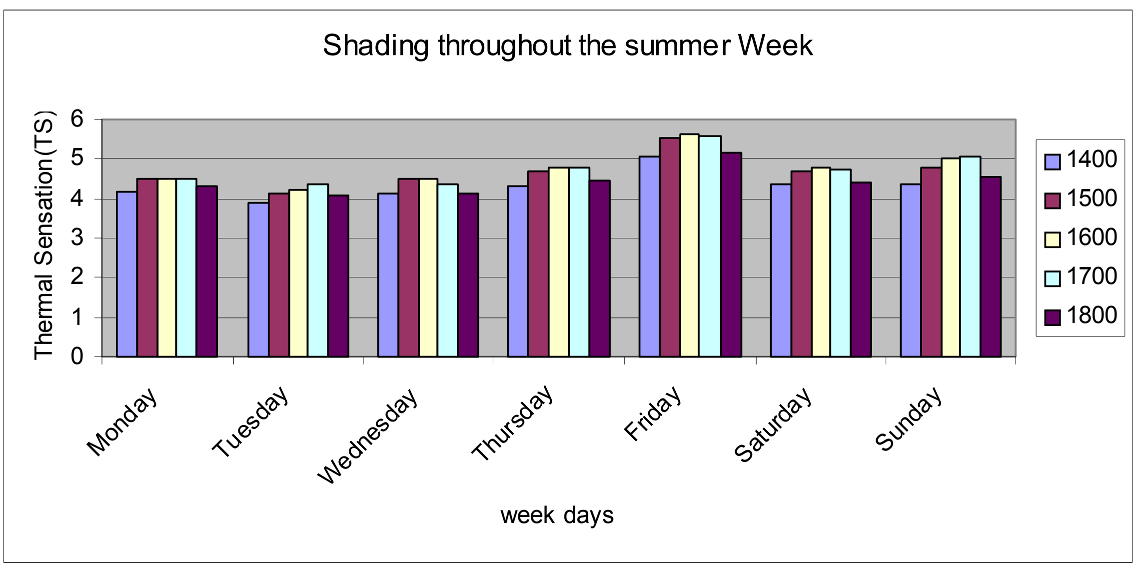

Figure 24: Impact of shading on the thermal sensation at different hours of each day in summer week.

According to Potter and De Dear [9] "*holiday makers deliberately seek outdoor thermal* *environments that would rate off the scale, if they were encountered indoors".*

Moreover the mean neutral temperature for outdoor spaces is 27°C instead of 24.1°C, which was estimated for indoors by Fanger. This higher of outdoor neutral temperature is also supported by Marialena [26]. He justified the neutral temperature for out door spaces are near to 27°C.

Keeping in view both theories, outdoor thermal conditions of a sport's stadium are very near to comfortable ones. Shading has provided sufficient reduction in solar radiation that has created nearly comfort conditions outdoor.

7.2.3 Shading Affect on the Seating Area:

Shading affect on thermal sensation of spectators sitting on stairs has been analysed in the above discussion. In the above case, seating area have been considered as one face but realistically shading devices will provide various levels of shading to different parts of seating at different hours of the day as the sun moves across the sky. To get a clear picture of shading affect on the thermal sensation of spectators, the seating area has been divided into three parts so that the shading effect can be analysed very closely.

To assess thermal sensation on three partitions of stadium seating area, shaded and un-shaded areas are calculated from the model at different hours of the day. To calculate this, sun path has been analysed from 1400 – 1800 hours of Monday. It has been found that at 1400 hours, obstructions had provided shading to all three parts of seating area. At 1500 hours of day, the lower seating area was uncovered by shading. On 1600 hours, complete lower and 10% of middle seating area were uncovered but rest of them were completely shaded by the solar obstructions. Again the sun changes its path through out the day, at 1700 hours the lower and 90% of middle seating area remains un-shaded but 10% of middle seating area and top seating area remain shaded. But at 1800 hours of the day, sun takes such a position where only top part of seating area will remain shaded but lower and middle will be un-shaded completely from solar obstruction.

Sun path has a notable effect on the thermal sensation of spectators because intensity of solar radiations as well as the shading areas will be changed with the passage of day. The solar radiation will fall directly on the un-shaded areas of seating area, which will increase thermal sensation and spectators will feel warmer as compared with the shaded areas. To analyse the hourly variation of thermal sensation, Monday of the simulation period has been selected. The situation will be similar in rest of the simulation days. The results of Monday are given below:

Hours	Seating area part	Air Temp(^{o}C)	Solar Radiation(W/m^{2})	Relative Humidity (%)	Surface Temperature(^{o}C)	Thermal Sensation(TS)
1400	Lower Seating area	17.09	435.09	47.03	25.38	4.19
	Middle Seating area	17.09	427.66	47.03	25.40	4.18
	Top Seating area	17.09	408.65	47.03	24.87	4.14
1500	Lower Seating area	17.86	710.81	46.06	28.16	4.83
	Middle Seating area	17.86	455.6	46.06	28.13	4.34
	Top Seating area	17.86	446.67	46.06	27.82	4.32
1600	Lower Seating area	18.36	646.06	45.96	30.11	4.77
	Middle Seating area	18.36	417.76	45.96	30.63	4.34
	Top Seating area	18.36	414.47	45.96	29.95	4.33
1700	Lower Seating area	18.9	514.24	43.14	30.69	4.60
	Middle Seating area	18.9	511.82	43.14	30.68	4.60
	Top Seating area	18.9	335.24	43.14	30.72	4.26
1800	Lower Seating area	18.47	414.05	40.01	29.61	4.38
	Middle Seating area	18.47	411.05	40.01	29.60	4.38
	Top Seating area	18.47	273.71	40.01	29.74	4.12

Table: 9 Monday analysis of Thermal Sensation (TS)

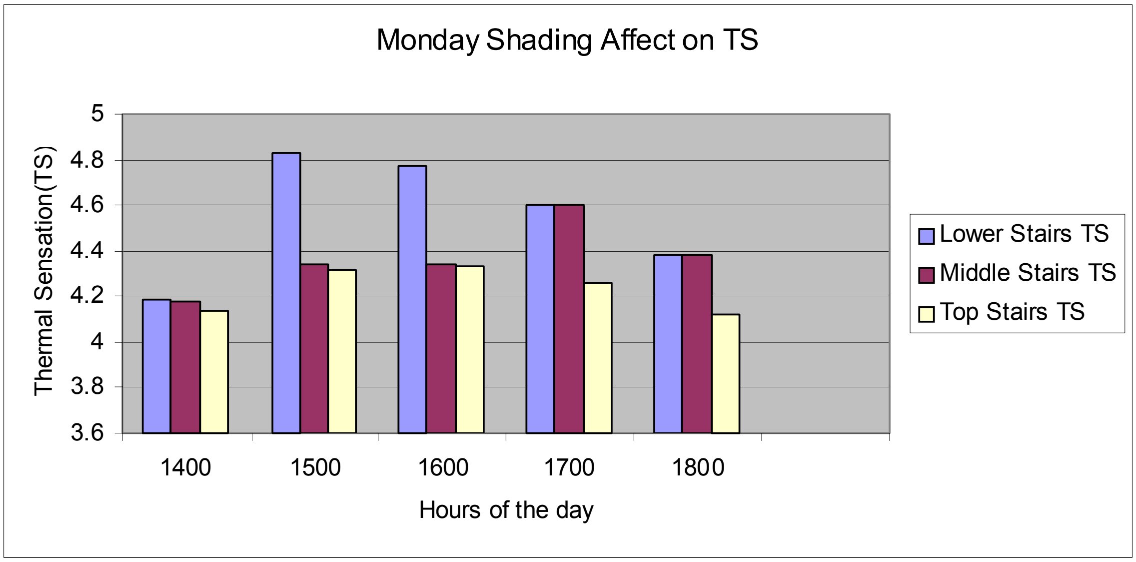

Figure 25: Thermal Sensation on different parts of seating area throughout the simulation hours on Monday.

In the analysis of seating area partition thermal sensation, it has been assumed that wind speed will remain the same throughout the five hours of simulation. Only the solar radiation and seating area surface temperature will be affected with solar path. Due to solar movement, air temperature and relative humidity will also be affected. It is clear from the above table that the intensity of solar radiation on the un-shaded areas has increased thermal sensation (TS), which means those areas are warmer than shaded ones. At 1400 hours of the day, obstructions have provided shading completely to all parts of seating area, so only 435.09 W/m^2 solar radiations has been absorbed on the seating area out of 795.5 W/m^2. Due to shading on the seating area at this time of the day, spectators will feel quite similar thermal conditions on all the three parts of seating area of stadium. Thermal comfort conditions will be near to neutral but much less than those of the base case.

With the passage of day, the intensity of solar radiations will decrease which is given in the above results table. There is also a slight difference in the temperatures of three parts of the seating area due to amount of solar radiations falling on them. Although surface temperature does not contribute too much to thermal sensation calculations, it can however affect the thermal comfort of spectators.

At 1500 hours of day, the lower part of the seating area is un-shaded and solar radiation can strike it with full intensity (710.81 W/m^2). But other parts (middle and top) of seating area are shaded, so intensity of solar radiations on them will be 446.4 W/m^2. On the other hand at 1800 hours, the lower and middle are un-shaded but top seating area are still covered by the shading obstruction. Here solar intensity has been decreased and solar radiation falling on lower and middle seating area is 414.05 W/m^2 but on top seating area these will be 273.71 W/m^2. At this time of the day, spectators will feel very comfortable or slightly cool because of lower solar radiations and lower air temperature. All other days of summer simulation week will behave in a similar way for the assessment of thermal sensation.

The above graph of thermal sensation on Monday summer day gives the brief effect of shading on thermal sensation. The variation of thermal sensation on three parts of the stadium seating area can be observed in the above figure. Shaded areas (top and middle seating area) have lower thermal sensation than un-shaded areas though out the simulation hours of the day.

7.2.4 Shading affect on incident Solar Radiations:

Shading has decreased the incident direct solar radiation hence the values of thermal sensation (TS) have been decreased. Reduction of these the solar radiation has been calculated for each day of the summer typical week at 1400hrs of every day. The comparison of base and shading cases solar radiations have been given below:

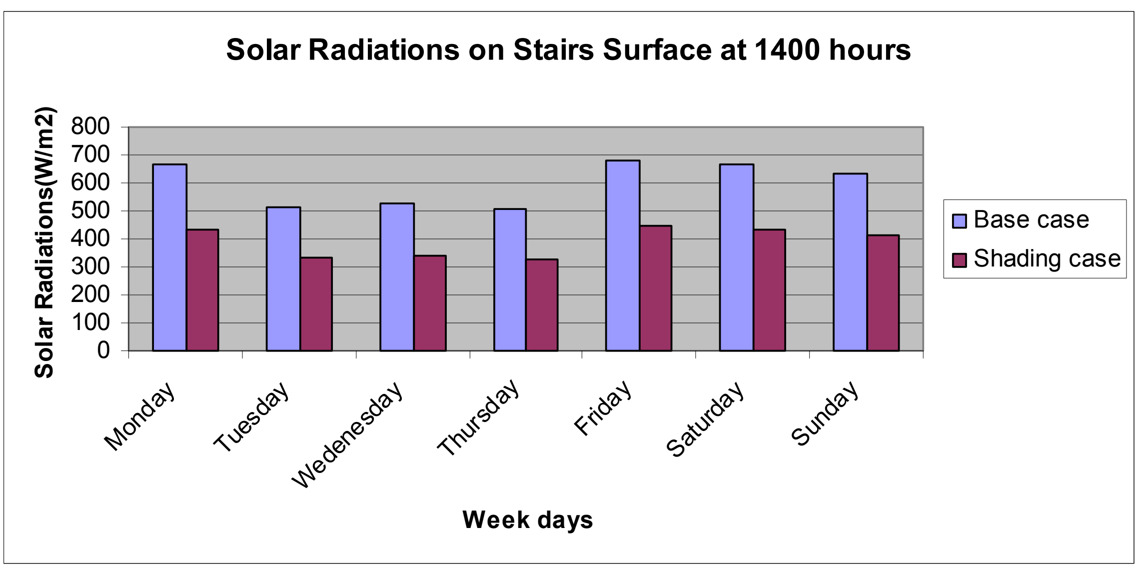

Figure 26: Affect of shading on direct incident solar radiations at 1400 hrs

7.3 Comparison between Thermal Sensation and Predictive Mean Vote

There is a major difference in the approaches of two comfort models for the assessment of occupant's thermal comfort. The PMV model of Fanger is based on the heat balance equation and TS model of Givone & Noguchi [TS] is based on the environmental parameters and incorporates the element of adaptation. The PMV model is used for the assessment of indoor thermal comfort but TS is being used for outdoors.

There is discrepancy in the assessment of a sport stadium's outdoor thermal comfort by these two comfort models. The results of winter and summer simulations are given below:

Summer Shading Case			Winter Heating Case		
Thermal Sensation(TS)	Predicted Mean Vote (PMV)	PPD (%)	Thermal Sensation (TS)	PMV	PPD (%)
4.27	-1.64	58.36	2.03	-2.28	85.86
4.03	-1.67	59.59	2.11	-2.21	84.24
4.23	-1.06	30.51	2.52	-2.27	88.55
4.49	-0.48	11.77	1.97	-2.62	95.31
5.19	0.88	24.91	1.94	-2.53	93.43
4.38	-1.38	45.29	2.01	-2.37	90.33
4.65	-0.47	16.29	2.66	-2.57	94.28

Table 10: Thermal Sensation (TS), Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) for summer shading and winter heating cases.

According to summer simulation results, TS values are more than neutral '4' that means spectators are feeling slightly warm. They are not in perfect thermal conditions because of solar radiation. Although the mean outdoor neutral temperature is 27^{o}C but still spectators are feeling warm especially on Friday. On the other hand according to PMV assessment at the same activity and clothing level, outdoor conditions are slightly cold. The neutral value for PMV is '0' but here its values are less than '-1' which gives the strong indication of cold out door thermal conditions. Only on Friday, according to PMV assessment, outdoor thermal conditions are slightly warm but according to TS, it is more than slightly warm.

The main reason of these discrepancies in the results of both models is they are mainly constructed on two different thermal assessment approaches. For indoor studies direct solar radiations are not taken into account because they are assumed not to reach the occupants inside the building. But for outdoor studies they have strong impact on the thermal sensations of people. Due to impact of solar radiation for outdoor assessment, TS predicts warmer conditions than PMV for the same level of activity and clothing. According to percentage people dissatisfied (PPD); outdoor thermal conditions are quite near to comfortable as most of the people are satisfied with the thermal environment. The mean values of PPD are 25% which is quite reasonable.

In the simulation of the winter heating case, PMV values are more negative than TS. According to PMV assessment, outdoor thermal conditions are very much cold but TS calculations describe cold conditions but less than those of the former. On Saturday of winter typical week, the value of TS is ‘2.01’ but that of PMV are ‘-2.37’for the same personal parameters (clothing and activity level). The percentage of people dissatisfied (PPD) in the winter cases are more than 90%, which means thermal conditions are very much severe outside and majority of them are feeling very cold.

8 Conclusion and Further Recommendations

8.1 Conclusion

The following conclusions can be drawn from this research work;

1 Due to rapid urbanisation, environmental issues have gained vital importance. The outdoor thermal comfort of people is an example of such an issue.

2 A purely physiological approach that is employed in the indoor thermal comfort assessment cannot be used outdoors. The outdoor environmental and personal activities are altogether different from indoors and therefore indoor comfort models are not capable of assessing outdoor comfort conditions.

3 The Thermal Sensation (TS) outdoor comfort model can predict the outdoor comfort conditions with a high level of accuracy because it is based on the environmental parameters which are difficult to control outdoors as compared with indoors.

4 The sports stadium case study simulation results revealed that outdoor comfort conditions are very difficult to achieve without heating in winter. Heating could only manage to increase the seating area surface rather than air temperature, which has a very limited affect on the Thermal Sensation (TS).

5 Summer outdoor conditions can be controlled with proper shading of the seating area of a stadium. Shaded areas are more comfortable as compared with un-shaded.

6 A comparative study of outdoor Thermal Sensation (TS) and Predicted Mean Vote (PMV) models revealed that both have some deficiencies to assess the outdoor thermal comfort of spectators. The TS model cannot incorporate the effect of adaptation which is very important to gain outdoor comfort conditions. It only relies on the environmental parameters and hence the effect of adaptation cannot be analysed with this outdoor comfort indicator.

7 On the other hand, indoor comfort models do not incorporate the affect of solar

radiations on the comfort of spectators. As this model is mainly for indoors, direct solar radiations are not considered which can have an effect on the thermal comfort of spectators. So the PMV model assesses slightly cold conditions for the same level of activity and clothing as compared with the TS model.

8 The TS model takes into consideration direct solar radiations in its calculations and so always evaluates slightly warmer outdoor conditions as compared with the PMV assessment which is slightly colder.

8.2 Recommendations

For future work the following recommendations can be suggested:

1 In this research work of a sports stadium thermal comfort, air velocity of 0.1 m/Sec was considered but it varies throughout the days of simulation week. Analysis should be done with exact air velocity at every hours of simulation.

2 Due to the huge volume of the stadium under study, exact solar distributions on the surface of the seating area are difficult to predict. This can be done by dividing the stadium zone into smaller zones and then analysing the environmental conditions in each zone.

3 Stadium orientation can also modify the direct solar radiation, especially in summer. So the orientation effect could be done throughout the hours of simulation.

4 Heating and cooling options can be changed and by analysis appropriate options can be discovered at reasonable economic cost.

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10 Appendices

Appendices of thesis contains all the information in table and graphs format about the sport stadium case study results for both the simulation periods of summer and winter. These are represented below:

Winter Results:

This simulation period has two broad cases, one is base case and other is heating case.

10.1 Winter Base case:

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.03	75.72	0.1	89.69	2.26	1.619689
1500	5.56	67.74	0.1	86.41	3.72	1.807409
1600	7.08	51.43	0.1	82.41	5.3	1.984088
1700	8.09	24.3	0.1	80.75	6.63	2.064759
1800	7.86	4.53	0.1	81.73	7.02	1.996434

Appendix 1: Monday base case results for every hours of simulation

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	6.53	84.56	0.1	84.99	5.96	1.970275
1500	7.35	86.74	0.1	82.34	7.04	2.09127
1600	8.09	70.27	0.1	79.43	8.19	2.170162
1700	7.67	34.63	0.1	77.25	8.73	2.07432
1800	5.98	7.45	0.1	75.62	7.88	1.841045

Appendix 2: Tuesday base case simulation results on hourly basis

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	6.94	216.66	0.1	66.29	7.04	2.409445
1500	7.71	234.01	0.1	60.49	9.51	2.584174
1600	7.99	212.81	0.1	55.21	11.55	2.624758
1700	7.38	142.09	0.1	52.67	12.22	2.444352
1800	5.85	44.59	0.1	54.69	10.89	2.06612

Appendix 3: Wednesday base case simulation results on hourly basis

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.38	81.27	0.1	64.37	4.59	1.866782
1500	4.64	68.55	0.1	62.08	5.16	1.891477
1600	5.29	45.83	0.1	61.31	5.7	1.929516
1700	5.7	20.72	0.1	62.51	6.06	1.920829
1800	5.22	4.53	0.1	65.81	5.77	1.810748

Appendix 4: Thursday base case simulation results

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.36	81.23	0.1	77.86	4.05	1.763077
1500	4.76	69.2	0.1	76.65	4.88	1.798255
1600	5.69	47.22	0.1	74.51	5.67	1.880355
1700	6.29	21.43	0.1	72.54	6.23	1.915839
1800	5.81	4.53	0.1	73.31	5.96	1.822986

Appendix 5: Friday winter base case simulation results

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	5.91	84.24	0.1	81.59	6.15	1.926197
1500	6.22	71.37	0.1	79.92	6.88	1.952535
1600	6.48	48.44	0.1	77.59	7.43	1.958015
1700	6.48	22.63	0.1	75.56	7.53	1.924335
1800	5.84	5.15	0.1	73.71	6.85	1.829404

Appendix 6: Saturday winter base case simulation results on hourly basis

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.86	297.63	0.1	64.79	6.92	2.341046
1500	5.37	443.12	0.1	59.99	9.79	2.725033
1600	6.02	439.24	0.1	58.02	12.86	2.82129
1700	6.16	248.24	0.1	58.34	14.51	2.480616
1800	4.93	61.88	0.1	62.5	12.97	1.950334

Appendix 7: Sunday winter base case results

10.2 Winter Heating Case (300kW):

In this heating option 300kW heating capacity plant is installed to heat the stadium seating area surfaces. The results are given below:

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.24	75.72	0.1	88.42	14.48	1.718426
1500	5.81	67.74	0.1	84.94	18.25	1.924552
1600	7.38	51.43	0.1	80.79	21.61	2.117528
1700	8.42	24.3	0.1	78.94	24.47	2.211202
1800	8.24	4.53	0.1	79.64	25.82	2.155695

Appendix 8: Monday Winter heating case on hourly basis

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	6.72	84.56	0.1	83.91	17.62	2.062365

1500	7.59	86.74	0.1	81	21.04	2.203484
1600	8.39	70.27	0.1	77.86	23.98	2.300429
1700	8.04	34.63	0.1	75.36	26.1	2.223281
1800	6.42	7.45	0.1	73.35	26.45	2.007086

Appendix 9: Winter heating on Tuesday with 300kW plant capacity

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	7.09	216.66	0.1	65.6	17.49	2.487682
1500	7.88	234.01	0.1	59.77	21.15	2.671292
1600	8.19	212.81	0.1	54.47	24.09	2.720236
1700	7.62	142.09	0.1	51.84	26.14	2.552411
1800	6.14	44.59	0.1	53.58	26.41	2.190453

Appendix 10: Winter heating on Wednesday, hourly analysis

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	4.56	81.27	0.1	63.56	15.85	1.953623
1500	4.9	68.55	0.1	61	18.96	2.002949
1600	5.6	45.83	0.1	59.99	21.62	2.059778
1700	6.08	20.72	0.1	60.88	23.92	2.071656
1800	5.67	4.53	0.1	63.8	24.88	1.978925

Appendix 11: Thursday winter heating case with 300kW plant capacity

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	4.55	81.23	0.1	76.87	15.5	1.853376
1500	5.01	69.2	0.1	75.35	18.72	1.910431
1600	6.01	47.22	0.1	72.97	21.55	2.013125
1700	6.67	21.43	0.1	70.74	24.03	2.067583
1800	6.25	4.53	0.1	71.15	25.09	1.991248

Appendix 12: Friday heating case with hourly analysis

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	6.08	84.24	0.1	80.66	17.18	2.011554

1500	6.46	71.37	0.1	78.62	20.33	2.061487
1600	6.79	48.44	0.1	75.98	22.9	2.087964
1700	6.85	22.63	0.1	73.65	24.97	2.07382
1800	6.28	5.15	0.1	71.51	25.73	1.996608

Appendix 13: Saturday heating case with hourly analysis

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	5.02	297.63	0.1	64.09	16.8	2.417396
1500	5.54	443.12	0.1	59.33	20.28	2.805503
1600	6.14	439.24	0.1	57.58	23.07	2.893052
1700	6.22	248.24	0.1	58.08	25.12	2.546516
1800	5.04	61.88	0.1	61.99	25.43	2.033639

Appendix 14: Sunday heating case with 300kW heating plant capacity

10.3 Winter Heating Case (500kW):

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	4.37	75.72	0.1	87.6	21.22	1.775342
1500	6.01	67.74	0.1	83.84	26.52	1.9996
1600	7.61	51.43	0.1	79.52	30.95	2.202949
1700	8.7	24.3	0.1	77.49	34.61	2.307847
1800	8.55	4.53	0.1	77.99	36.26	2.258774

Appendix 15: Winter heating (500kW) case on Monday with hourly analysis

Hours	**Air Temp(C)**	**Solar Radiation(W/m2)**	**Wind Speed(m/sec)**	**Relative Humidity (%)**	**Surface Temperature(C)**	**Thermal Sensation(TS)**
1400	6.86	84.56	0.1	83.11	24.32	2.120037
1500	7.8	86.74	0.1	79.92	29.22	2.279018
1600	8.63	70.27	0.1	76.58	33.19	2.386339
1700	8.32	34.63	0.1	73.91	36.06	2.318954
1800	6.73	7.45	0.1	71.78	36.67	2.108393

Appendix 16: Winter heating on Tuesday with 500kW plant capacity

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	7.23	216.66	0.1	65.01	24.22	2.543983
1500	8.08	234.01	0.1	58.98	29.34	2.743645
1600	8.44	212.81	0.1	53.57	33.29	2.804436
1700	7.91	142.09	0.1	50.83	36.08	2.645882
1800	6.46	44.59	0.1	52.41	36.62	2.289904

Appendix 17: Wednesday winter heating case with hourly analysis

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.71	81.27	0.1	62.92	22.57	2.011353
1500	5.1	68.55	0.1	60.14	27.17	2.075921
1600	5.85	45.83	0.1	58.96	30.87	2.145197
1700	6.37	20.72	0.1	59.68	33.97	2.167108
1800	5.99	4.53	0.1	62.41	35.24	2.080792

Appendix 18: Thursday winter heating case with 500kW heating plant

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	4.7	81.23	0.1	76.1	22.26	1.912271
1500	5.21	69.2	0.1	74.29	26.97	1.985079
1600	6.25	47.22	0.1	71.73	30.86	2.099283
1700	6.95	21.43	0.1	69.35	34.13	2.163574
1800	6.56	4.53	0.1	69.59	35.49	2.093454

Appendix 19: Winter heating (500kW) case for Friday

Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	6.22	84.24	0.1	79.87	23.88	2.069153
1500	6.66	71.37	0.1	77.56	28.5	2.135703
1600	7.03	48.44	0.1	74.7	32.1	2.17382
1700	7.14	22.63	0.1	72.22	34.94	2.170519
1800	6.6	5.15	0.1	69.98	35.99	2.098957

Appendix 20: Saturday winter heating case results

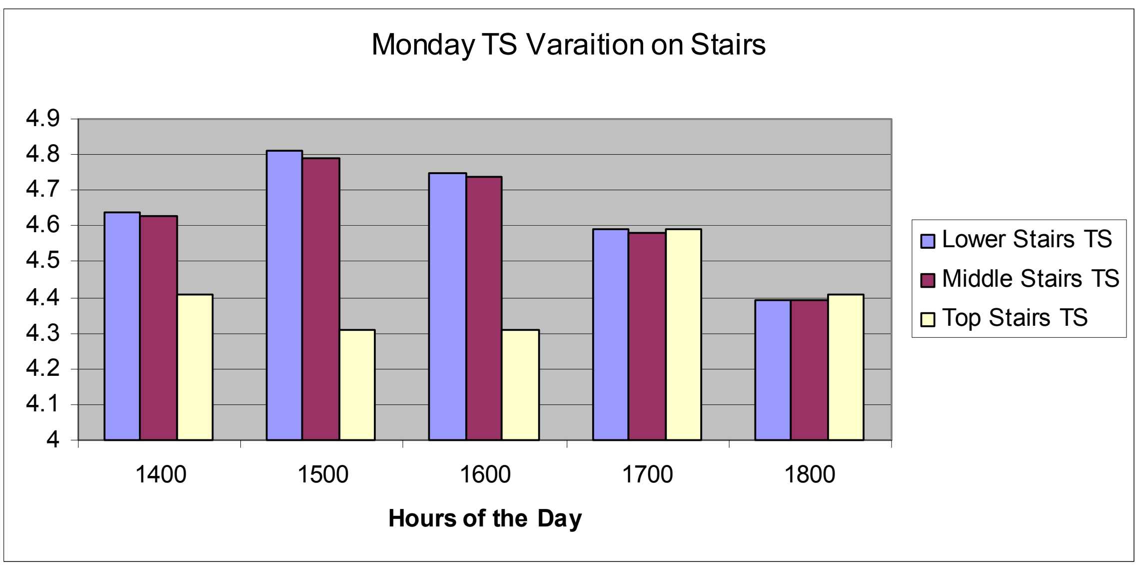
Hours	Air Temp(C)	Solar Radiation(W/m2)	Wind Speed(m/sec)	Relative Humidity (%)	Surface Temperature(C)	Thermal Sensation(TS)
1400	5.15	297.63	0.1	63.48	23.44	2.472239
1500	5.73	443.12	0.1	58.52	28.38	2.876398
1600	6.38	439.24	0.1	56.62	32.19	2.97614
1700	6.51	248.24	0.1	56.95	35	2.640539
1800	5.35	61.88	0.1	60.66	35.61	2.132978

Appendix 21: Sunday winter heating case results with 500kW heating plant

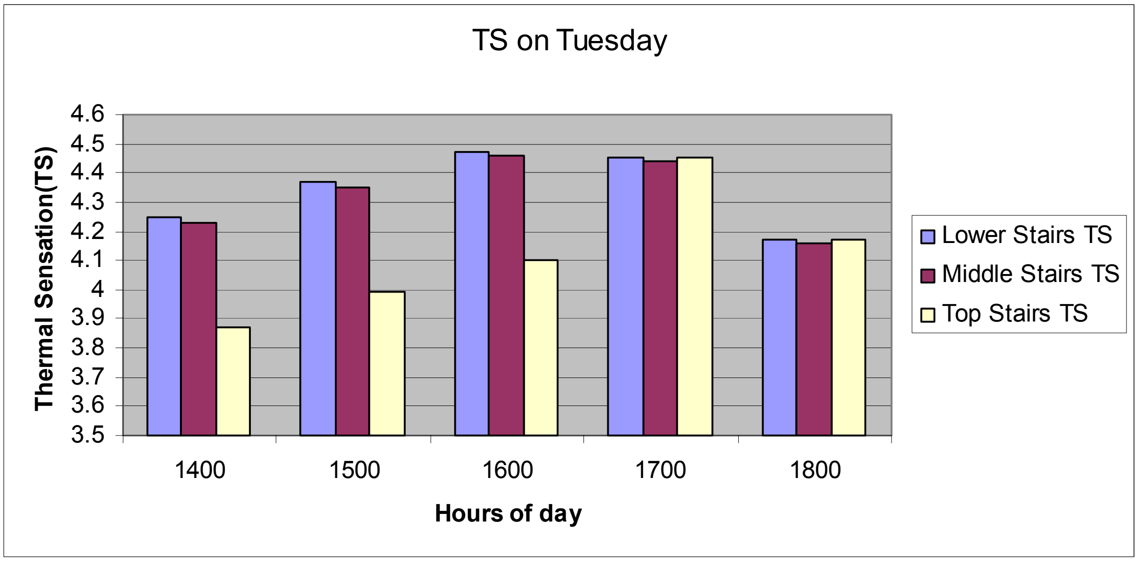
Summer Simulation Results:

Summer simulations of sport stadium have been done for a typical summer week. Like winter simulation, summer also have two cases. One is base case and other with shading of stadium seating area.

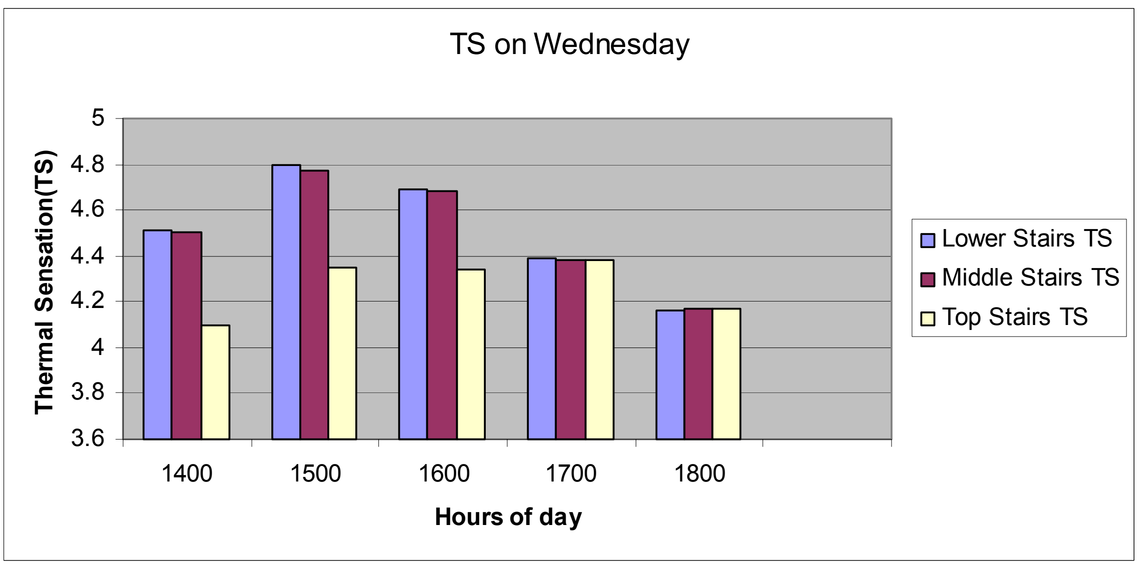
10.4 Summer Base Case Results:



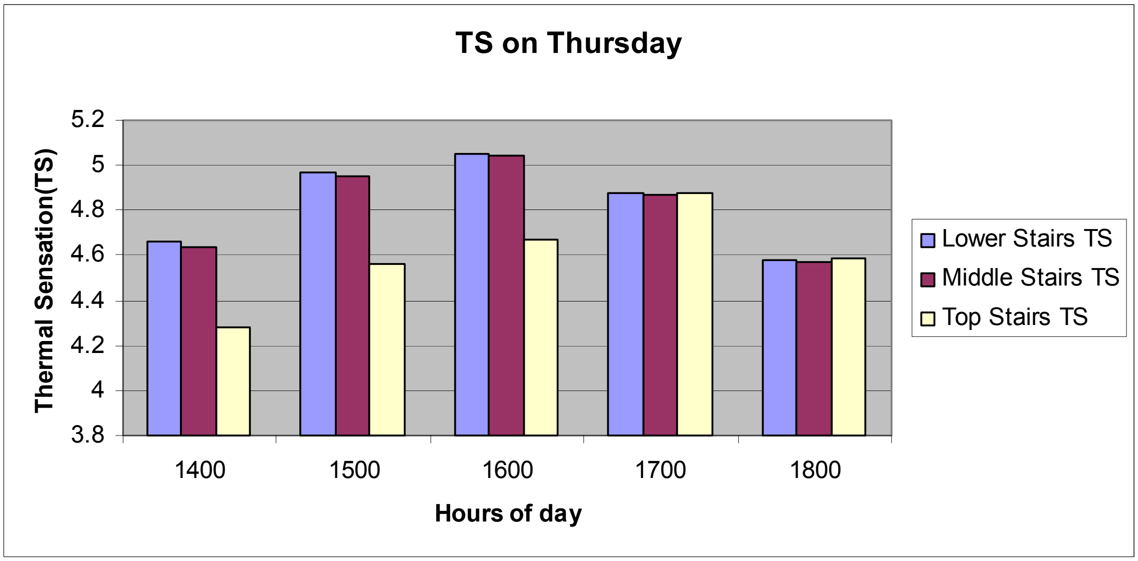
Appendix 22: Thermal sensation situation on Monday in summer week



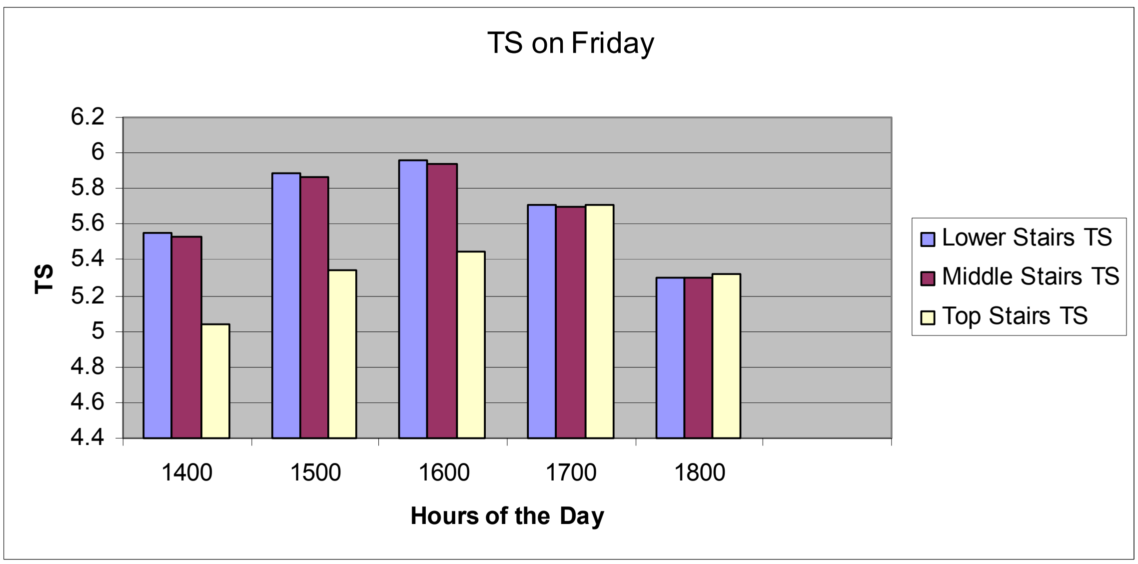
Appendix 23: Summer base case situation on Tuesday



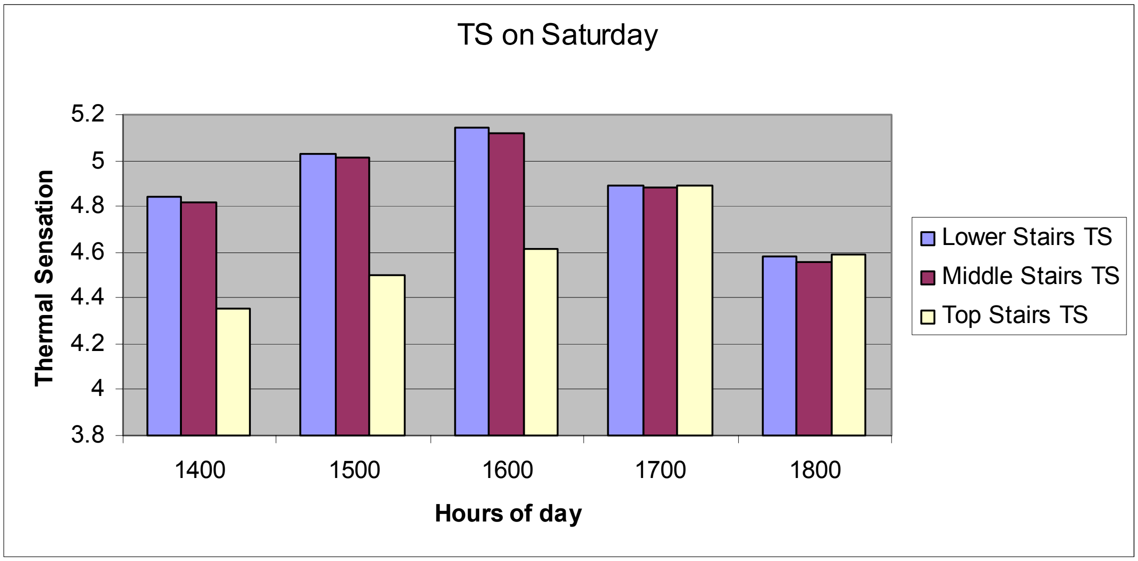
Appendix 24: Thermal Sensation on Wednesday for summer base case



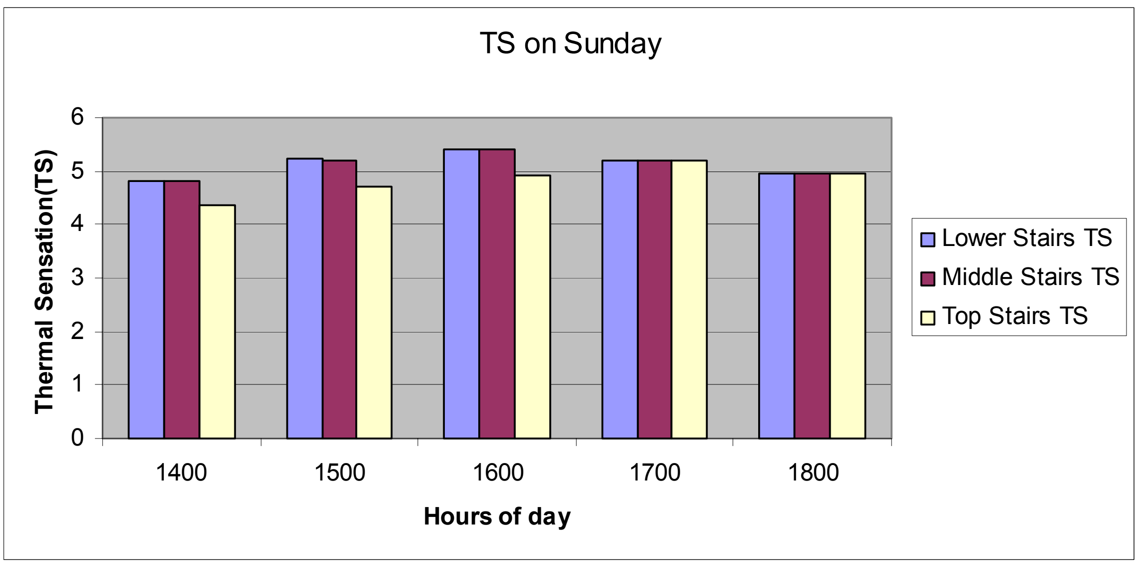
Appendix 25: TS values on Thursday for summer base case



Appendix 26: TS values on Friday summer base case

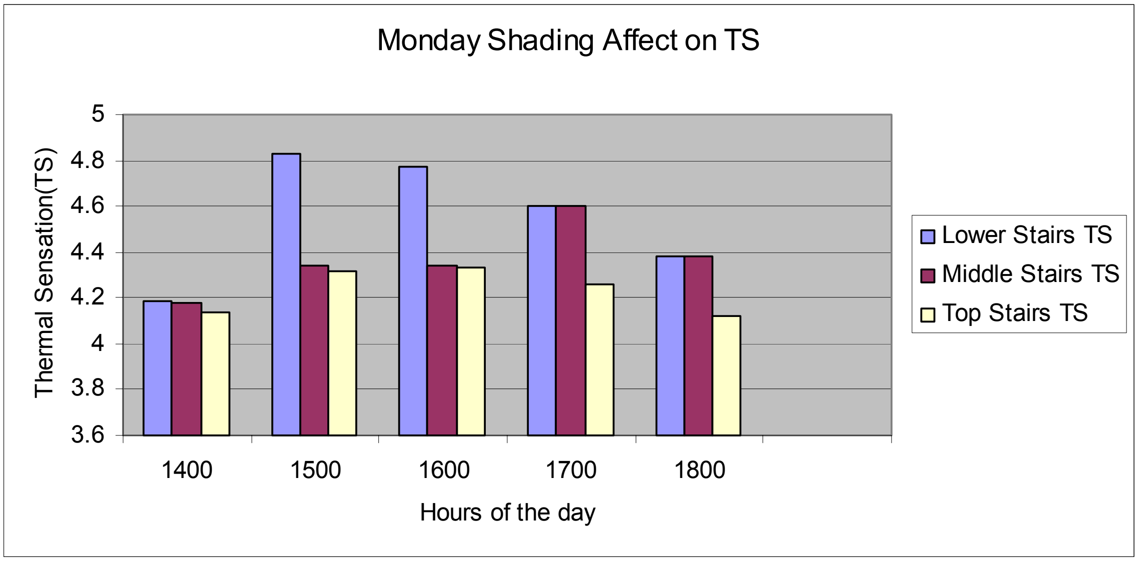


Appendix 27: TS situation on Saturday summer base case week

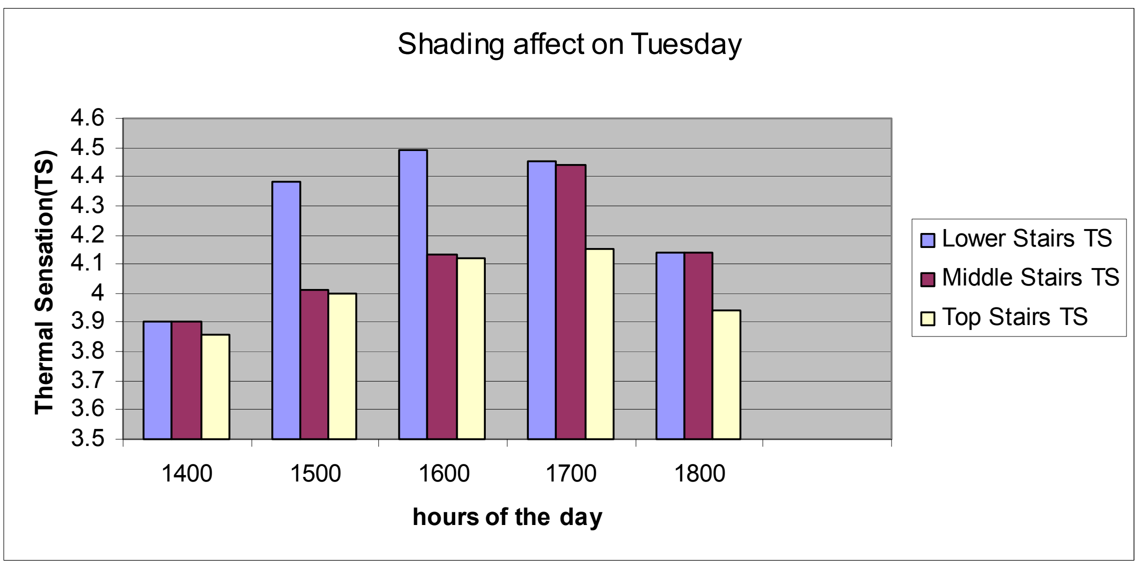


Appendix 28: Thermal sensation on Sunday summer base case

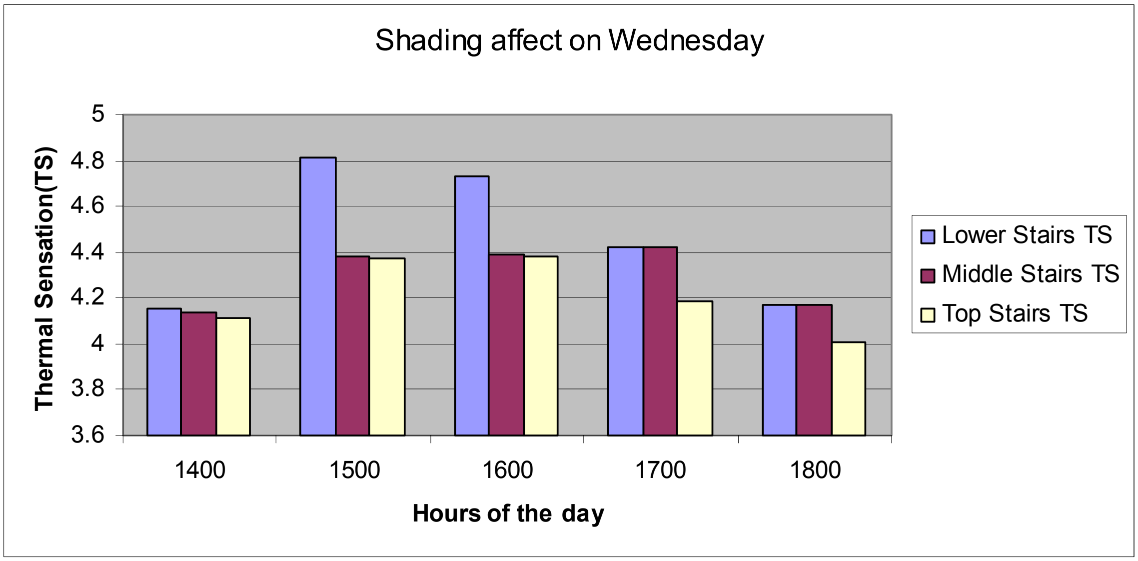
10.5 Summer Shading Case:



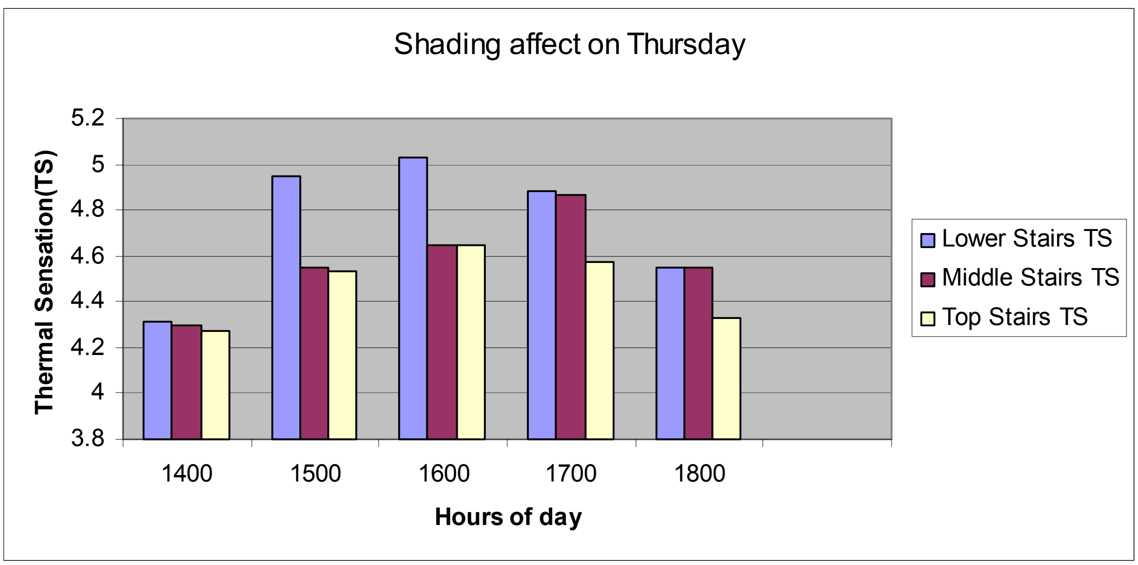
Appendix 29: Affect of shading on TS on Monday summer week



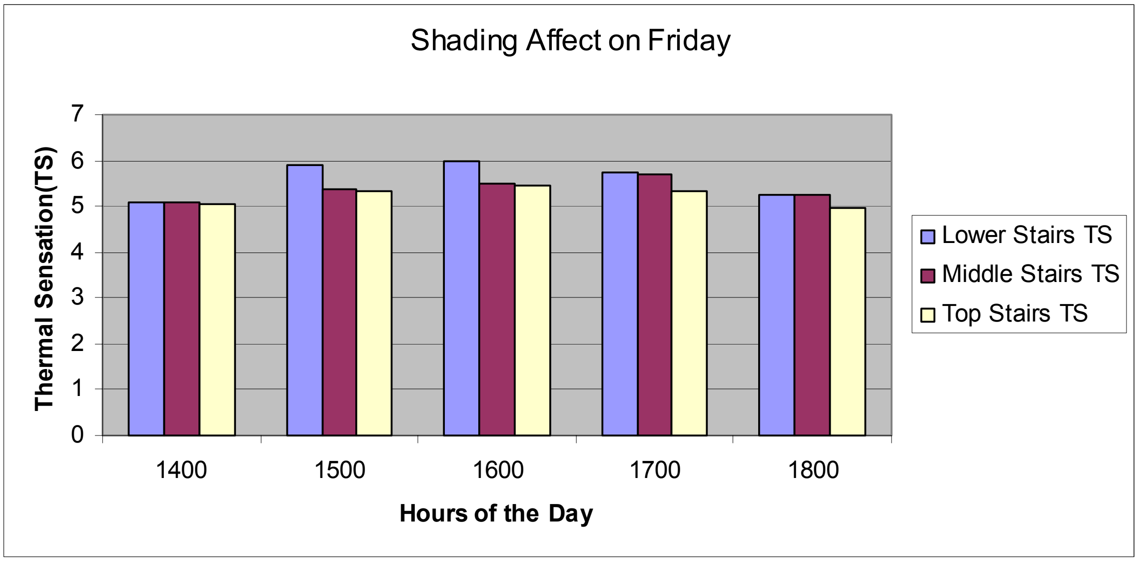
Appendix 30: shading affect on TS for Tuesday summer case



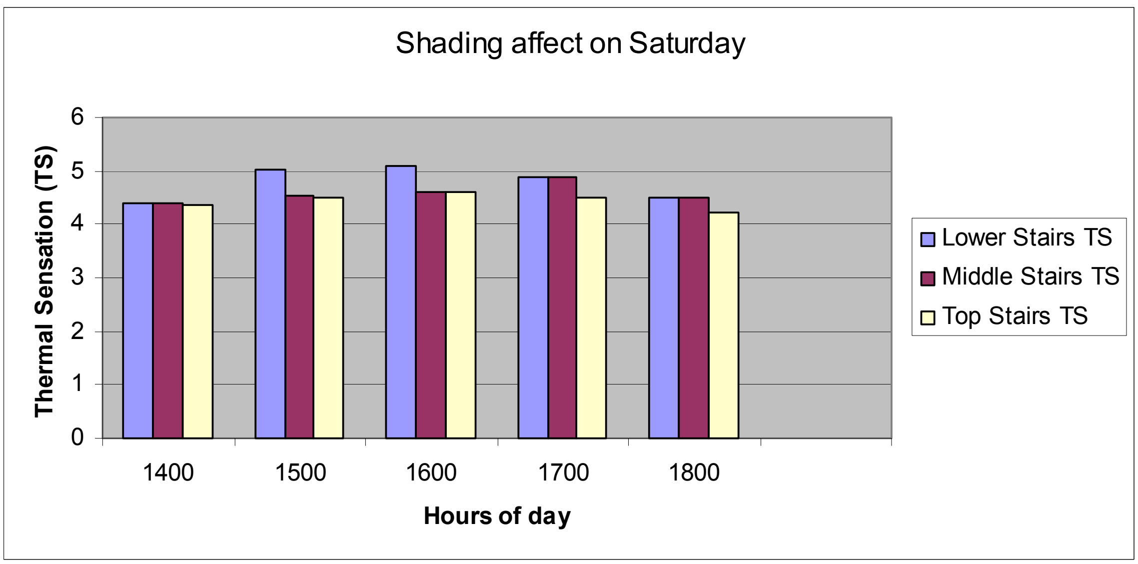
Appendix 31: shading affect on Thermal sensation for Wednesday



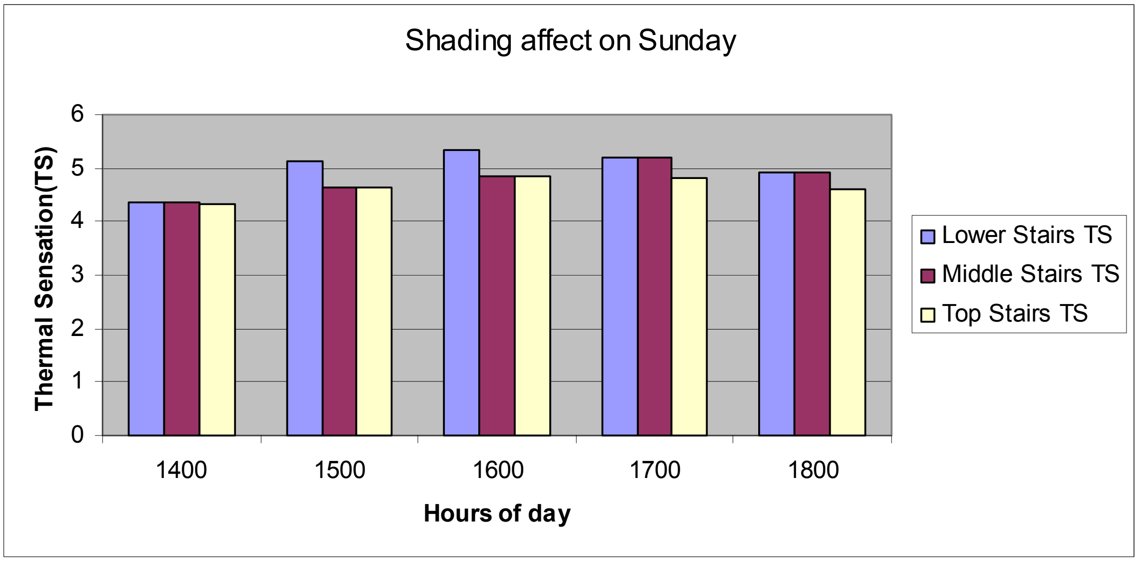
Appendix 32: shading affect on TS for Thursday



Appendix 33: Shading affect on Friday for summer typical week



Appendix 34: Shading affect on Saturday for summer typical week



Appendix 35: Shading affect on Sunday

10.6 Reduction in Solar Radiations due to shading:

Solar radiations on seating area surface at 1400 hrs

	Base case	**Shading case**
Monday	666.64	435.09
Tuesday	511.9	334.94
Wednesday	529.49	342.06
Thursday	509.06	329.42
Friday	683.28	445.17
Saturday	663.51	433.01
Sunday	633.8	413.06

Appendix 36: Reduction in direct solar radiation on seating area at 1400hrs in summer week

Week Days	Summer Base case	Summer shading case
Monday	4.54	4.38
Tuesday	4.27	4.13
Wednesday	4.43	4.31
Thursday	4.74	4.59
Friday	5.57	5.39
Saturday	4.78	4.59
Sunday	5.02	4.75

Appendix 37: Comparison of summer base and shading case for full week