SUMMARY: This paper describes the application of scale model and computer simulation techniques to the prediction of microclimate variables important to spectator comfort, turf growth and ice surfaces. These techniques have become increasingly powerful and provide valuable information during the design of sports facilities that will enhance their quality and functionality. Keywords: comfort, ice surfaces, shadows, solar radiation, turf, wind.

INTRODUCTION

Stadia and sports arenas of today's society are ever changing. Fifty years ago a sports facility was a simple structure designed as a venue to hold sporting events while supplying seating areas for spectators. As the business of sports developed, so too did the demand for more sophisticated facilities for the athletes and spectators alike. Stadia built in North America twenty five years ago began to include special amenities which increased the comfort of the spectators. Today stadia and arenas are being designed as large entertainment complexes which offer a multitude of services and convenience. Stadia and arenas only ten years old are being modified or replaced in favour of the more lavish facility.

The demand on sports facility designers has been tremendous. Each new facility is to be unique, offering just a little more than the most recent facility built. Therefore, designers have looked to specialized methods of engineering to assist in the design and operation of these very large and often complex facilities. As the design requirements have changed over the years so too have the types and methods of specialty engineering services. A discussion of the types of specialty services and how they have evolved, follows.
Over the last fifteen to twenty years physical scale models tested in wind tunnels have been used to aid with the structural design of stadia, along with the exterior loading for cladding/curtain wall design. Also, scale model testing in wind tunnels and in open channel water flumes combined with various levels of computer simulation has allowed for the determination of many other environmental aspects affecting stadia. Apart from structural issues, there are also others which can be just as important. A brief description of the various issues and how they are addressed follows.

**Wind loading on the main structural systems**
Wind loads on the main roof system, scoreboards, and lighting systems. These loads are typically determined through boundary layer wind tunnel tests on a rigid model [1], although preliminary estimates are often made based on approximate calculation to help early design iterations.

**Wind loading on cladding**
The wind loads on the cladding of the roof and walls are typically established by boundary layer wind tunnel tests [2].

**Snow loads**
Large span roof designs in areas subject to cold winters can be sensitive to snow loads, including unbalanced and concentrated loads created by drifting. Snow loads are established through a combination of scale model tests and computer simulations [3,4].

**Spectator comfort**
Moderate to high winds can have an adverse affect on spectators, particularly in colder climates. The determination of wind speeds in the seating bowl during the design stage will identify areas of concern and allow for the design of mitigative measures, prior to construction[5].

**Air Quality**
Contamination of air by exhausts from traffic or stationary sources may give rise to problems in some areas (e.g. bus drop off zones, cooling towers, boiler exhausts). Typically an initial screening of various sources by approximate computational methods is sufficient to identify potential problem areas. If solutions are proving difficult to develop, then more detailed and accurate information from wind tunnel tests using tracer gas and flow visualization methods are helpful.

**Wind-induced vibrations**
Large span roofs can become subject to vibrations or oscillations due to their flexibility. Aerodynamic stability needs to be assured. In cases where stability may be an issue, wind tunnel tests on an aeroelastic model (a flexible model) are typically undertaken [1].
Wind loads on roof drive and braking systems
For operable roofs, the power requirements for moving and braking the roof are usually governed by the wind drag loads. Uplift may also be important in some cases. These loads are best evaluated by wind tunnel studies on either a rigid or a flexible model representing various stages of the opening process. Limiting loads for operation of the drive system are usually selected to have a recurrence interval of between about one and five years.

Mechanical heating and air conditioning
Since stadia and arenas have large internal volumes, the variations of air temperatures and velocities within the volume can be very significant. What is important is to ensure the conditions are comfortable in all the areas occupied by spectators and players, i.e., in the seats and on the field. Frequently the detailed design of the mechanical systems can be improved and optimized with the aid of CFD studies [6,7], leading to better value for dollars spent on the mechanical systems, and perhaps, reduced capital and operating costs. The transient performance of the mechanical systems may need to be evaluated (i.e. in bringing the stadia from ambient to comfortable conditions in a short period) as well as the steady state conditions.

Rain infiltration
Knowledge of the extent of rain infiltration rates through openings at the edges of roofs or under cantilever roofs, along with frequency of occurrence, is sometimes needed. The rain drop trajectories are best predicted with the aid of Computational Fluid Dynamics (CFD) studies [6], supplemented by wind tunnel tests to provide boundary conditions such as wind velocities or pressures at the perimeter of the computational domain.

Noise and acoustics
Preventing excessive noise inside the facility may be important in some cases, especially if located near an airport or major transportation artery. Also, good acoustics may be required inside for concerts or similar events. Therefore, input from noise and acoustics experts, early in design, is important.

Wind affects on the play of the game
Games such as baseball, North American football, soccer, rugby, and some track and field events can be adversely affected by strong wind currents within the stadia. There has been strong interest by the baseball team owners to know the effect of wind on the trajectories of baseballs in the new stadia prior to construction. An assessment of these effects is possible through wind tunnel tests and computer simulation studies.

The aforementioned studies have been described in some detail in a previous paper[9]. The present paper focuses on three new areas:

1) Spectator overall comfort including thermal effects;
2) Impact of the local environment and stadia design on the turf; and
3) Impact of the local internal environment and ventilation on ice stability and quality in arenas.

A more detailed discussion of these areas follows.
SPECTATOR COMFORT

Outdoor Stadia
One of the keys to the design of a good sports facility is the comfort of the spectators. In outdoor stadia, this can be influenced by many factors: temperature, wind speed, humidity, precipitation, solar radiation, clothing level, activity and exposure time. In arenas and covered stadia, the effects of the mechanical ventilation system with respect to air speed, temperature and humidity is important. These components can be readily assessed through physical models and numerical models.

The assessment of spectator comfort in outdoor stadia is achieved through computer modelling of the solar exposure, wind tunnel testing of a scale model of the stadia, analysis of local meteorological data (temperature, humidity, wind) and application of comfort criteria. A comprehensive description of this methodology is described by Soligo et al [5] and will only be summarized here.

Figure 1 shows a typical stadia model in a boundary layer wind tunnel. The wind tunnel provides a simulation of the natural wind occurring in the boundary layer close to the earth’s surface at the study site. The model of the stadia is instrumented with wind speed sensors to measure mean and gust wind speeds in the seating areas. Solar conditions (shade or sun) are determined at the same locations using a computer sun/shadow analysis. Long term meteorological data (degree of cloud opacity, cloud cover, ambient temperature, relative humidity, wind speed and direction) recorded at the local weather station are analysed. This information is formatted on hourly basis for each day of the 20 to 30 years of data typically available.

Figure 1: Miller Park, Milwaukee, Wisconsin in the wind tunnel
Using this weather data in combination with the wind tunnel and solar modelling data, the climatic conditions at each location in the stadia are predicted for each hour of record. The resulting climatic conditions are then compared to the criteria for spectator comfort. The following table shows how these predicted comfort levels are typically presented.

Table 1: Spectator Comfort Analysis - percentage of the time comfort levels are achieved

<table>
<thead>
<tr>
<th>Loc</th>
<th>Wind chill</th>
<th>Mechanical</th>
<th>Thermal</th>
<th>Overall</th>
<th>Category rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pass</td>
<td>Sit</td>
<td>Stand</td>
<td>Walk</td>
<td>Sit</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>82.9</td>
<td>94.9</td>
<td>98.4</td>
<td>94.8</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>50.7</td>
<td>72.2</td>
<td>85.7</td>
<td>97.3</td>
</tr>
</tbody>
</table>

In this table, Wind Chill represents heat lost through exposed skin due to the combined effect of wind velocity and cold air temperature. Wind chill applies only to rather extreme cold climates and is defined as unsatisfactory when the wind velocity and air temperature combine to create an equivalent temperature of -20°C or lower. For Mechanical effects, the wind force component of the pedestrian comfort criteria is evaluated for: sitting allowing mean wind speed up to 2.5 m/s; standing for wind speeds up to 3.8 m/s; and walking for mean wind speeds up to 5 m/s. Mean wind speeds higher than 5 m/s are considered uncomfortable.

The Thermal component represents the heat balance of two body compartments: the core and the skin. Given a set of environmental conditions (temperature, humidity, etc.), personal conditions (activity, clothing level, etc.), and exposure time, the thermal comfort model predicts the overall body temperature. The thermal component evaluates the percentage of time an individual is comfortable for three different activity levels (sitting, standing and walking) and also the percentage of failures due to being too cold or too hot.

Finally, the three comfort components (wind chill, wind force and thermal comfort), are combined into a single Overall comfort evaluation for each of the three standard activities (sitting, standing and walking). In order to receive a comfort rating in the overall columns, all three individual comfort components must meet the criterion in any given hour. If one out of the three components fails, then a fail rating is applied to the overall comfort recorded for that hour. Failure implies that a given location has not received a level of comfort suitable for one of the three activity levels (sitting, standing or walking) 80% of the time or more. This 80% criterion is based on research that suggests the public can tolerate a limited number of uncomfortable days before they perceive an area as having a problem.

The purpose of assessing these three comfort components individually is to identify which component(s) cause a specific location to fail the overall comfort analysis. By identifying the component(s), the type of mitigation required to improve conditions can be determined.
Covered Stadia and Arenas

In covered stadia and arenas, modified criteria can be used to assess spectator comfort based on their expectations for an indoor space. For these facilities, the ambient meteorological conditions are clearly much less important. Instead factors such as heat sources (e.g. roof conduction, convective and radiative loads for lighting, displays and spectators), moisture sources (e.g. natural grass or ice), and the mechanical ventilation system can have a significant impact on spectator comfort.

To assess the interaction of these parameters, a computer model of all or part of the facility is used with Computational Fluid Dynamics (CFD) techniques. An example of a CFD model of the seating area of a covered stadia is shown in Figure 2. CFD enables the fine details of the flow patterns and temperature required within the facility to be mapped, including the effects of air supplies and returns, supply temperature, solar loading, moisture sources and heat sources. The results of the CFD analysis is a detailed prediction of the temperature, air speed and humidity levels in seating areas. This information can be analysed and compared with a thermal comfort index [8] to assess spectator comfort. A commonly used seven point thermal comfort index (TEENS) is as follows:-

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
<td>Hot</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly Warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>

Figure 2: CFD model of the seating area of a covered stadia
An example of the output from this analysis is shown in Figure 3.

![Figure 3: Predicted Spectator Comfort Levels for Covered Stadia](image)

Should undesirable conditions be noted in the seating areas, modifications to the mechanical system (e.g. throw trajectory of the supply air, supply air temperature, mix of return air, etc) can be adjusted and the CFD simulation repeated until more acceptable conditions are achieved.

**TURF MICROCLIMATE**

In North America the preference for artificial turf is over and the trend is predominantly towards building stadia with natural turf fields once again. Aesthetically, the playing field is more pleasing to the eye and harmonizes well with the nostalgic design style in many of today’s recently developed stadia. However, it may not be pleasing to the hometown fans’ pride if the field is worn and patchy, or to the owner if regular maintenance requires replacement of portions of the field.

A healthy natural turf playing field in a stadia environment depends on many factors. Sunlight for proper growth of the turf is one such factor. To accommodate turf growth in closed roof stadia palette systems can be used thus providing the added benefit of removal of the playing field for a setup other than field sports (i.e. conventions, concerts). In stadia with operable/retractable roofs either a palette system, a retractable field system or a permanent natural turf field are being designed or used. With a retractable field the entire field can be stored outside the stadia to benefit the maintenance of the turf and again convert the stadia for other uses. If the field is a permanent dedicated fixture, the roofs are left open most of the time to allow for proper growth of the natural turf.
Wherever the playing field ends up, fixed in the stadia or beside it when not in use, sunlight is a key ingredient in maintaining healthy turf, and the health can be compromised by the shadows cast by the stadia bowl and roof, along with surrounding structures, at different times of the year. Other factors such as cloud coverage, soil temperature in the root zone, air temperature, diurnal fluctuations of air temperature, ventilation, proper irrigation and maintenance regimes are also important for healthy natural turf. With an understanding of these factors and others, the turf consultant at the design stage can help to develop a system that either provides for a healthy permanent natural turf field or recommends a palette, hybrid or artificial system.

In order to answer some of these design questions the turf consultant needs input on the meteorological conditions. The frequency distribution of the wind speed over the turf as well as that of other parameters such as solar radiation, cloud cover, air temperature, dew, precipitation and humidity, all of which can be predicted by wind tunnel and/or computer studies[9]. RWDI has conducted a number of such meteorological studies for stadia designs as well as many other applications. Specifically for stadia design, turf consultants have been provided with sun shadow pattern studies of the stadia site, and solar radiation studies on the playing field. A feel for shadow effects can be gained by examining each hour of the day on March 21, June 21, September 21, and December 21. This includes the summer and winter solstice representing extreme patterns, and the autumn and spring equinox representing average or middle patterns. Additional dates, such as those during months with potential turf growth problems may also be of interest. A sample rendering for March 21 at 8:00 am is shown in Figure 4. This figure shows the effect of the Paul Brown Stadia in Cincinnati on the stadia playing field as well as the practice fields to the left of the stadia.
While this information provides the sun and shadow patterns, more detailed information is also needed on the predicted hours of solar radiation reaching the playing field. The sun shadow pattern study gives a view without cloud cover while a solar radiation study involves a meteorological analysis of the Global Hourly Radiation (GHR) and Opaque Sky Cover (OSC) data recorded locally.

GHR is the total amount of direct and diffused solar radiation in Wh/m² received on a horizontal surface. This data can be combined to provide average cloud cover and solar radiation given the actual hourly weather conditions for the local area. Radiation in Wh/m² can be converted to Equivalent Hours of Sunshine (EHS) per day. This is a unit of measure which defines the maximum amount of solar exposure an unobstructed surface would receive at solar noon on June 21, assuming a clear day.

For the Solar Radiation Study, a three-dimensional computer model is constructed of the stadia and surroundings. Locations are set on the playing field and hourly predictions on the 15th day of each month are assessed as to sun and shadow exposures. This data is then combined with the meteorological assessment to determine the EHS at each location. These data are then presented in graphical contour form. An example is provided as Figure 5.

![Figure 5: Contour of Equivalent Hours of Sunshine](image)

The results of the Solar Radiation Study and Sun Shadow Study and as well as other meteorological studies provides the turf consultant with useful data to answer many important questions at the design stage. Relevant questions might be: What turf specification would best suit this field? If an area of the field gets little or no direct solar radiation, can the placement of a billboard, or scoreboard be adjusted, or should a palette system be designed into that area from the beginning? Is the field temperature too low during part of the playing season to maintain proper growth, and, if so, can it be corrected with a heating system below the field? With the aid of rational predictions of the microclimate, the turf system can be better tailored to local conditions and better assurance obtained that the turf will indeed be greener.
ICE SURFACE QUALITY AND STABILITY

A high quality ice surface is necessary in facilities housing a number of sporting events such as ice hockey, figure skating, speed skating and curling. Each of these events presents differing requirements from the ice surface. In facilities housing Olympic style events many of these activities may occur on the same ice surface with little time between.

Complicating the ice surface requirements are the air flow patterns produced by the internal ventilation system, the heat and humidity given off of the spectators in the facility and high power lighting systems necessary for television production. In addition to different ice events, in order to keep a facility cost effective it is common to create a multiple use facility in which non-ice events such as concerts, trade shows and basketball games are booked into the facility in rapid succession. This requires the ice to be continually covered and uncovered. It is clear that the job of the ice-keeper in such a facility can get very complicated.

Figure 6 illustrates the typical construction of an ice producing surface. Also shown in the figure are some of the interior space effects acting on the ice surface. The construction of the surface begins with the soil. On top of this is generally a layer of insulation which reduces the heat conducted into the ice from below. Chiller pipes carrying a refrigerant or an antifreeze fluid are placed below or in a concrete slab poured on top of the insulation. It is on top of the slab that the ice is formed. Temperature sensing instrumentation is often placed within the concrete slab to assist in control of the cooling plant.

If this system in a facility were not in use for an extended period of time all of these components would come to an equilibrium temperature distribution and production of consistent ice would be as simple as setting the cooling plant controls to the desired temperature. However, in the real world the conditions are in a state of continual change, particularly during an event, just the point in time when the highest ice quality is required. This makes the design of the ice producing and control system a highly transient problem.
As an example of this transient nature, each time the ice is resurfaced using a resurfacing machine, a layer of liquid water is laid down. To freeze this layer, heat must be conducted from the top downwards into the existing ice which is typically at a temperature of about -6°C. This means that the top surface of the ice where the freezing is occurring is by definition at 0°C as a “wave” of heat passes downwards through the ice pack and slab to be removed by the cooling system. A high quality surface laid down prior to an event can require many applications of water and if sufficient time is not available for equilibrium to be regained then the surface may deteriorate rapidly through being too soft or through chipping of the various layers of uneven hardness due to temperature variations. See Figure 6 for examples of these effects. Lighting and ventilation systems contribute to the variability through uneven air flow speed and temperature and the additional heat applied by lighting in the upper portion of the ice typically just before the event.

Humidity can play major role in ice quality during curling events where frosting of the areas off the normal line can change the path of the stone. The amount of frosting depends to a large extent on the numbers of spectators in the facility.

What can be done? Engineering analyses of the external conditions for each of the intended use scenarios are carried out. CFD studies determine the effects of heat transfer and humidity between air and ice with and without people in the facility. This CFD analysis includes the effect of lighting heat loading. An example indicating airflow, and temperature variations within a similar enclosed space is provided in Figure 7.

Once the external (boundary) conditions are known. A transient thermal analysis of the temperature variations within the ice production system is carried out for representative locations over the surface of the ice. This analysis can incorporate cooling plant algorithms to determine optimal methods of operation of the plant and optimal sizing. If it is determined that change over from one use to another does not allow sufficient ice quality to be provided then corrective measures can be taken early in the process to avoid loss of revenue from certain types of events.
Although many of these things will inevitably become known through hands-on experience with the facility over time, knowing the performance characteristics at the design stage can provide critical information required to design out operational quirks which can be expensive to rectify after the facility is in use.

CONCLUSIONS

This paper has focussed on three aspects of the design of sports facilities: Spectator Comfort; Natural Turf; and Ice Surfaces. The common theme for all three of these aspects is that, with the aid of modern techniques of physical and computer modelling, it is possible to make detailed rational predictions of the microclimate affecting each one. Past experience with actual facilities will always be most important, but it is often difficult to sort out which of many variables are having most effect. The ability to predict the microclimate in a detailed way helps to identify which ones are important and achieve success, with less hit and miss, to produce facilities where spectators are comfortable, the turf is greener, and the ice is smooth and of appropriate hardness.

REFERENCES