Biometeorological Evaluation of Stadium Microclimate to Determine Spectator Thermal Comfort: A Pilot Study

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Abstract:

Studying human thermal comfort with respect to spectators at sport events is important to ensure: (1) favorable spectator experience (2) health and safety protocols, (3) conditions favoring return trips – a university financial incentive. College football events subject thousands of spectators to similar thermal conditions simultaneously; assessing the microclimate of college football stadiums is essential. This case study utilized in situ microclimate parameters to assess the spectator thermal comfort through the Kilma-Michel predicted mean vote (PMV), predicted percentage of dissatisfied (PPD), and physiological equivalent temperature (PET) thermal comfort indices during a late fall (11/3/2012) football game at Shippensburg University of Pennsylvania. The collection and analysis procedure acts as a pilot study to determine if the methodology applied is valid for determination of spectator thermal comfort in collegiate sports stadia. Analysis indicates thermal comfort to be far below acceptable conditions with a stadium-wide average PMV of -3.41, PPD of 98.79%, and a PET of 3.20°C. Temporally, spectator thermal comfort was lowest before the game (prior to spectator arrival), highest during the game (spectator presence), and dropped again after the end of the game (after spectator exit). Spatially, thermal comfort was generally highest in the lower and central portions of the stadium, but was highly varied throughout the event over all seating sections. Final results indicate the procedure utilized in this study is both feasible and applicable for use in large scale outdoor human thermal comfort studies such as those in collegiate sports venues.

Introduction:

Human thermal comfort is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as “the condition of mind that expresses satisfaction with the thermal environment” (“BSR/ASHRAE” 2003). This definition describes the local environment where the individual in question would not know if he/she would prefer it to be warmer or cooler (Fanger 1973), which gives a sense of neutrality with the surroundings. The ability to quantify outdoor human thermal comfort has real-world applications such as advancing the science of forecasting for those engaged in outdoor activities - enabling a better determination on how to dress for the occasion (Höppe 1999). Studying thermal comfort also leads to the possibility of enacting preventative measures to protect the population such as providing warnings, or shelters for those experiencing extreme discomfort (Szucs et al. 2009, Stamou et al. 2008, Fiala and Lomas 1999). Additionally, thermal comfort analysis is useful to
urban planners to assist in lowering heat stress on its population (Matzarakis et al. 1999) as well as improve and create more attractive urban spaces such as semi-outdoor restaurants, cafes, and sporting events (Oliveira and Andrade 2007, Spagnolo and de Dear 2003).

Several studies have been conducted to study the outdoor influence of urban environments on human comfort (Honjo 2009, Oliveira and Andrade 2007, Mayer and Höppe 1987). Country wide and regional analysis has taken place in more synoptic scale biometeorological experiments (Höppe 1999, Matzarakis and Mayer 1997). Additionally, numerous studies have been performed on outdoor and semi-outdoor stadium’s architectural influence on human thermal comfort inside the venue (Szucs et al. 2009, Bouyer et al. 2007, Szucs et al. 2007, Szucs 2004, Spagnolo and de Dear 2003, Fiala and Lomas 1999). Sporting events offer the rare opportunity for thousands of people to be subjected to a similar microclimate at once, therefore simultaneously subjecting these spectators to similar experiences of human thermal comfort.

This study collects and analyzes in situ meteorological parameters to assess human thermal comfort sensations felt by spectators in Shippensburg University’s Seth Grove Memorial Stadium during the November 3, 2012 contest versus Cheyney. Thermal comfort indices of predicted mean vote (PMV), predicted percentage of dissatisfied (PPD), and psychological equivalent temperature (PET) were assessed for spatial and temporal patterns in the stadium prior to, throughout the duration of, and after the event. A qualitative examination of the methodology set forth in this pilot study was completed to determine viability for future, more expansive, research.
Study Applicability:

Millions of people attend college sporting events nationwide each year with little to no assessment of human thermal comfort within the sports stadia. There is a need to assess human thermal comfort within college football sports stadia for multiple reasons which are very important to the given university. For instance, the university needs to receive feedback on their efforts to provide a favorable experience, as well as guarantee spectator thermal health and safety standards are met, which can be analyzed through thermal comfort assessments. Additionally, spectators who experience thermal discomfort, especially on a consistent basis, will be less likely to return for another event, resulting in a negative economic impact for the university.

Microclimate analysis studies completed on college football stadiums at the Arizona State University (Brazel and Marcus 1987) and the University of Alabama (Gutter and Brommer 2010) indicate significantly different conditions occur within the structure as compared to the surrounding ambient conditions. Due to the development of a distinct microclimate within a sports stadium, forecasts based on surrounding conditions are can be unrepresentative of the conditions spectators will be subjected to. This discrepancy is further compounded when spectators prepare for conditions based on these inaccurate forecasts rather than the actual conditions they will experience within the stadium.

The results of a human thermal comfort analysis can be utilized as a consultation for appropriate actions to enhance the spectator experience (e.g. construction projects, game time shifts to avoid unpleasant conditions, protective measures if necessary). A human thermal comfort analysis provides stadium owners with a powerful tool to assess, and possibly enhance, the spectator experience.
Literature Review:

Calculating the human thermal comfort into a quantified index is based on a complex combination of both meteorological and biophysical parameters that affect the thermal sensations of an individual (Matzarakis and Mayer 1997). To assess human thermal comfort, gathering data at a micro-meteorological scale of less than one kilometer (“Micrometeorology” 2011) is typically employed. As localized conditions around a person can vary greatly from the surrounding conditions, close proximity measurements are necessary to ensure high accuracy in the study. Four key meteorological factors contribute to the calculations of thermal comfort: ambient air temperature, mean radiant temperature (MRT), relative air velocity, and surrounding vapor pressure. Additionally, two non-meteorological contributors are: the spectator’s activity level’ and the thermal resistance of their clothing (“BSR/ASHRAE” 2003, Matzarakis et al. 1999, Fanger 1973). These parameters have very use-specific definitions for human thermal comfort assessments (Gagge and Nishi 2011); Table 1 outlines these definitions.

Thermal Comfort Indices:

Multiple methods of quantifying human thermal comfort have been established over the past 70 years, mainly in indices, which rank the comfort level of the given situation based on established comfort and discomfort zones. After a thorough review of the literature on this subject, three key indices best suited for use in semi outdoor stadium environments will be employed: Kilma-Michel PMV (predicted mean vote), PPD (predicted percentage of dissatisfied), and PET (psychological equivalent temperature).
Table 1: The key parameters which factor into human thermal comfort assessments, their definitions from Gagge and Nishi (2011)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Air Temperature</td>
<td>The temperature of the air within the vicinity of the individual being assessed in the human thermal comfort assessment, but outside the heat flux region, or boundary layer, of the skin.</td>
</tr>
<tr>
<td>Mean Radiant Temperature (MRT)</td>
<td>The temperature in an imaginary black box enclosure that will exchange the same amount of heat in a non-uniform (long and short wave) radiation environment as the body of a human being does; incoming radiation as felt on the body to raise the temperature; all surfaces emit (and absorb) radiation in a very complex manner</td>
</tr>
<tr>
<td>Relative Air Velocity</td>
<td>The velocity of air in the vicinity of the individual being assessed in the human thermal comfort assessment, but outside the range of influence from the individual i.e. updraft from body heat, disruptions in the mean free path of air by body turbulence displacement.</td>
</tr>
<tr>
<td>Surrounding Vapor Pressure</td>
<td>Fundamentally a measure of relative humidity (RH) as measured in a zone free of influence from the individual being assessed.</td>
</tr>
<tr>
<td>Individual Activity Level</td>
<td>This term is tied to the metabolic work rate of a person at any given time for any given activity due to the relationship between thermal comfort and the human heat balance equation, these values act as a constant.</td>
</tr>
<tr>
<td>Thermal Resistance of Clothing</td>
<td>The insulation properties displayed by any given garment, combined together to form an entire ensemble yields the total thermal resistance of the individual. - tied to the thermal comfort assessment through the human heat balance equation, and acts as a constant.</td>
</tr>
</tbody>
</table>

Predicted Mean Vote:

Predicted Mean Vote (PMV) is one of the most extensively used human thermal comfort assessment methods in the discipline (Mayer and Höppe 1987). Initially developed by Fanger (1973), the PMV is an equation replicating a population-wide assessment of what the mean comfort level vote will be if all subjects were surveyed (psychological assessment). Derivation of this index is based on the connections between actual psychological assessments (the initial study conducted over 1,300 actual surveys) (Fanger 1973), physiological principles, and environmental factors. The PMV utilizes the human energy equation as a basis for transferred heat flux and exchanges with the environment. Combining that principle with clothing insulation
and metabolic activity levels as well as the micrometeorological parameters previously noted completes the equation (Honjo 2009, Shakir 2006, Fanger 1973).

The PMV uses a 7 point thermal sensation scale ranging from -3 to +3 where a ‘vote’ of 0 indicates thermal preference has been reached. Originally the PMV was only useful indoors, due to the necessity of a static environment in the calculations. In order to remedy that limitation, the ‘Kilma-Michel PMV Model’ (KMM) was produced by Jendritzky and Nübl (1981). This adaptation began with the original PMV equation and redeveloped it through the addition of short and long wave radiation budgets (MRT), making it viable in the outdoor environment (Honjo 2009, Matzarakis and Mayer 1997). The calculation of the PMV, as stated in public reports (ISO 1994, BSR/ASHRAE 2011) is shown below in equations 1 - 4.

\[
\text{PMV} = \left\{ \begin{array}{l}
0.303 \cdot \exp(-0.036 \cdot M) + 0.028 \cdot (M-W) \\
-3.05 \cdot 10^{-3} \cdot [5733 \cdot 6.99 \cdot (M-W) - \rho_a] \\
-0.42 \cdot [(M-W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - \rho_a) \\
-0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \\
\cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \\
\end{array} \right. \quad \text{Eqn. 1}
\]

\[
t_{cl} = \left\{ \begin{array}{l}
35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \\
[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \\
\end{array} \right. \quad \text{Eqn. 2}
\]

\[
h_c = \left\{ \begin{array}{l}
2.38 \cdot | t_{cl} - t_a |^{0.25} \text{ for } 2.38 \cdot | t_{cl} - t_a |^{0.25} > 12.1 \sqrt{v} \\
12.1 \sqrt{v} \text{ for } 2.38 \cdot | t_{cl} - t_a |^{0.25} < 12.1 \sqrt{v} \\
\end{array} \right. \quad \text{Eqn. 3}
\]

\[
f_{cl} = \left\{ \begin{array}{l}
1.00 + 1.290 \cdot I_{cl} \text{ for } I_{cl} \leq 0.078 \text{ m}^2 \text{K}/\text{m} \\
1.05 + 0.645 \cdot I_{cl} \text{ for } I_{cl} > 0.078 \text{ m}^2 \text{K}/\text{m} \\
\end{array} \right. \quad \text{Eqn. 4}
\]

Where \( M \) is the metabolic rate (W/m\(^2\)) = MET \cdot 58.15, \( W \) is the effective mechanical power (W/m\(^2\)) = WME \cdot 58.15, \( I_{cl} \) is the clothing insulation (m\(^2\)K/W) = 1.55 \cdot \text{CLO}, \( f_{cl} \) is the clothing surface area factor, \( t_a \) is the air temp (°C) \( t_r \) is the mean radiant temperature MRT (°C), \( v \) is the air velocity, \( \rho_a \) is the vapor pressure (Pascals), \( h_c \) is the convective heat transfer coefficient (W/m\(^2\)K) and \( t_{cl} \) is the clothing surface temperature (°C).
Predicted Percentage Dissatisfied (PPD):

The PPD is a derivation of the PMV as developed by Fanger to display the proportion of people in a population that would be dissatisfied with a particular environment (Shakir 2006). The PPD is a statistical distribution based on the PMV, which can be determined both graphically and numerically through calculations (ISO 1994). This study will employ numeric calculations of PPD shown below in Eqn 5.

$$PPD = 100 - 95 \cdot \exp\left(-0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2\right)$$  \hspace{1cm} \text{Eqn. 5}

The lowest percentage of people dissatisfied one can ever reach is 5%, due to individual preference in the population (Fanger 1973), which can be seen through calculations with a PMV of zero corresponding to 5% PPD. Due to the revamping of the PMV model with the KMM model, the PPD is also applicable to outdoor situations (Mayer and Höppe 1987).

Physiological Equivalent Temperature (PET):

The Physiological Equivalent Temperature (PET), developed by Mayer and Höppe (1987), is a means to establish an outdoor human thermal comfort index based on temperatures rather than a quantitative ranking system, making it more easily understood by the public (Matzarakis et al. 1999, Mayer and Höppe 1987). PET is defined as the outside ambient temperature (with its specific certain skin and core temperatures) where in a typical indoor setting, the heat balance of a human body is maintained with equal core and skin temperatures (Bouyer et al. 2007, Höppe 1999). PET is based on the advanced Munich Energy balance Model for Individuals (MEMI), enabling it to quantify outdoor thermal exchanges with high accuracy (Höppe 1999). Calculation of PET depends on a highly complex system of equations which solve for a hypothetical value of ambient air temperature; the value obtained is the PET. Approximation of PET, however, can be achieved with high confidence from a relationship to
PMV (Eqn 6) as derived by the author from the results of Matzarakis *et al.* (1999); this approximation of PMV was adopted for this pilot study.

\[
PET \approx (5.3214 \cdot PMV) + 21.375 \quad \text{Eqn 6}
\]

**Previous Stadium Studies:**

Many studies have addressed stadium micrometeorology and spectator thermal comfort within a variety of assessment techniques and indices. Few studies, however, made *in situ* measurements of parameters during an event. Aero-thermal comfort was assessed in multiple studies focusing on the influence of air velocities on the perceived drop in temperature (Szuks *et al.* 2009, Szuks *et al.* 2007, Szuks 2004). Several studies focused on the architectural design influences of the structure (Szuks *et al.* 2009, Bouyer *et al.* 2007, Szuks 2004, Fiala and Lomas 1999), and modeled air flows through the stadium using fluid dynamics (Stamou *et al.* 2008, Stamou *et al.* 2007, Szuks *et al.* 2009, Szuks 2007, Szuks 2004), which was then correlated to the thermal comfort index and wind chill indices to perform their assessment. Bouyer *et al.* (2007) utilized PET to model spectator thermal comfort in semi outdoor stadia: Stade de France (Paris), and Atatürk Olympic Stadium (Istanbul) in daytime hours. This study found severe thermal comfort discontinuities throughout the stadium as a result of direct solar radiant asymmetry. However, this study, as well as the study conducted by Fiala and Lomos (1999), modeled *theoretical* human thermal comfort as calculated through parameters either modeled from averages or gathered when no spectators were present in the stadium. This method does not fully represent the conditions which would be experienced, and therefore is not entirely applicable to the proposed study.
Microclimate and heat island analyses completed on college football stadiums at the Arizona State University (Brazel and Marcus 1987) and the University of Alabama (Gutter and Brommer 2010) provide useful information on methods to collect accurate data. Though neither of these studies directly assessed the human thermal comfort experienced within the stadium, the parameters gathered could be analyzed for human thermal comfort in the stadium, as suggested by Gutter and Brommer (2010). Evaluation of Sun Devil Stadium at The Arizona State University by Brazel and Marcus (1987) concluded that spectator influence tended to create an isothermal microclimate (at a higher temperature than the surrounding outside conditions) as direct solar radiation diminished through the evening. Thermal inertia was found to be prevalent from radiational heat trapping effects of the stadium structure. This observation, which was also observed by Gutter and Brommer (2010) has a direct correlation to the proposed study, which will be conducted during an afternoon and evening timeframe.

The measurement methods employed by Brazel and Marcus (1987) and Gutter and Brommer (2010) were critical to data collection methods utilized in this pilot study. Sensors were distributed throughout the stadium in each seating section (Brazel and Marcus 1987), and in each seating level and field level on a straight transect across the stadium as well as in the concourses behind the seating sections (Gutter and Brommer 2010). This distribution method works well for generalizing the sections as having the same thermal comfort as analyzed at the point of collection, however, it has been suggested that a concentrated distribution of collections need to be taken within a small area i.e. one section of the stadium, in order to accurately assess the thermal comfort over that sector (Tse and Chan 2008). Nevertheless, to assess conditions throughout the entire stadium, the sensor distribution method set forth by Brazel and Marcus (1987) and that of Gutter and Brommer (2010) is the most feasible.
Both studies measured conditions prior to, during, and after an event to allow for the influence of the spectators to be directly measured. The ability to monitor the conditions during this time span will display human effects on the micrometeorological conditions, and consequently their effects on thermal comfort indices. As a pilot study, analysis of such human influences are outside the scope, however, this study lays out the procedures necessary for future, more in depth, studies to answer.

Gaps in Literature:

The vast majority of literature reviewed on stadium human thermal comfort focuses on regions outside of the United States, with the majority of stadium assessments occurring in European nations. Those conducted in the United States (Gutter and Brommer 2010, Brazel and Marcus 1987) did not directly assess human thermal comfort, but rather took measurements of stadia microclimates for purely academic purposes (e.g. long wave radiation studies). This pilot study acts as a basis to applying such thermal comfort assessments to U.S. sporting stadia.

Assessments of sporting events, where a majority of the spectators are highly energetic and involved, have not been considered appropriately in terms of spectator’s activity levels. A majority of the literature used a variety of levels of which were not related to the nature of energetic sporting event spectators.

For example Spagnolo and de Dear (2003) used an activity level of walking, while others have used a sedentary activity level for the crowds (Szucs et al. 2007, Fiala and Lomas 1999). To gain a more accurate

<table>
<thead>
<tr>
<th>Classification</th>
<th>M (mets)</th>
<th>Heart Rate (bpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal</td>
<td>0.7 - 0.8</td>
<td>~ 70</td>
</tr>
<tr>
<td>Sedentary</td>
<td>0.9 - 1.1</td>
<td>70 - 80</td>
</tr>
<tr>
<td>Very Light</td>
<td>1.3 - 1.7</td>
<td>80 - 85</td>
</tr>
<tr>
<td>Light</td>
<td>2.2 - 2.8</td>
<td>90 - 95</td>
</tr>
<tr>
<td>Moderate</td>
<td>3.7 - 4.5</td>
<td>105 - 115</td>
</tr>
<tr>
<td>Heavy</td>
<td>5.2 - 6.4</td>
<td>125 - 135</td>
</tr>
<tr>
<td>Very Heavy</td>
<td>6.7 - 8.3</td>
<td>145 - 155</td>
</tr>
<tr>
<td>Exhausting</td>
<td>10.0 - 12.0</td>
<td>&gt; 165</td>
</tr>
</tbody>
</table>
assessment of the activity level of the crowd, this study will utilize spectators’ heart rates as a proxy to metabolic activity. Heart rates have been correlated to various metabolic activity levels (Table 2) necessary for the calculation of human thermal comfort (Gagge and Nishi 2011).

Another prevalent gap in the literature which will be addressed by this pilot study is conducting the data collection in a game day event environment - while spectators are physically present in the stadium. Brazel and Marcus (1987) demonstrated spectators presence led to slightly warmer and nearly uniform temperatures within the entirety of the stadium. Also, spectator presence is likely to affect the wind field within the stadium, causing a frictional boundary layer at the head/shoulder height and minimizing air speeds below that level. To gain an accurate assessment of true experienced human thermal comfort, data collection while spectators are present in the stadium is essential.

The climatic conditions sought in a majority of similar studies were limited to hot (Fiala and Lomas 1999, Spagnolo and de Dear 2003), or cold (Szucs et al. 2009, Szucs 2004, Spagnolo and de Dear 2003) environment extremes in an effort to correlate human thermal comfort to thermal stress and physiological danger thresholds. Transitional climatic periods, such as spring and autumn have not been evaluated for spectator thermal comfort. This pilot study takes into account that not all events occur in extreme conditions, and studies transitional conditions.

**Study Area:**

Shippensburg University is located in Shippensburg, Pennsylvania; a small town in the south central portion of the state. Seth Grove Memorial Stadium, located on the northwestern edge of campus, is an outdoor football stadium (Figure 1) with a two open air bleacher seating areas on either side of the field. Seth Grove Memorial Stadium has an official seating capacity of
7,700 with an average of 5,225 people in attendance per game in 2004 (Athletic 2012) making it an excellent candidate for a pilot study for thermal comfort assessment of college football stadiums. The assessment was conducted on the home bleachers of the stadium as indicated in Figure 1.

November 3, 2012 experienced partly sunny conditions with a high temperature of 46.5 °F and low of 38 °F (Hawkins 2014). These temperatures conformed to desired study conditions: to assess the human thermal comfort in a transitional environment, rather than very hot or very cold environments as previous studies have focused on.

Methods:

Sensor Selection & Assembly:

Sensor selection for the collection of necessary meteorological parameters is based on three key parameters: 1. best method of collection, 2. previous studies, and 3. availability/budget limitations. Use of instrumentation readily available at Shippensburg University was heavily
relied upon to assist in budgetary feasibility (i.e. the Department of Geography and Earth Science owns 24 HOBO U23 Pro v2 instruments, of which 20 were employed for this study).

To measure ambient temperature and relative humidity conditions, the HOBO U23 Pro v2 with built in data logger produced by the Onset Computer Corporation (“HOBO” 2011), as was utilized by Gutter and Brommer (2010), was employed. The specifications for the HOBO u23 Pro v2 are listed in Table 3.

**Table 3: Specification briefing of the HOBO u23 Pro v2 temperature and humidity sensor.**

| HOBO U23 Pro v2 | **Temperature** |  | **Humidity** |
|-----------------|-----------------|-----------------|
| **Range**       | -40 °C to 70 °C | **Accuracy**    | ± 0.2 °C       |
| **Resolution**  | 0.02 °C         | **Resolution**  | 0.03 %         |

Mean radiant temperature (MRT) was measured by proxy of a black globe temperature (T_{bg}) through the same HOBO U23 Pro v2 with built in data logger. To measure T_{bg}, a black metal (radiation absorbent) sphere (i.e. black globe) was constructed around the temperature sensor to account for the 360° fluxes of radiant energy. Construction of the black globe followed guidelines set forth by Purswell and Davis (2008). MRT (T_r) was then calculated via Eqn 7 presented by Lui *et al.* (2011) where T_a is the ambient air temperature at the location of the black globe apparatus.

\[
T_r = \left[ (T_{bg} + 273)^4 + 0.4 \cdot 10^{-8} \cdot (T_{bg} - T_a)^{5/4} \right]^{1/4} - 273 \quad \text{Eqn 7}
\]

Air velocity was measured via HOBO station anemometers. Due to the small size of the stadium, wind speeds can be generalized as horizontally consistent, eliminating the need for measurements from each monitoring point. Two anemometers were used in the data collection: one at the bottom and one at the top of the seating area to ensure capture of the vertical differences in air velocity across the height of the seating area. All sensors (summarized in Table...
Table 4: The instrumentation utilized in this study, the parameters that they are measuring, and the quantity being deployed.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Parameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOBO U23 Pro v2</td>
<td>Temperature, Relative Humidity</td>
<td>7</td>
</tr>
<tr>
<td>HOBO U23 Pro v2 w/ Black Globe Housing - In House Construction</td>
<td>Mean Radiant Temperature</td>
<td>7</td>
</tr>
<tr>
<td>HOBO Anemometer</td>
<td>Wind Velocity</td>
<td>2</td>
</tr>
<tr>
<td>Octivtech OT-99 Sports Oximeter</td>
<td>Pulse</td>
<td>1</td>
</tr>
</tbody>
</table>

4) were attached to a mounting apparatus custom designed for application in sporting venues. The mounting apparatus consists of a cement weighted bucket with a ½ inch diameter PVC pipe extending 3 feet from the center - bottom of the bucket. Sensors were attached to the PVC pipe using both stock housings (HOBO U23 Pro v2 sun shield, HOBO anemometers) and custom attachments (black globe thermometer). Finally, a document stating “METEOROLOGICAL EXPERIMENT” and a description of the study were attached to each sensing apparatus to ensure surrounding individuals were aware its function. An assembled sensor array as deployed for the study is shown in Figure 2.

Equipment Testing:

All sensors were put through a ‘trial run’ of testing in a controlled laboratory environment prior to deployment. The entire data collection procedure for field tests was conducted in the same manner as the actual study to ensure proper techniques and protocols are being followed. The resulting data were downloaded and reviewed (to ensure the sensors are working correctly) then discarded without analysis.

Figure 2: The sensing array deployed at the study site for data collection.
Data Collection:

Data were collected by the aforementioned array of sensors on a 1 second measuring interval for 2 hours before to 2 hours after the contest. Additional data collection of heart rate (correlated to activity level) and average clothing worn (to gain an average clothing insulation value) was conducted by the principle researcher through 25 individual random surveys. Heart rate monitoring was conducted through use of a fingertip Octivetech OT-99 Sports Oximeter and pulse monitor on each of the 25 randomly selected spectators throughout the entire duration of the sporting event. Since this pilot study did not assess for differential thermal comfort within different sections of the stadium, results of the heart rate monitoring were averaged to obtain a single value of (stadium-wide) metabolic work rate. Similarly, clothing was assessed through a simple survey (Appendix A) on each of the 25 randomly selected spectators during the event to obtain an average clothing insulation value for use in analysis.

Sensor Location:

Seven sensor arrays were located throughout the entirety of the stadium (Figure 3) with at least one in each section (A – E), creating a distributed network for analysis as suggested by Brazel and Marcus (1987) and Gutter and Brommer (2010). As per these previous studies’ methodology, each tier of the stadium was taken into account, as thermal differences could occur due to differences in elevation, openness to outside conditions (less stadium architecture influence), and differences in spectator quantity. Wind measurements were collected at both the lower tier and upper tier of stadium section B; the arrays housing the anemometers are denoted in Figure 3 by yellow stars.
**Measurement Height:**

The sensor array were placed on the floor of the stadium and adjusted as per Mayer and Höppe’s (1987) guideline which states measurements of meteorological parameters should follow an average center of gravity (COG) of a seated adult. This COG height was measured on site during set up and adjustments to sensor heights were made.

**Study Site Modeling:**

A three-dimensional rendering of Seth Grove Memorial Stadium and the seven sensor arrays was created for visualization ease and use in data analysis procedures (Figure 3). Three-dimensional model creation was completed via Trimble SketchUp ® software and exported to COLLADA file (which was used as a data exchange medium). The COLLADA file was then imported into the ArcGIS suite for incorporation into three-dimensional data analysis.

![Figure 3: The sensing array (black circles) dispersed pattern of deployment throughout the stadium; yellow stars denote those equipped with anemometers. Image produced by the author for use in 3D analysis.](image)
Data Analysis:

 Upon completion of data collection and subsequent downloading of data to the principal research computer, a custom FORTRAN program, written by the author, was used to analyze each sensor array’s data separately for PMV, PPD, and PET as per the previously mentioned equations. The complete FORTRAN program is included in Appendix B. These results were analyzed for trends and anomalies, then graphed accordingly for visual recognition.

Three-dimensional analysis was conducted through the ESRI ArcGIS® 10.2 suite. Inverse distance weighted interpolation (IDW) was completed for the spatial extent of the stadium seating area using each of the seven collection stations’ data. Interpolation provided a continuous surface of values necessary for an accurate assessment of spatial variations between seating areas (e.g. higher and lower index values dependent on location around the stadium).

Temporal variations in thermal comfort were also explored through the use of three-dimensional analysis. In particular, three-dimensional analysis was used to create a time lapse (one minute interval) over the duration of the event to assess the effect of spectator presence at the study site.

Results & Discussion:

Predicted Mean Vote (PMV):

The predicted mean vote (PMV) for each of the seven individual sensing arrays proved to fall well below the ‘thermal preference’ PMV of zero for the entire duration of the event (Figure 4). PMV was the highest in the stadium (-1.46) at sensing station B–6 near the halftime point of the game (time 14:09). The PMV was found to be lowest (-4.63) at sensing station D–6 prior to the start of the game (time 11:16). Station B–6 saw the highest average PMV (-3.17) while
Figure 4: Predicted Mean Vote (PMV) results for each of the seven individual sensing arrays.
station D–45 experienced the lowest average PMV (-3.68).

Further analysis to discern the variability of PMV reveals a relatively even distribution of values for all sensing arrays (Figure 5). All stations experienced an average PMV value in the -3 to -4 range, indicating extreme thermal [cold] stress as per Matzarakis and Mayer (1997). A statistical summary of individual station PMV calculations is below in Figure 5.

![Figure 5: Statistical summary of Predicted Mean Vote (PMV) results for each of the seven individual sensing arrays. The center of the box represents the median value of all collections, with the top / bottom of the box representing Q1 & Q3 respectively and their spread representing the inter quartile range (IQR); whiskers are set at ±1.5* IQR. Max/min outliers and average are also shown.]

Results of the spatial analysis for thermal comfort, as calculated through PMV, is demonstrated at 30 minute intervals (beginning at the inception of data collection) in Figure 6. The spatial distribution of PMV displays a trend of higher thermal comfort experiences lower in the stadium. Additionally, spatial distribution shows the more central the location of the sensing array within the stadium, the higher the thermal comfort experienced.

Higher thermal comfort is shown to be experienced in lower, central portions of Seth Grove Memorial Stadium. This may be attributed to spectator presence or stadium structure buffering ambient conditions, urban heat island effect, cloud cover, etc. As a pilot study, this research does not attempt to pinpoint these causes, but rather present future research possibilities.
Figure 6: Stadium-wide Predicted Mean Vote (PMV) at half hour intervals.
Stadium-wide, average PMV (Figure 7) displays a trend which may, however, enforce the possibility of spectator presence having an effect on thermal comfort. When analyzed as three different durations (before, during, and after the game), average PMV is seen to increase from -3.66 before the game to -3.18 during the game; it decreases back to -3.47 after the game. Additionally, the standard deviation and variance in PMV experienced during the game ($\sigma = 0.125$, $\sigma^2 = .354$) are significantly less than experienced before ($\sigma = 0.192$, $\sigma^2 = .438$) or after the game ($\sigma = 0.161$, $\sigma^2 = .402$). These results may indicate, such as the findings of Brazel and Marcus (1987), that spectator presence creates a more uniform environment, though such conclusions are outside of the scope of this pilot study, and require more research.

![Stadium Wide Average: Predicted Mean Vote](image)

**Figure 7**: Stadium wide average Predicted Mean Vote (PMV) results.

**Predicted Percentage Dissatisfied (PPD):**

The predicted percentage dissatisfied (PPD): for each of the seven individual sensing arrays indicate extremely high levels of dissatisfaction with the thermal environment, with nearly all PPD values higher than 80% for the entire duration of the event (Figure 8). PPD reached a high of 100% over all sensing stations multiple times throughout the duration of data collection. The
Figure 8: Predicted Percent Dissatisfied (PPD) results for each of the seven individual sensing arrays.
PPD was found to be lowest (48.94) at sensing station B–6 near the halftime point of the game (time 14:09). Station D–45 saw the highest average PPD (99.65) while station B–6 experienced the lowest average PPD (97.24). The results of PPD mirror that of PMV, higher values indicated less satisfaction with the thermal environment.

Further analysis to discern the variability of PPD reveals a highly skewed (towards 100%) distribution of values for all sensing arrays (Figure 9). All stations experienced an average PMV value in the 95% to 100% range, indicating extreme thermal dissatisfaction as per Fanger (1973). The results of individual station PPD calculations are summarized in Figure 9.

**Figure 9:** Statistical summary of Predicted Percent Dissatisfied (PPD) results for each of the seven individual sensing arrays. The center of the box represents the median value of all collections, with the top / bottom of the box representing Q1 & Q3 respectively and their spread representing the inter quartile range (IQR); whiskers are set at ±1.5* IQR. Max/min outliers and average are also shown.

Results of the spatial analysis for thermal comfort, as calculated through PPD, is demonstrated at 30 minute intervals (beginning at the inception of data collection) in Figure 10. The spatial distribution of PPD displays a trend of higher thermal comfort experiences lower in the stadium. Additionally, the analysis shows the more central the location of the sensing array within the stadium, the higher the thermal comfort experienced.
Figure 10: Stadium-wide Predicted Percent Dissatisfied (PPD) at half hour intervals. Note: while rare, votes closer to zero (maximum thermal preference) are typically focused in the central and lower portions of the stadium.
Stadium-wide, average PPD (Figure 11) displays the opposite trends as experienced in stadium-wide PMV analysis, but can be interpreted in the same manner. When analyzed as three different durations (before, during, and after the game), average PPD is seen to decrease from 99.45 before the game to 98.05 during the game; it increases back to 99.11 after the game. These results may indicate, such as the findings of Brazel and Marcus (1987), spectator presence influences the thermal environment and consequently human thermal comfort.

The standard deviation and variance in PPD experienced during the game ($\sigma = 7.678$, $\sigma^2 = 2.771$) were significantly higher than experienced before ($\sigma = 1.448$, $\sigma^2 = 1.203$) or after the game ($\sigma = 3.035$, $\sigma^2 = 1.742$). This contrast to Brazel and Marcus (1987) can be partly attributed to the exponential in the PPD calculation (Eqn. 5), which amplifies the variability found in PMV.

**Figure 11:** Stadium wide average Predicted Percent Dissatisfied (PPD) results.

**Physiological Equivalent Temperature (PET):**

The physiological equivalent temperature (PET) for each of the seven individual sensing arrays proved to fall well below the ‘thermal preference’ PET of 20.5 (Matzarakis et al. 1999) for majority of the event duration (Figure 12). PET was the highest in the stadium (13.59 °C) at sensing station B–6 near the halftime point of the game (time 14:09). The PET was found to be
Figure 12: Physiological Equivalent Temperature (PET) results for each of the seven individual sensing arrays.
lowest (-3.25 °C) at sensing station D–6 prior to the start of the game (time 11:16). Station B–6 experienced the highest average PET (4.49 °C); station D–45 saw the lowest (1.77 °F).

Further analysis to discern the variability of PET reveals a relatively even distribution of values for all sensing arrays (Figure 13), much like that experienced with PMV. The stations experienced more variation in average PET values; ranging from 1.5 °C – 4.5 °C. These PET values are still indicative of extreme thermal [cold] stress, as per (Matzarakis et al. 1999); a determination which is in line with thermal comfort as quantified by PMV and PPD. A statistical summer of the individual station PET calculations is shown below in Figure 13.

![Figure 13: Statistical summary of Predicted Percent Dissatisfied (PPD) results for each of the seven individual sensing arrays. The center of the box represents the median value of all collections, with the top / bottom of the box representing Q1 & Q3 respectively and their spread representing the inter quartile range (IQR); whiskers are set at ±1.5* IQR. Max/min outliers and average are also shown.](image-url)

Results of the spatial analysis for thermal comfort, as calculated through PET, is demonstrated at 30 minute intervals (beginning at the inception of data collection) in Figure 14. The spatial distribution of PET displays a trend similar to that of PMV, higher thermal comfort experiences in the lower / central sections of the stadium.
Figure 14: Stadium-wide Physiological Equivalent Temperatures (PET) at half hour intervals. Note: warmer temperatures are focused in the central and lower portions of the stadium.
Stadium-wide, average PET (Figure 15) shows a trend similar to the trend found in PMV. When analyzed as three different durations (before, during, and after the game), average PET is seen to increase from -1.88 °C before the game to 4.44 °C during the game; it decreases back to -2.89 °C after the game. Additionally, the standard deviation and variance in PET experienced during the game (σ = 3.543, σ² = 1.882) are significantly less than experienced before (σ = 5.432, σ² = 2.331) or after the game (σ = 4.572, σ² = 2.138). These results may indicate, such as the findings of Brazel and Marcus (1987), that spectator presence creates a more uniform environment. Such conclusions on spectator influence are, however, outside of the scope of this pilot study; requiring much more research into alternate possibilities of changes in conditions unrelated to spectator presence.

![Stadium Wide Average: Physiological Equivalent Temperature](image)

**Figure 15:** Stadium wide average Physiological Equivalent Temperatures (PET) results.

**Conclusion:**

The results of this study indicate spectators experienced severe thermal discomfort (cold) at Seth Grove Memorial Stadium on November 11, 2012. These results show that even during a
transitional climatic period like autumn, extreme thermal discomfort can occur. It is important to recall, however, that human thermal comfort as analyzed in this study does not solely depend on the environmental conditions of ambient temperature, mean radiant temperature, and wind speed, but also on human controlled variables of clothing insulation and activity level. It is not unreasonable to hypothesize that if the spectators dressed in more insulated clothing, or were more active, that the thermal comfort within Seth Grove Memorial Stadium on November 11, 2012 could have been much higher and closer to thermal preference. Additionally, it is not unreasonable to assume that had the ambient conditions been much colder there could have been much lower thermal comfort experienced, and it could have approached the extremes of physical danger.

It is the author’s opinion that properly forecasting a range of thermal comfort, rather than providing the conventional forecast of meteorological parameters, prior to an event could make spectators more aware of anticipated conditions, and how to properly dress for events to maximize their thermal experience. An interesting future study opportunity arises from such conjecture – determine what standardly forecasted (meteorological conditions) thresholds are necessary for spectators to modify their clothing selection to achieve a higher level of comfort. The research could then be taken a step further and set up a comparison study between those informed on such standard forecasts and those informed via forecasted human thermal comfort conditions to determine if a different response and resulting comfort occurs between the two groups.

Another research opportunity presented itself in the results of this pilot study as the experienced thermal comfort seemingly both increased and became more uniform with spectator presence (as based on game times). Additional large scale and in-depth studies are necessary to
conclude if spectator presence is indeed an influential factor as implicated in the results of this study, or whether changing ambient conditions are responsible for such results, and coincidently occurred during spectator presence.

This study’s main goal, however, was not to analyze and interpret human thermal comfort results, but rather to serve as a pilot study. The pilot study was designed to address the gaps found in the current literature: cost effective way to collect and analyze *in situ* data for the purpose of assessing the human thermal comfort of large outdoor stadia during an event. The act of computing accurate human thermal comfort assessments of PMV, PPD, and PET with the designed methodology provides verification of the pilot study’s feasibility.

As a successful pilot study, the methodology set forth paves the way for *in situ* human thermal comfort analyses to be efficiently employed in countless large sporting stadia around the world. These large scale studies could provide invaluable insight to stadium design, spectators’ health concerns, and general spectator comfort. For instance, human thermal comfort analysis provides stadium owners with a powerful tool to enhance the spectator experience through the use of modeling and forecasting. By performing multiple thermal comfort analyses, analysts can hone a model for forecasting spectator thermal comfort. By combining stadium design and average spectator activity levels (as gained by multiple studies as samples) with forecasted temperatures, winds, and cloud cover, a clothing recommendation for spectators could be provided to maximize spectator thermal comfort, and minimizes thermal stress.

This pilot study collected and analyzed *in situ* meteorological parameters to assess human thermal comfort sensations felt by spectators in Shippensburg University’s Seth Grove Memorial Stadium during the November 3, 2012 contest versus Cheyney. The study was successful in outlining an effective and efficient manner to assess the thermal comfort *in situ.* Spectator
thermal comfort was found to fall below the threshold of “thermal preference” for the entirety of the data collection duration for each assessed thermal comfort index. The successful methodology of this study, however, provides a basis for future, more expansive, research in similar environments.
Sources Cited:


Appendix A:

Shippensburg University Department of Geography & Earth Sciences
Informed Consent

Biometeorological Evaluation of Stadium Microclimate to Determine Spectator Thermal Comfort

Contact Information

**Principle Investigator:**
Kevin Eaton  
K6466@ship.edu  
717-477-3037

**Faculty Sponsor:**
Timothy Hawkins  
TWHawk@ship.edu  
717-477-1662

Research Overview

Human thermal comfort is the thermal sensation experienced by an individual where there is complete satisfaction and no preference for a warmer or cooler environment. Studying human thermal comfort with respect to spectators at sporting events is important to ensure: (1) the spectator’s experience is enjoyable, (2) health and safety guidelines are being met, (3) a thermal environment which favors return trips exists – a university financial incentive. This study will gather microclimate & human parameters to assess the human thermal comfort you are experiencing today.

The key goals of this research are to answer the following questions:

- What is the average thermal comfort experience in the stadium during this study; how many people were dissatisfied?
- Where are the highest and lowest values of thermal comfort?
- How does thermal comfort vary throughout the course of the event?

The results of this study will:

- Provide feedback to the stadium managers so they can:
  - maximize the thermal comfort experienced within the stadium
  - plan for events with discomfort
  - provide more accurate forecasts of conditions to expect
- Enhance understanding of spectator comfort during football games

Information we need from you:

- Info on clothing you are currently wearing (Attached Survey)
- Pulse measurement - this measurement poses no discomfort as it is taken from fingertip with IR reading (which does not penetrate or disturb the skin) in less than 30 seconds

Confidentiality Statement

All personal data will be kept confidential and kept in a locked cabinet in the primary investigators office. Results will not include personal identifiers, and upon completion of the research all personal data will be destroyed as per proper protocols to ensure confidentiality. You have the right to refuse participation.

Consent

I have been informed of the research and protocols as stated above. At any time during the study, I understand that I may contact the primary investigator or faculty sponsor for more information. Additionally, the chair of the Shippensburg University Human Subjects Committee: **Dr. Dorlisa Minnick**, can be contacted at (717) 477-1785 or djminnick@ship.edu. I have read this form and understood both the form and the explanations given to me. I was given the opportunity to ask questions and am satisfied with the answers. I certify I am at least 18 years of age.

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<td>Jacket</td>
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Other Unlisted

Pulse Measurement: ____________BPM
Appendix B:

```plaintext
PROGRAM HumanThermalComfort
IMPLICIT NONE

* Declaration of Variables *

INTEGER ierror
REAL CLO, MET, WME, Ta, RE, Tbg, Vel, PMV, PPD, PET
CHARACTER (LEN=159) IN_FileName, OUT_FileName
CHARACTER (LEN=16) Date_Time, ArrayLoc, Choice

* List What Variables Are *

CLO is Thermal Resistance of Clothing (Clo)
MET is the Metabolic Work Rate (mets)
WME is the External Work Rate - Typically 0 (mets)
Ta is the Ambient Air Temperature (Celsius)
RE is the Relative Humidity (Percent)
Tbg is the Black Globe Temperature (Celsius)
Vel is the air velocity (m/s)
PMV is the Predicted Mean Vote
PPD is the Predicted Percent Dissatisfied (Percent)
PET is the Physiological Equivalent Temperature (Celsius)
IN_FileName is the input file name & path
OUT_FileName is the output file name & path
Date_Time is the Date & Time of the single observation
ArrayLoc is the location of the sensor array in format Section_Row
Choice is the selection of input type

* Import Data *

WRITE(*,*) 'Do you wish to enter data manually (enter "man") or via file (enter "file")?'
Read(*,*) Choice
IF(Choice == 'file') THEN
  WRITE(*,*)
  WRITE(*,*) 'Ensure the file in the following order: Air Velocity (m/s), Ambiant Air Temp'
  WRITE(*,*) '(Celsius),Relative Humidity (Percent), Black Globe Temp (Celsius)'
```
WRITE(4,*) ;
WRITE(4,*) ;
WRITE(4,*) 'Enter the file path and name of the input file (.prn)'
WRITE(4,*) 'Note: you must use "\" in place of ": Must be entered in quotes " "
WRITE(4,*) ;
READ(4,*) IN_FileName
WRITE(4,*) ;
WRITE(4,*) 'Enter the file path and name of the output file (.prn)'
WRITE(4,*) 'Note: you must use "\" in place of ": Must be entered in quotes " "
WRITE(4,*) ;
READ(4,*) OUT_FileName
WRITE(4,*) ;
WRITE(4,*) ;
WRITE(4,*) 'Enter Thermal Resistance of Clothing (clo)'
READ(4,*) CLO
WRITE(4,*) 'Enter Metabolic Work Rate (met)'
READ(4,*) MET
WRITE(4,*) 'Enter External Work Rate (met) !Typically Zero
READ(4,*) WME

ELSE
WRITE(4,*) 'Enter Thermal Resistance of Clothing (clo)'
READ(4,*) CLO
WRITE(4,*) 'Enter Metabolic Work Rate (met)'
READ(4,*) MET
WRITE(4,*) 'Enter External Work Rate (met) !Typically Zero
READ(4,*) WME
WRITE(4,*) 'Enter Ambient Air Temperature (Celsius)'
READ(4,*) Ta
WRITE(4,*) 'Enter Relative Humidity (Percent)'
READ(4,*) RH
WRITE(4,*) 'Enter Black Globe Temperature (Celsius)'
READ(4,*) Tbg
WRITE(4,*) 'Enter Air Velocity (m/s)'
READ(4,*) Vel
WRITE(4,*) 'Enter Location of the Sensor Array in format Section Row'
READ(4,*) ArrayLoc
WRITE(4,*) 'Enter the Date and Time (mm/dd/yyyy hh:mm)'
READ(4,*) Date_Time
WRITE(4,*) ;
WRITE(4,*) ;
WRITE(4,*) ;
WRITE(4,*) ;
WRITE(4,*) ;
END IF

! Perform Calculations of HTC indices and Write Output

IF(Choice == 'file') THEN
ioerror = 0

OPEN(UNIT=75, FILE = IN_FileName, STATUS = 'OLD', ACTION = 'READ', IOSTAT = ioerror)
IF(ioerror.ne.0) THEN
  WRITE(4,*) 'An error has occurred. Perhaps the input file is not closed or is not in quotes.'
  WRITE(4,*) ''
  STOP
END IF

OPEN(Unit=9, FILE = OUT_FileName, STATUS = 'REPLACE', ACTION = 'WRITE', IOSTAT = ioerror)
IF(ioerror.ne.0) THEN
  WRITE(4,*) 'An error has occurred. Perhaps the input file is not closed or is not in quotes.'
  WRITE(4,*) ''
  STOP
END IF

DO WHILE(ioerror == 0)
  READ(75,*,IOSTAT=ioerror) Vel, Ta, RH, Tbg
  ! WRITE(4,*) 'Vel', Vel, 'Ta', Ta, 'RH', RH, 'Tbg', Tbg
IF (ioerror == 0) THEN
   CALL Calculate_HTC (CLO, MET, WME, Ta, RH, Tbg, Vel, PMV, PPD, PET)
   WRITE(9, '(F7.3,1X,F7.3,1X,F7.3)') PMV, PPD, PET
ELSE
   IF (ioerror < 0) THEN
      WRITE(*,*) 'End of file reached'
      STOP
   ELSE
      IF (ioerror > 0) THEN
         WRITE(*,*) 'An error has occurred'
         STOP
      END IF
   END IF
END IF
END IF

ELSE
   CALL Calculate_HTC (CLO, MET, WME, Ta, RH, Tbg, Vel, PMV, PPD, PET)
   WRITE(*,*) 'For sensor location ', ArrayLoc
   WRITE(*,*) Date_Time
   WRITE(*,*) 'The PMV is ', PMV
   WRITE(*,*) 'The PPD is ', PPD
   WRITE(*,*) 'The PET is ', PET
END IF

! ******************************************************************************
! * Conclusion of HTC Calculations, Program Terminated
! ******************************************************************************

END HumanThermalComfort

Subroutine to calculate human thermal comfort
SUBROUTINE Calculate_MTC (CLO1, MET1, WME1, Tal, RH1, Tbg1, Vell, PMV1, PPD1, PET1)

IMPLICIT NONE

INTEGER n
REAL, INTENT(IN) :: CLO1, MET1, WME1, Tal, RH1, Tbg1, Vell
REAL, INTENT(OUT) :: PMV1, PPD1, PET1
REAL MRT, MRTk, e, Icl, M, W, MW, Fcl, TS, FPNS
REAL HC, HCF, HCN, C1, C2, C3, C4, C5, Tc1g, Tc1, IF, ZN, criteria, TAK, HL1, HL2, HL3, HL4, HL5, HL6

!**********************************************************************************************
! * Declaration of Variables                                                           *
!**********************************************************************************************

CLO1 is Thermal Resistance of Clothing Dummy Variable (clo)
MET1 is the Metabolic Work Rate Dummy Variable (mets)
WME1 is the External Work Rate Dummy Variable - Typically 0 (mets)
Tal is the Ambient Air Temperature Dummy Variable (Celsius)
RH1 is the Relative Humidity Dummy Variable (Percent)
Tbg1 is the Black Globe Temperature Dummy Variable (Celsius)
Vell is the air velocity Dummy Variable (m/s)
PMV1 is the Predicted Mean Vote Dummy Variable
PPD1 is the Predicted Percent Dissatisfied Dummy Variable (Percent)
PET1 is the Physiological Equivalent Temperature Dummy Variable (Celsius)
M is the Metabolic Work Rate (W/m²)
W is the External Work Rate (W/m²)
MW is the Total Work Rate (W/m²)
TAK is the Ambient Air Temperature (Kelvin)
TD is the Dewpoint Temperature (Celsius)
MRT is the Mean Radiant Temperature (Celsius)
MRTk is the Mean Radiant Temperature (Kelvin)
e is the water vapor pressure (Pascals)
Icl is the Clothing Insulation Factor
Fcl is the Clothing Area Factor
HC is the Heat Transfer Coefficient
HCF is the Heat Transfer via Forced Convection Coefficient
HCN is the Heat Transfer via Natural Convection Coefficient
Tc1g is the Clothing Surface Temperature First Guess (Kelvin)
Tc1 is the Clothing Surface Temperature (Celsius)
C1 - C5 are calculation placeholders
n is a count term
criteria refers to iteration criteria
XF and XM are iteration criteria quantifiers
TS is the Thermal Sensation Coefficient

! **********************************************************************************************
! * Vapor Pressure Calculation                                                          *
! **********************************************************************************************

FPNS = exp(16.6536 - 4030.18 / (Tal + 235))
e = RH1 * 10 * FPNS

! **********************************************************************************************
! * Clothing Insulation Calculation (m²2K/W)                                               *
! **********************************************************************************************

Icl = CLO1*0.155

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**Work Rate Conversions to (W/m²)**

\[ M = \text{MET1} \times 50.15 \]
\[ W = \text{WME1} \times 58.15 \]
\[ MN = M - W \]

**Clothing Surface Area Factor**

\[ \text{IF}(\text{lcl} \leq 0.070) \text{ THEN} \]
\[ \text{Fcl} = 1 + (1.29 \times \text{lcl}) \]
\[ \text{ELSE} \]
\[ \text{Fcl} = 1.05 + (0.645 \times \text{lcl}) \]
\[ \text{END IF} \]

**Mean Radiant Temp Calculations**

\[ \text{MRT} = \left( (\text{Tbg1} + 273)^{0.64} + (40000000 \times (\text{Tbg1} - \text{Ta}_1)^{0.15}) \right)^{0.15} - 173 \]

**Forced Convection Heat Trans Coefficient**

\[ \text{HCF} = 12.1 \times \text{SQRT}(\text{Ve}1) \]

**Conversion of Temps to Kelvin**

\[ \text{MRTk} = \text{MRT} + 273 \]
\[ \text{Tak} = \text{Ta}_1 + 273 \]

**Initialize PMV & PPD**

\[ \text{PMV1} = 0 \]
\[ \text{PPD1} = 0 \]

**Calculation of Clothing Surface Temp by Iteration**

\[ \text{Tclg} = \text{Tak} + \left( 35.5 - \text{Tal} \right) / \left( 3.5 \times (6.45 \times \text{lcl}) + 1.1 \right) \] \quad \text{Initial Guess of Tclg} \]

\[ \text{C1} = \text{lcl} \times \text{Fcl} \]
\[ \text{C2} = \text{C1} \times 3.96 \]
\[ \text{C3} = \text{C1} \times 100 \]
\[ \text{C4} = \text{C1} \times \text{Tak} \]
\[ \text{C5} = 308.7 - 0.028 \times \text{MN} + \text{C2} \times (\text{MRTk} / 100)^{0.4} \]
\[ \text{ZN} = \text{Tclg} / 100 \]
\[ \text{ZF} = \text{Tclg} / 50 \]
n = 0
criteria = 100

DO WHILE(criteria > .0015)
  ZF = (ZF + ZN)/2
  HCN = 2.38*(ABS(100*ZF-Tak))**.25  !Heat Transfer via Natural Convection Coefficient
  IF(HCF>HCN) THEN
    HC = HCF
  ELSE
    HC = HCN
  END IF
  ZN = (C5+(C4+HC)-(C2+ZF**4))/(100+C3*HC)
  n = n+1
  IF(n>150) THEN
    PMV1 = 999999.
    PPD1 = 999999.
    STOP
  END IF
  criteria = ABS(ZN-ZF)
END DO
Tci = (100*ZN) - 273

! *************************************************************************!
! " Calculation of Heat Loss Components                                    "
! *************************************************************************!

HL1 = 3.05*0.001*(5733-6.99*MW-e)  !Heat Loss Differential Through Skin
IF(MW>58.15) THEN
  HL2 = 0.42*(MW-58.15)
ELSE
  HL2 = 0
END IF
HL3 = 1.7*0.00001*M*(5867-e)  !Heat Loss by Latent Respiration
HL4 = 0.0014*M*(34-Tal)  !Heat Loss by Dry Respiration
HL5 = 3.66*Fol*(ZG**-4 - (MRTK/100)**-4)  !Heat Loss by Radiation
HL6 = Fol1*HC*(Tci-Tal)  !Heat Loss by Convection

! *************************************************************************!
! " Predicted Mean Vote Calculations                                       "
! *************************************************************************!

TS = 0.303 * EXP(-.038*M) +.028
IF(PMV1 .ne. 999999.) THEN
  PMV1 = TS * (MW-HL1-HL2-HL3-HL4-HL5-HL6)
END IF

! *************************************************************************!
! " Predicted Percent Dissatisfied Calculations                            "
! *************************************************************************!

IF(PPD1 .ne. 999999.) THEN
  PPD1 = 100 - (55 * EXP(-.003353*(PMV1**4) - 0.2179*(PMV1**2)))
END IF
PET1 = 5.3214*(PMV1) + 21.375

END SUBROUTINE Calculate_HTC