CHAPTER 6
THERMAL PERFORMANCE ANALYSIS OF THE CONSTRUCTED SOLAR PASSIVE ARCHITECTURE INCORPORATED RESIDENCE

A modern residence is constructed in Thanjavur, Tamilnadu; incorporating solar passive architecture design features and the thermal performance of the building is analyzed in this chapter.

INTRODUCTION
The main function of the building is to provide a barrier between the desirable conditions inside the building against the extreme weather conditions outside. Comfort is a subjective experience and not all people have the same opinion about optimal comfort. An essential requirement for normal body function is that deep body temperature should be maintained around 37 °C (ASHRAE). If the heat generated cannot be dissipated to the environment or more heat is dissipated than it is being generated, it will lead to change in body temperature causing discomfort. Poor thermal comfort in buildings will affect occupant health and work efficiency.

The standards created by International Green Building Council (IGBC) state that overcooling of space had a drop in people performance by four percent and overheating of space resulted in six percent drop. Many studies have proved that working capacity and performance is very much impaired by exposure to a hot environment. The hot environment prevails in the tropical regions of the earth in which nearly seventy nations including India, with more than 70% of the world population are living in them (Kaushik et al., 1988). Hence, thermal comfort is a very important aspect in designing buildings for tropical region. Analysis of thermal comfort is very essential; as it is associated with the comfort of the occupants as well as consumption of energy.

The performance of the constructed modern building is studied and analyzed to evaluate the effectiveness in providing comfort by incorporating solar passive design features.
6.1 INSTRUMENTATION

The field measurement for thermal performance analysis is carried out in indoor and outdoor during the study. Various parameters measured in:

1. Outdoor are
   - Air temperature
   - Relative humidity
   - Solar insolation

2. Indoor are
   - Air temperature
   - Relative humidity
   - Air velocity
   - Globe temperature/ Mean radiant temperature

The calibrated and certified instruments used for measuring the parameters are as follows:

6.1.1 Measurement of temperature and humidity

![Figure 6.1 Digital Data loggers](image)

Two digital data loggers (HTC Easy Log) are used to measure outdoor temperature, indoor temperature and humidity. The data loggers are designed with high accuracy temperature and humidity sensors. The data loggers used for the study are shown in Figure 6.1 and the specifications are given in Table 6.1.
### Table 6.1 Specifications of temperature and humidity Data logger

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. range</td>
<td>-40°C~70°C</td>
</tr>
<tr>
<td>Temp. Accuracy</td>
<td>-40°C~40°C ± 1.0°C</td>
</tr>
<tr>
<td></td>
<td>40°C~70°C ± 2.0°C</td>
</tr>
<tr>
<td>Humidity range</td>
<td>0 ~ 100 % RH</td>
</tr>
<tr>
<td>Humidity</td>
<td>35 ~ 80 % RH:±3.0%RH</td>
</tr>
<tr>
<td></td>
<td>0 ~ 35 % RH &amp; 80 ~ 100 % RH &lt;±5%RH</td>
</tr>
<tr>
<td>Memory</td>
<td>32000 readings (16000 each for temperature and humidity)</td>
</tr>
<tr>
<td>Measuring rate</td>
<td>1 sec. to 24hrs</td>
</tr>
</tbody>
</table>

#### 6.1.2 Measurement of Wind speed

A three-in-one digital anemometer (MASTECH MS 6252B: ±1% accuracy) used to measure ambient temperature, relative humidity and air flow rate from wind speed is shown in Figure 6.2. The relative humidity is measured at indoor and outdoor of the building. Every time, the digital anemometer is kept ON for about 1 minute before recording the observation. While measuring air velocity, care is taken in such a way that normal functioning of the building and airflow are not disturbed or altered.

![Figure 6.2 Digital Anemometer](image)
6.1.3 Measurement of Solar Insolation
A solar power meter (TES 1333) is used to measure the hourly variation of solar insolation. The meter measures the solar power radiated from any direction, angle or position, and is mounted firmly on a tripod.

![Solar power meter](image)

**Figure 6.3 Solar power meter**
During measurement, the meter is just held parallel to the axis of the building aligned according to the latitude of the location to read the solar insolation falling on the building. The meter has time setting function which can integrate the measured solar power of every second after the desired time is set up in order to get average solar energy. Solar power meter used for the study is shown in Figure 6.3.

6.1.4 Measurement of Day lighting
The day lighting is measured using digital Lux meter (HTC LX-101A). It is a precise and delicate instrument with durable structure. The protective cap is removed from the sensor, so that the white domed light sensor is exposed to the light. It senses brightness or amount of intensity (lux) of any environment. Measurement displayed in the meter is the difference between the measured light level and a stored reference value. It is used to assess the availability of adequate day lighting in all the rooms during the field study of the building. The Lux meter used for the study is shown in Figure 6.4 and the specifications are given in Table 6.2.
Figure 6.4 Digital LUX meter

Table 6.2 Specifications of digital LUX meter

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display</td>
<td>3 ½ digits, big LCD, max display 1999</td>
</tr>
<tr>
<td>4 ranges</td>
<td>200 Lux, 2000 Lux, 20,000 Lux, 200,000 Lux</td>
</tr>
<tr>
<td>Accuracy</td>
<td>≤ 10,000 Lux: ± 4% of reading</td>
</tr>
<tr>
<td></td>
<td>≥ 10,000 Lux: ± 5% of reading</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>2 times/s.</td>
</tr>
<tr>
<td>Sensor</td>
<td>photo diode and filter</td>
</tr>
<tr>
<td>Operation environment</td>
<td>0°C ~ 40°C</td>
</tr>
</tbody>
</table>

6.1.5 Measurement of Globe Temperature and Mean Radiant Temperature

Heat Stress WBGT meter (EXTECH HT30) is used to measure the Wet Bulb Globe Temperature (WBG), Globe Temperature (t₉), Relative Humidity (RH) and ambient temperature (tₐ). The instrument used for the present study is shown in Figure 6.5 and the specifications are shown in Table 6.3. It consists of a hollow copper sphere painted matt black to absorb radiant heat, with the help of temperature sensor placed at its centre. When it reaches a steady state (after 15 minutes) the temperature recorded by the sensor will be between air and radiant temperature. The globe temperature recorded resembles the thermal conditions felt by human body.
Figure 6.5 Heat stress WBGT meter

Mean Radiant Temperature (MRT) is a measure of average temperature of the surfaces surrounding a body. Globe temperature \( t_g \), air temperature \( t_a \) and air velocity \( v_a \) can be used to determine MRT using the Equation 6.1.

\[
\text{MRT} = t_g + 2.42 \, v_a \, (t_g - t_a)
\]  

(6.1)

| Table 6.3 Specifications of Heat Stress WBGT meter |
|----------------------------------|------------------|
| Wet Bulb Globe Temperature (WBGT) | 0 °C to 50 °C     |
| \( T_g \) Black Globe Temperature range | 0 °C to 80 °C     |
| \( T_g \) Accuracy                 | ± 3 °C            |
| \( T_a \) Air Temperature range   | 0 °C to 50 °C     |
| \( T_a \) Accuracy                | ± 3 °C            |
| Relative Humidity (RH)            | 0 to 100% RH      |
| RH Accuracy                       | ±3% (at 25°C, 10 to 95% RH) |
6.1.6 Measurement of Surface temperature

Digital Infrared Thermometer gun (DT8380) is a digital non-contact infrared thermometer with a 4-digit back-lit LCD display to measure the surface temperature of the walls and roof. The instruments used for the study is shown in Figure 6.6. With its built-in laser pointer and single-chip microprocessor, this digital device offers accurate measurement from distance. The specifications are shown in Table 6.4.

Figure 6.6 Infrared Thermometers

<table>
<thead>
<tr>
<th>Table 6.4 Specifications of Digital Infrared Thermometer</th>
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<tbody>
<tr>
<td>Measurement Range</td>
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<tr>
<td>Operating Range</td>
</tr>
<tr>
<td>Accuracy, (T_{amb}=25°C)</td>
</tr>
<tr>
<td>Emissivity</td>
</tr>
<tr>
<td>Response Time (90%)</td>
</tr>
<tr>
<td>Distance: Spot</td>
</tr>
</tbody>
</table>
6.2 METHODOLOGY

6.2.1 Thermal Comfort Factors
The factors that influence thermal comfort can be grouped as environmental factors and personal factors. Environmental factors include air temperature, air velocity, humidity and mean radiant temperature.

Personal factors include metabolic activity of the person and insulation of the clothing.

Metabolic rate: Metabolic activity (m) per unit surface area of the human body is expressed in terms of the unit ‘met’. The metabolic rates of some typical activities are given in Table 6.5.

a) Clo value calculations: Clothing reduces the heat loss from body. It is classified according to its insulation value. Typical summer clothing has a clo value of 0.5 while for winter clothing, the value is 1.0 clo.

Table 6.5 Metabolic rates for some common activities

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Activity</th>
<th>Metabolic rate (met)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Seated, quiet</td>
<td>1.0</td>
</tr>
<tr>
<td>2.</td>
<td>Seated, reading or writing</td>
<td>1.0</td>
</tr>
<tr>
<td>3.</td>
<td>Typing</td>
<td>1.1</td>
</tr>
<tr>
<td>4.</td>
<td>Standing, relaxed</td>
<td>1.2</td>
</tr>
<tr>
<td>5.</td>
<td>Cooking</td>
<td>1.6 – 2.0</td>
</tr>
</tbody>
</table>

6.2.2 Thermal Comfort indices
Thermal comfort performance analysis of a building can be carried out using thermal comfort index. A thermal index combines two or more variables that affect thermal comfort in a building. Indices can be empirical (from results of experimental investigations done with people) or rational (obtained using laws of heat transfer). The thermal indices used for the present study are as follows:

6.2.2.1 Fenestrations to Floor area ratio & Roof opening to Floor area ratio
According to IS 3362-1977; Code of practice for warm humid climate, fenestrations having 15-20% of floor area is found adequate for both ventilation and adequate day lighting. Ratio of roof opening to floor area having 2-5% in a building will have good stack effect.
6.2.2.2 National Building Code (NBC) Standard
The thermal comfort conditions given in National Building Code (NBC) of India are based on the study of Tropical Summer Index (TSI). According to NBC, the thermal comfort limit of a person ranges from 25 °C to 30 °C. Similarly, the comfortable indoor relative humidity and air flow ranges from 30-60% and 0-2 m/s respectively.

6.2.2.3 Bio-Climatic Chart
Victor Olgyay defined thermal comfort using the bioclimatic chart as shown in Figure 6.7. The Bioclimatic chart combines temperature, relative humidity, wind speed and radiant temperature to define the human comfort zone. The chart is based on outdoor climatic conditions, which resulted in some limitations while analyzing the physiological requirement of indoor conditions of the building. Hence, the chart can be used as a tool in warm humid climate to assess the comfort zone.

![Figure 6.7 Bio climatic chart used for Thermal comfort analysis](image)

6.2.2.4 Day Light requirements
According to Green Rating for Integrated Habitat Assessment (GRIHA) version 5, Useful Daylight Illuminance (UDI) should fall within the range of 100 to 2000 lux. A building with less than 100 lux would be considered to have insufficient daylight while more than 2000 lux is considered to have excessive day light.
According to other standards, the adequate day light requirement is given in Table 6.6.

**Table 6.6 Adequate day light requirement for comfort conditions**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Optimum range</th>
</tr>
</thead>
<tbody>
<tr>
<td>International LEED (Leadership in Energy and Environmental Design)</td>
<td>75% of the regularly occupied spaces be lit with day light</td>
</tr>
<tr>
<td>IGBC (Indian Green Building Council) Green Homes</td>
<td>50% of the regularly occupied spaces be lit with day light</td>
</tr>
</tbody>
</table>

**6.2.2.5 Ventilation requirement for thermal comfort:**

The ventilation requirement for the building based on the temperature and relative humidity can be assessed using the recommendations given in NBC. The desirable wind speed for thermal comfort is shown in Table 6.7.

**Table 6.7 Desirable wind speed (m/s) for thermal comfort conditions**

<table>
<thead>
<tr>
<th>Dry bulb temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 °C</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>30 °C</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.24</td>
<td>0.53</td>
<td>0.85</td>
</tr>
<tr>
<td>31 °C</td>
<td></td>
<td>*</td>
<td>0.06</td>
<td>0.24</td>
<td>0.53</td>
<td>1.04</td>
<td>1.47</td>
<td>2.10</td>
</tr>
<tr>
<td>32 °C</td>
<td></td>
<td>0.2</td>
<td>0.46</td>
<td>0.94</td>
<td>1.59</td>
<td>2.26</td>
<td>3.04</td>
<td>-</td>
</tr>
<tr>
<td>33 °C</td>
<td></td>
<td>0.77</td>
<td>1.36</td>
<td>2.12</td>
<td>3.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>34 °C</td>
<td></td>
<td>1.85</td>
<td>2.72</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>35 °C</td>
<td></td>
<td>3.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(Source: Clause 5.2.3.1, National Building Code)

**6.2.2.6 Tropical Summer Index (TSI)**

Central Building Research Institute, Roorkee has developed Tropical Summer Index (TSI) suitable for Indian climatic conditions. TSI is defined as the temperature of still air at 50% relative humidity, which produces the same thermal sensation as the environment under consideration (BIS, 1987). TSI is determined using Equation 6.2 where \( t_g \) is the globe temperature, \( t_w \) is the wet bulb temperature and \( v_a \) is the air velocity.

\[
\text{TSI} = (0.308 \times t_w) + (0.743 \times t_g) - (2.06 \times v_a^{1/2}) + 0.80
\]

(6.2)
Ranges of TSI for different thermal sensations are given in Table 6.8.

<table>
<thead>
<tr>
<th>Thermal sensation</th>
<th>Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slightly Cool</td>
<td>19.0 – 25.0</td>
</tr>
<tr>
<td>Comfortable</td>
<td>25.0 – 30.0</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>30.0 – 34.0</td>
</tr>
</tbody>
</table>

6.2.2.7 Adaptive Comfort Model
As per Madhavi Indraganti (2015), the adaptive comfort model is a linear regression model which relies on the fundamental principle that “if a change occurs that produce discomfort, people react in ways which tend to restore comfort” (Nicol, 1993). It therefore integrates various environmental, behavioral and psychological adaptations and thus forms the basis for sustainable thermal comfort standards. Accordingly, the thermal comfort limit based on adaptive comfort for a person in the southern region of India (Hyderabad) ranges from 26.0 °C and 32.5 °C.

6.2.2.8 Statistical Analysis of the building using SPSS
Correlation and linear regression enables to represent the relationship between two parameters by simple algebraic expressions. In the present study, SPSS statistical package is used to carry out regression analysis and to estimate correlation coefficients using ANOVA table. Using one-way ANOVA table, the Pearson correlation co-efficient (R), coefficient of determination (R²), regression equation for the designed building are determined for all the twelve months separately and overall for one year. For an equation of good fit,
- Correlation coefficient (R) should be close to 1
- Coefficient of determination (R²) should be highest
- Reduced Chi-square (χ²) should be lowest
- Root Mean Square Error RMSE should be lowest

6.3 RESULTS AND DISCUSSION
To analyse the thermal performance of the designed building; temperature, relative humidity, air velocity, day lighting and solar radiations are measured on hourly basis
during all the twelve months. Indoor parameters measured in living cum dining area of the building are used for analysis, as this space of the house is utilized maximum by the residents.

6.3.1 Design aspects

6.3.1.1 Fenestrations to Floor area ratio

In the designed building the total wall area is 2500 sq. ft. and the total fenestration area is 320 sq. ft. resulting in 17.8% Fenestrations to Floor area. This is in accordance with IS 3362-1977 and contributes for adequate ventilation and lighting.

6.3.1.2 Roof opening to floor area ratio

In the designed building the total floor area is 1200 sq. ft. and the roof openings is 50 sq. ft. Roof opening to floor area ratio is 4.17%. The ratio is adequate that promotes stack effect and ventilation.

6.3.2 Thermal comfort Analysis of the designed building from January to December

Table 6.9 to Table 6.11 shows the mean of indoor and outdoor temperature recorded from January to December and Table 6.12 gives the yearly mean of indoor and outdoor temperature & relative humidity. From the data, a similarity could be observed between the maximum outdoor temperature and maximum indoor temperature inside the designed building with SPD features during all the 12 months. A distinct variation could also be observed in indoor temperature which depends on outdoor temperature. Maximum outdoor temperature occurs at 14.00 hours during all the months. The maximum indoor temperature is found to lag behind the maximum outdoor temperatures by two hours during summer and ranges up to four hours during winter. This is attributed to high solar insolation during summer which allows heat readily to enter into the building when compared to winter due to low solar insolation. The maximum and minimum indoor temperature as well as outdoor temperature is indicated in Table 6.9 - 6.11 using different shades for every month. The outdoor temperature at the building site taken for study ranges from 20.8 °C to 39.9 °C during the study period. The temperature inside the designed building ranges from 24.1°C to 32 °C.

Variation of yearly mean indoor temperature with respect to outdoor temperature is shown in Figure 6.8. From the graph, it is found that the temperature inside the building is much lesser than the outdoor temperature during day time (from 9.00 am to 8.00 pm).
During night, the indoor is slightly warm than the outdoor due to thermal insulation of the building elements which retain heat. Similarly, Variation of yearly mean indoor humidity with respect to outdoor humidity is shown in Figure 6.9. It is also observed that the indoor temperature and indoor relative humidity do not have much dispersion when compared to outdoor temperature and outdoor relative humidity. The thermal comfort in the building is maintained even during harsh outdoor conditions. This characteristic is similar to traditional buildings and is contrary to modern buildings without SPD. Hence, it is apparent the solar passive features incorporated in the designed building contribute for thermal comfort.

According to NBC Standards, occupants feel uncomfortable inside a building when it exceeds 30°C. Number of hours exceeding 30°C inside the designed building is found to be 66 hours out of 288 hours recorded throughout the year. This shows that only 23% of the duration in a year has uncomfortable temperature in the designed building which can be compensated by very minimal airflow thus making the designed building comfortable throughout the year in a natural way.
Table 6.9 Temperature data (in °C) during January to April

<table>
<thead>
<tr>
<th>Hour</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
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<tbody>
<tr>
<td></td>
<td>$T_i$</td>
<td>$T_o$</td>
<td>$T_i$</td>
<td>$T_o$</td>
</tr>
<tr>
<td>1</td>
<td>25.5</td>
<td>21.5</td>
<td>27.2</td>
<td>26.3</td>
</tr>
<tr>
<td>2</td>
<td>25.3</td>
<td>22.1</td>
<td>27.2</td>
<td>26.0</td>
</tr>
<tr>
<td>3</td>
<td>25.3</td>
<td>21.5</td>
<td>27.2</td>
<td>25.6</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>21.2</td>
<td>27.1</td>
<td>25.2</td>
</tr>
<tr>
<td>5</td>
<td>24.8</td>
<td>21.0</td>
<td>27.1</td>
<td>25.4</td>
</tr>
<tr>
<td>6</td>
<td>24.7</td>
<td>21.9</td>
<td>27.0</td>
<td>26.3</td>
</tr>
<tr>
<td>7</td>
<td>24.8</td>
<td>22.1</td>
<td>27.1</td>
<td>27.4</td>
</tr>
<tr>
<td>8</td>
<td>24.9</td>
<td>23.4</td>
<td>27.2</td>
<td>28.2</td>
</tr>
<tr>
<td>9</td>
<td>25.2</td>
<td>24.8</td>
<td>27.5</td>
<td>29.1</td>
</tr>
<tr>
<td>10</td>
<td>25.4</td>
<td>26.3</td>
<td>27.7</td>
<td>30.3</td>
</tr>
<tr>
<td>11</td>
<td>25.8</td>
<td>27.9</td>
<td>27.8</td>
<td>31.0</td>
</tr>
<tr>
<td>12</td>
<td>26.0</td>
<td>28.7</td>
<td>27.9</td>
<td>31.9</td>
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<td>13</td>
<td>26.1</td>
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<td>28.1</td>
<td>33.7</td>
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<td>15</td>
<td>26.3</td>
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<td>16</td>
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<td>22.2</td>
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</table>
Table 6.10 Temperature data (in °C) during May to August

<table>
<thead>
<tr>
<th>Hour</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$T_i$</td>
<td>$T_o$</td>
<td>$T_i$</td>
<td>$T_o$</td>
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<tr>
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<td>29.5</td>
<td>29.9</td>
<td>28.1</td>
</tr>
<tr>
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- $T_i$ max
- $T_i$ min
- $T_o$ max
- $T_o$ min
Table 6.11 Temperature data (in °C) during September to December

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Figure 6.8 Yearly Mean Temperature Data for the constructed SPD building

Figure 6.9 Yearly Mean RH Data for the constructed SPD building
6.3.3 Comfort zone Analysis using Bioclimatic chart
Bioclimatic chart is used as a tool for analyzing the performance of the building. The chart helps to locate the comfort zone using dry bulb temperature and relative humidity. The mean maximum and minimum temperature during the study period and its corresponding relative humidity are marked on the chart for both summer and winter which is shown in Figure 6.10.
It is observed that the thermal comfort parameters lie well within the comfort zone for the designed building in both summer and winter. This ensures the proper design of the building.

![Bioclimatic chart analysis of designed building in summer and winter](image)

Figure 6.10 Bio climatic chart analysis of designed building in summer and winter

6.3.4 Day lighting in the designed building
Day lighting measured on hourly basis from 9.00 hours to 14.00 hours in the designed building during summer and winter in all the rooms are given in Table 6.13 and Table 6.14 respectively. It is observed that almost 95% of the regularly occupied spaces are lit with adequate day light during the period of study. Day lighting in the designed building is in accordance with GRIHA, LEED, IGBC and NBC standards. Sufficient day lighting in the building also contributes for power saving, as artificial lighting is totally avoided in the rooms during day time.

100
Table 6.13 Measured Day light data for the SPD building during summer

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<th>Time (hours)</th>
<th>Living</th>
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<th>Courtyard</th>
<th>Kitchen</th>
<th>Bedroom</th>
<th>Room</th>
<th>Parking</th>
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Table 6.14 Measured Day light data for the SPD building during winter

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6.3.5 Tropical Summer Index (TSI)

Based on the observations made for a period of 5 days during peak summer, the thermal sensation range of TSI for the designed building in Thanjavur is determined using wet bulb temperature ($t_w$), globe temperature ($t_g$) and air velocity ($v_a$). The results are shown in Table 6.15 and it is observed that the value of TSI is within 25-30 °C. It is evident that the designed building is within the comfortable range of the TSI.

Table 6.15 Tropical Summer Index (TSI) for the designed building

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<th>RH (%)</th>
<th>$t_w$ (°C)</th>
<th>$t_g$ (°C)</th>
<th>$v_a$ (m/s)</th>
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<th>TSI (°C)</th>
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<td>30.7</td>
<td>41.8</td>
<td>21.4</td>
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<td>30.5</td>
<td>29.0</td>
</tr>
<tr>
<td>15</td>
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<td>34.5</td>
<td>19.7</td>
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<td>0.40</td>
<td>30.5</td>
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<td>30.8</td>
<td>0.50</td>
<td>30.6</td>
<td>28.0</td>
</tr>
<tr>
<td>17</td>
<td>31.2</td>
<td>27.5</td>
<td>18.2</td>
<td>31.0</td>
<td>0.60</td>
<td>30.7</td>
<td>27.8</td>
</tr>
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<td>30.6</td>
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<td>30.3</td>
<td>27.6</td>
</tr>
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<td>19.8</td>
<td>30.4</td>
<td>0.60</td>
<td>30.0</td>
<td>27.9</td>
</tr>
<tr>
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<td>43.0</td>
<td>20.8</td>
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<td>21</td>
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<td>48.8</td>
<td>22.0</td>
<td>29.6</td>
<td>0.10</td>
<td>29.6</td>
<td>28.9</td>
</tr>
<tr>
<td>22</td>
<td>29.8</td>
<td>51.4</td>
<td>22.3</td>
<td>28.6</td>
<td>0.10</td>
<td>28.3</td>
<td>28.3</td>
</tr>
<tr>
<td>23</td>
<td>28.9</td>
<td>56.4</td>
<td>22.4</td>
<td>28.6</td>
<td>0.00</td>
<td>28.6</td>
<td>28.9</td>
</tr>
<tr>
<td>24</td>
<td>28.5</td>
<td>57.5</td>
<td>22.6</td>
<td>28.2</td>
<td>0.10</td>
<td>28.1</td>
<td>28.1</td>
</tr>
</tbody>
</table>
6.3.6 Thermal Comfort models

Various thermal comfort models have been proposed to predict the comfortable indoor temperature based on the monthly mean temperature. The monthly mean temperature $T_o$ for Thanjavur during the month of May (summer) and December (winter) is 32.25 °C and 24.6 °C respectively. Comfortable temperature for the designed building during summer and winter has been calculated for different models and is given in Table 6.16.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Thermal comfort models</th>
<th>Model Equation</th>
<th>Predicted Comfortable temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T_c = 12.1 + 0.53T_o$</td>
<td>Summer: 29.19 Winter: 25.14</td>
</tr>
<tr>
<td>1</td>
<td>Humphreys (1978)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Nicol and Roaf (1994)</td>
<td>$T_c = 17.0 + 0.38T_o$</td>
<td>Summer: 29.26 Winter: 26.35</td>
</tr>
<tr>
<td>3</td>
<td>Auliciems and de Dear (1978)</td>
<td>$T_c = 17.6 + 0.31T_o$</td>
<td>Summer: 27.60 Winter: 25.23</td>
</tr>
<tr>
<td>4</td>
<td>Humphreys and Nicol (2000)</td>
<td>$T_c = 13.5 + 0.54T_o$</td>
<td>Summer: 30.92 Winter: 26.78</td>
</tr>
</tbody>
</table>

The observed indoor temperature in the building ranges between 25.1 °C and 26.9 °C during winter and from 29.2 °C to 31.9 °C during summer which is close to the predicted value of all the models. Observations show that the predicted comfortable temperature proposed by Humphreys and Nicol (2000) is the most suitable model as compared to other models for the solar passive designed building under study.

6.3.7 Correlating indoor and outdoor temperature using regression analysis

Equation of least squares line that approximates the regression of the indoor temperature of the constructed modern SPD house on outdoor temperature determined by linear regression analysis using statistical package SPSS is given in Table 6.17 and the summary of analysis is given in Appendix B.

Variation of indoor temperature with respect to outdoor temperature and the best-fit correlation corresponding to the observed data for all the twelve months (January to December) and for mean of one year data are separately shown in Figure 6.11 – 6.13 and Figure 6.14 respectively.
The correlation coefficient (R) is observed to be positive and close to 1, ranging from 0.805 to 0.944. This shows that the outdoor temperature has a significant impact on indoor temperature.

The coefficient of determination ($R^2$) is observed to vary from 0.648 to 0.891. This shows that there are other outdoor parameters that contribute to indoor temperature in addition to outdoor temperature.

The correlation function between $T_i$ and $T_o$ for the designed building (determined using the mean of one year data) is as follows:

$$T_i = 22.979 + 0.188T_o$$  \hspace{1cm} (6.3)

$$R^2 = 0.808; \text{ standard error of } \pm 0.294 ^\circ C$$

### Table 6.17 Results of linear regression analysis for the designed house using SPSS

<table>
<thead>
<tr>
<th>Month</th>
<th>Regression Equation</th>
<th>Correlation coefficient (R)</th>
<th>Coefficient of determination ($R^2$)</th>
<th>Reduced Chi-square ($\chi^2$)</th>
<th>Root Mean Square Error RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>$T_i = 0.147T_o + 21.975$</td>
<td>0.814</td>
<td>0.662</td>
<td>0.116</td>
<td>0.341</td>
</tr>
<tr>
<td>February</td>
<td>$T_i = 0.138T_o + 23.590$</td>
<td>0.918</td>
<td>0.842</td>
<td>0.031</td>
<td>0.176</td>
</tr>
<tr>
<td>March</td>
<td>$T_i = 0.385T_o + 17.499$</td>
<td>0.944</td>
<td>0.891</td>
<td>0.213</td>
<td>0.462</td>
</tr>
<tr>
<td>April</td>
<td>$T_i = 0.125T_o + 25.933$</td>
<td>0.811</td>
<td>0.657</td>
<td>0.125</td>
<td>0.354</td>
</tr>
<tr>
<td>May</td>
<td>$T_i = 0.222T_o + 22.930$</td>
<td>0.916</td>
<td>0.839</td>
<td>0.133</td>
<td>0.364</td>
</tr>
<tr>
<td>June</td>
<td>$T_i = 0.235T_o + 22.733$</td>
<td>0.805</td>
<td>0.648</td>
<td>0.421</td>
<td>0.649</td>
</tr>
<tr>
<td>July</td>
<td>$T_i = 0.314T_o + 20.191$</td>
<td>0.914</td>
<td>0.835</td>
<td>0.153</td>
<td>0.391</td>
</tr>
<tr>
<td>August</td>
<td>$T_i = 0.161T_o + 25.379$</td>
<td>0.901</td>
<td>0.812</td>
<td>0.068</td>
<td>0.261</td>
</tr>
<tr>
<td>September</td>
<td>$T_i = 0.143T_o + 22.411$</td>
<td>0.867</td>
<td>0.751</td>
<td>0.051</td>
<td>0.226</td>
</tr>
<tr>
<td>October</td>
<td>$T_i = 0.099T_o + 24.434$</td>
<td>0.833</td>
<td>0.694</td>
<td>0.027</td>
<td>0.163</td>
</tr>
<tr>
<td>November</td>
<td>$T_i = 0.114T_o + 24.519$</td>
<td>0.858</td>
<td>0.736</td>
<td>0.026</td>
<td>0.161</td>
</tr>
<tr>
<td>December</td>
<td>$T_i = 0.133T_o + 22.530$</td>
<td>0.892</td>
<td>0.796</td>
<td>0.078</td>
<td>0.279</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td><strong>$T_i = 0.188T_o + 22.979$</strong></td>
<td><strong>0.899</strong></td>
<td><strong>0.808</strong></td>
<td><strong>0.087</strong></td>
<td><strong>0.294</strong></td>
</tr>
</tbody>
</table>

Overall (1 year )
Figure 6.11 Regression analysis of temperature data from January to April
Figure 6.12  Regression analysis of temperature data from May to August
Figure 6.13 Regression analysis of temperature data from September to December
6.3.8 Correlating indoor temperature ($T_{i}$) and outdoor relative humidity (RH)

Linear regression analysis is carried out to determine the correlation between indoor temperature ($T_{i}$) and outdoor relative humidity (RH) using SPSS and the variation between the two parameters with best-fit correlation is shown in Figure 6.15. It is observed that there is strong correlation between the two parameters and is found that indoor temperature decreases with increase in outdoor relative humidity. The correlation function between $T_{i}$ and $RH_{out}$ is as follows:

$$T_{in} = 30.779 - 0.032 RH_{out} \quad (6.4)$$

$$R^2 = 0.776: \text{standard error of } \pm 0.317 \degree C$$
6.3.9 Thermal performance of the designed building during summer and winter

To study the performance of the designed building during summer and winter; solar insolation, temperature, humidity and air velocity are recorded during the month of April to assess the thermal comfort during summer and during the month of November, to assess the thermal comfort during winter. The parameters are recorded on hourly basis from 9.00 hours to 17.00 hours during the study period and its mean is given in Table 6.18 and Table 6.19.

Solar insolation has a significant impact on outdoor and indoor temperature. It can be observed that the outdoor temperature generally follows the fluctuation of solar insolation without any time delay whereas indoor temperature follows the fluctuation of solar radiation with a thermal time lag of about 2-4 hours in winter and 1-2 hours in summer. The time delay is due to thermal inertia of the building materials and buffer spaces used in the design. The solar radiation is found to vary between 499.7 W/m² to 1258 W/m² with 10 hours of sunshine each day during April, whereas the solar insolation varies from 421.3 W/m² to 1115 W/m² during November.
From Table 6.18 and 6.19, indoor temperature is found to be much lesser than the outdoor temperature. The maximum indoor temperature recorded during the study period for summer and winter is 30.7 °C and 28.1 °C. During summer, in the month of April, the difference between indoor and outdoor temperature varies from 2.2 – 4.9 °C. During winter, in the month of November, the difference between the indoor and outdoor temperature varies from 0.6 – 3.3 °C. The drastic decrease in temperature is mainly attributed due to solar passive architecture incorporated in the building design. It is also found that indoor air temperature and relative humidity inside the designed building are well within the comfort zone during winter season and is close to the comfort zone during summer, according to NBC (25-30 °C). When outdoor temperature drops down and humidity raises very high, adequate comfort is attained in the designed building. The presence of stack effect and cross ventilation in the building facilitates sufficient air flow. The air velocity inside the building is found to be varying from 0.05 m/s to 0.4 m/s during summer and winter. This air flow contributes to the thermal comfort of the occupants when the temperature or humidity exceeds the comfortable limit. This air flow is sufficient enough to keep the indoor comfortable in a natural way. Hence, the use of electromechanical gadgets is minimized thereby reducing the power consumption.

<table>
<thead>
<tr>
<th>Time</th>
<th>Solar Insolation (W/m²)</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (W/m²)</th>
<th>Air Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April</td>
<td>November</td>
<td>April</td>
<td>November</td>
</tr>
<tr>
<td>9.00</td>
<td>619.5</td>
<td>512.9</td>
<td>29.4</td>
<td>26.6</td>
</tr>
<tr>
<td>10.00</td>
<td>840.8</td>
<td>662.2</td>
<td>31.6</td>
<td>28.2</td>
</tr>
<tr>
<td>11.00</td>
<td>1049.0</td>
<td>880.7</td>
<td>32.9</td>
<td>29.8</td>
</tr>
<tr>
<td>12.00</td>
<td>1104.0</td>
<td>1009.0</td>
<td>33.6</td>
<td>30.3</td>
</tr>
<tr>
<td>13.00</td>
<td>1258.0</td>
<td>1115.0</td>
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<td>30.8</td>
</tr>
<tr>
<td>14.00</td>
<td>1164.0</td>
<td>1029.0</td>
<td>35.2</td>
<td>31.2</td>
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<tr>
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<td>1087.0</td>
<td>35.0</td>
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</tr>
<tr>
<td>16.00</td>
<td>778.6</td>
<td>494.0</td>
<td>34.7</td>
<td>29.6</td>
</tr>
<tr>
<td>17.00</td>
<td>499.7</td>
<td>421.3</td>
<td>34.0</td>
<td>29.0</td>
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</table>
### Table 6.19 Indoor Parameters measured for the constructed SPD

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (W/m²)</th>
<th>Air Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April</td>
<td>November</td>
<td>April</td>
</tr>
<tr>
<td>9.00</td>
<td>29.2</td>
<td>27.4</td>
<td>71.6</td>
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<td>27.8</td>
<td>54.6</td>
</tr>
<tr>
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<td>52.0</td>
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<td>28.1</td>
<td>46.0</td>
</tr>
<tr>
<td>17.00</td>
<td>30.7</td>
<td>28.1</td>
<td>46.2</td>
</tr>
</tbody>
</table>

#### 6.5 SUMMARY

A modern residence has been constructed with solar passive designs such as courtyard, atrium, roof level ventilators, light coloured exterior, reflective white coloured roofing tiles, landscaping, shading and buffer spaces in Thanjavur district and the thermal comfort in the building is studied during summer and winter. It should be noted that the techniques used are highly site specific and climate specific. The indoor air temperature of the modern building designed with SPD is observed to be much lower than the outdoor temperature. The study proves that the temperature and relative humidity are well within the comfortable limits ranging very close from 25-30 °C for both the seasons as per TSI and NBC standards. Bioclimatic chart also indicates that the parameters of designed building lie in the comfortable zone. Different thermal comfort models are studied and it is found that the predicted comfortable temperature given by Humphreys and Nicol (2000) is the best fit for the building under study. Using regression analysis, it is observed that outdoor temperature and relative humidity have good correlation with indoor temperature. Thus, coupling of techniques adopted in traditional buildings into the present day constructions with available modern materials will certainly be an example towards sustainable development.