PLEA 2018

VOLUME 1

34th International Conference on
Passive and Low Energy Architecture

Smart and Healthy
Within the Two-Degree Limit

Edited by:

Edward Ng, Square Fong, Chao Ren

PLEA 2018:

Smart and Healthy Within the Two-Degree Limit

Proceedings of the 34th International Conference on

Passive and Low Energy Architecture;

Dec 10-12, 2018

Hong Kong, China

Organised by:

香港中文大學
The Chinese University of Hong Kong

建築 中大

INSTITUTE OF
Future Cities

香港中文大學環境、
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Conference Proceedings Edited by:
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AIT Building
Shatin, New Territories
Hong Kong SAR, China

Electronic version as:
ISBN: 978-962-8272-36-5

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Volume 1 – Long Paper

Assessment of ThermODrain System on Thermal Comfort:
Study of a Multi-Storied Office Building in Nashik, India

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ABSTRACT: A ThermODrain (TOD) is a system that uses water cooled by night sky to drain the radiant heat within a building. In office buildings, 'all air-cooled' systems are most prevalent. The study aimed to assess the thermal comfort of occupants in a ground and two storied naturally ventilated office building in the composite climate of Nashik in India where TOD system was installed. Assessment was conducted by taking hourly readings over a 25-hour period in peak summer of May 2017. Primary data collected included Dry Bulb Temperature (DBT) and Relative Humidity (RH) indoors, surface temperature of top and bottom of roof slab and Globe temperature within the office. Secondary data for the same period was obtained from the Indian Meteorological Department (IMD). Monthly electricity bills were used to measure the Energy Performance Index (EPI). The Tropical Summer Index (TSI), an index suggested in the National Building Code (NBC) 2016 of India, was calculated. Results show that the indoor operative temperature in the peak of summer with outdoor temperature of 36.30C was found to be close to the neutral temperature of 27.50C. The EPI of 26.5 kwh/m^2/year falls within the BEE 5-star rating of below 40 kwh/m^2/year.
KEYWORDS: ThermODrain (TOD) system, Thermal Comfort, Office Building, Tropical Summer Index (TSI), Energy Performance Index (EPI)

1. INTRODUCTION

A ThermODrain (TOD) system is not a common practice in modern office buildings where predominantly air-cooled systems prevail. Unlike radiant cooling systems with active coolants and pump, the ThermO-Drain system uses water cooled by night sky as a sink to drain radiant heat from the structure.

As per the data from the Indian Meteorological Department (IMD), the city of Nashik in Maharashtra located at an elevation of 700m above mean sea level, has a maximum Dry Bulb Temperature (DBT) of 37^{0}C in April and May, while minimum temperatures can reach 10^{0}C in January and February. Daily diurnal range of temperature is about 15^{0}C. Average annual rainfall is about 705mm.Relative humidity fluctuates significantly in a single day.

The case study office building is a ground + 2 storied building with flat roof admeasuring 258.5 sq.m carpet area. The building is oriented north-south. Entrance is from the North while South wall is common to adjacent plot building. WWR (Wall Window Ratio) on North is 35%, East 20% and West 57%. Overall WWR is 30%. Windows are well shaded and have an overall equivalent SHGC of 0.66. Passive design strategies used in the building include appropriate orientation (South side is a common wall with neighboring building), use of double wall in the building envelope made of fly ash bricks and Gujarat brick cladding with air gap, use of turbo ventilators to facilitate stack ventilation and use of high albedo reflective paint with SRI>0.5 to reduce heat gain from horizontal surfaces. The plan and section of the building are shown in Figure 1a and b.

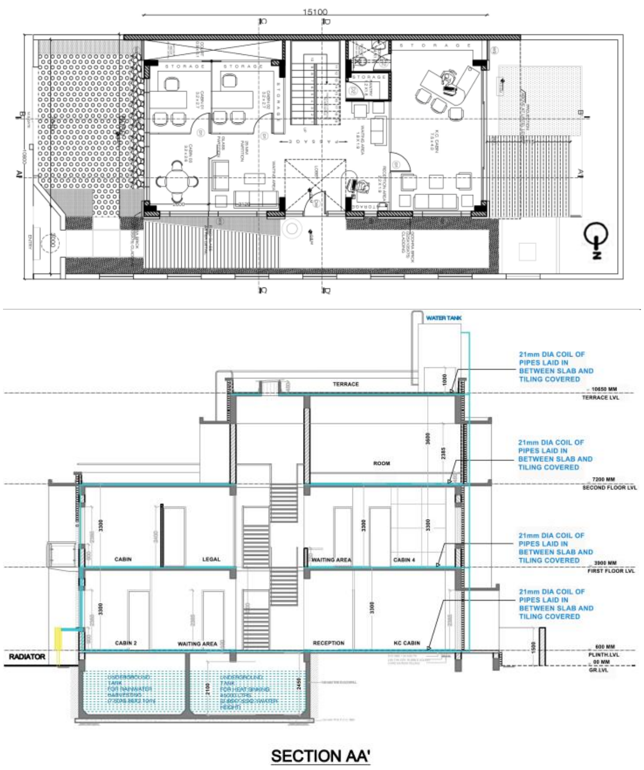

Figure 1: (a) Plan and (b) Section of the office building in Nashik

2. THERMO-DRAIN (TOD) SYSTEM

ThermODrain (TOD) system is a method based on the principal of removing heat from the floor and roof of the structure by laying a loop of plastic pipes between the slab screed and the tiling. Water from an underground water tank is circulated in the pipes that are cooled by a radiator that cools the water through night sky radiation. Figure 2a and b show the TOD system on terrace slab - during construction and post construction - the finished terrace slab.

Figure 2: Top (a)Laying out of the TOD system during construction and below (b) the finished terrace slab with the TOD system within

The TOD system installed at the office building in Nashik comprises of 21 mm diameter plastic pipes laid out in a grid at 0.3m center to center distance on the plinth of all floors. The system is designed to remove 242 Btu/ sq. ft. / hour (763 W/m^2) of heat from the plinth mass of the structure. The thermal conductance of the pipe in the grid is 4.5 W/m^{2}C. Thus heat removed by the pipe is 77 Btu/ Hr (22.56 W) for every 1 m of the pipe. The schematic layout of the system is shown in Figure 3.

The water picks up the roof heat (water absorbs 4100 joules per liter per Deg. C) and passes through a radiator which rejects most of it. Lukewarm water is stored in the tank and re-cycled through the radiator at night, when the cool night air absorbs the residual heat. The cycle starts again the next morning. Energy for the pump and the fan is supplied by solar PV system.

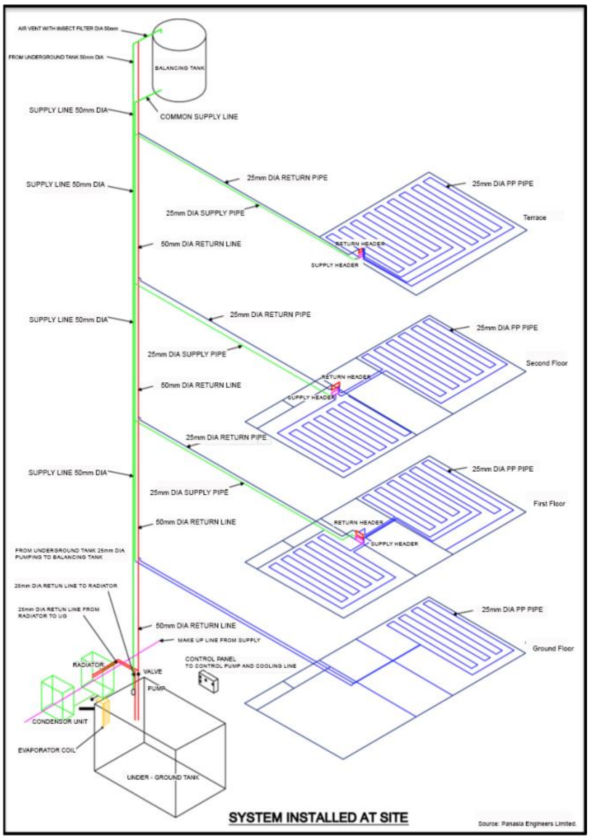

Figure 3: Schematic Layout of the ThermODrain (TOD) system used in the office building at Nashik, India

3. RATIONALE FOR TOD SYSTEM

Indoor Thermal comfort means that a body can effortlessly remove its metabolic heat from itself. Air conditioning uses chilled air in sufficient quantity to remove the heat and moisture gains from the space and maintain its temperature and humidity to specified values. It also provides treated outside air to maintain indoor air quality through ventilation. However, the assumption is that all solar gains, both direct and transmitted, are sensible loads to be absorbed by air and carried away before they reach the occupants.

This assumption is true in the Temperate zone. The houses are light-weight and insulated. They are designed to reduce the heating load during the cold winters by keeping the heat in. Summers are mild. So the cooling loads are low and so are the energy rates.

In India, we have hot summers and buildings are un-insulated. They absorb the solar heat and pass it inside. The interior surfaces get heated up and radiate heat. In a tropical country like India, the challenge is to keep the heat out. Instead conventional structures allow it to come in (through the structure) and then use an energy hungry technology of air conditioning to pump it out.

There is sufficient evidence today to show that un-insulated buildings in India have a typical thermal behavior pattern wherein they absorb solar radiation during the day and release it in the night [7]. Figure 4 indicates the typical pattern of temperature indoors and outdoors in naturally ventilated buildings. This affects the comfort level of occupants and the resulting energy usage to reduce the heat load.

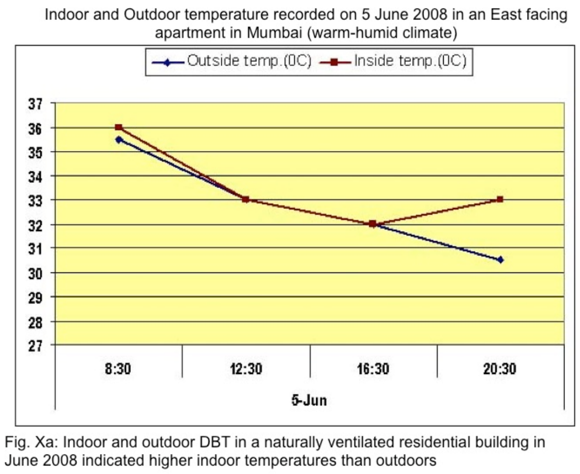

Figure 4: Indoor and outdoor DBT in a naturally ventilated residential building in Mumbai, June 2008 indicated equal or higher indoor temperatures than outdoors.

An ASHRAE study [1] conducted in 1938 shows that the ratio of radiant to evaporative cooling changes with the environment (Figure 5). At 90^0F (32.2^0C), about three quarters of the body heat is rejected as perspiration, which is easily absorbed by the low humidity in the room. The indoor building surface temperatures in summer are at or above the human skin temperature during the day. Under these conditions, a person sitting in still air will be sweating all the time. Since still air can carry very little convective heat, the person will be very uncomfortable. We can also conclude that if the structure is below the body temperature, it will absorb its heat. If it is above, then it transmits heat to the body through radiation.

The disadvantage in using air for cooling is that it has very low capacity for absorbing heat. One liter of air weighs one gram and can absorb only one Joule of heat per Kelvin. So to remove 150 watts (150 Joules/sec) would require 150x3600=540,000 liters /hour of air per person. For 10 K rise, the required flow would be 54000 Lit/hour. This figure will increase due to low coefficient of convective transfer for air. While dry air does not need much energy to cool, the moisture in it condenses while chilling and releases its latent heat. Pumping this heat out through refrigeration requires tons of energy.

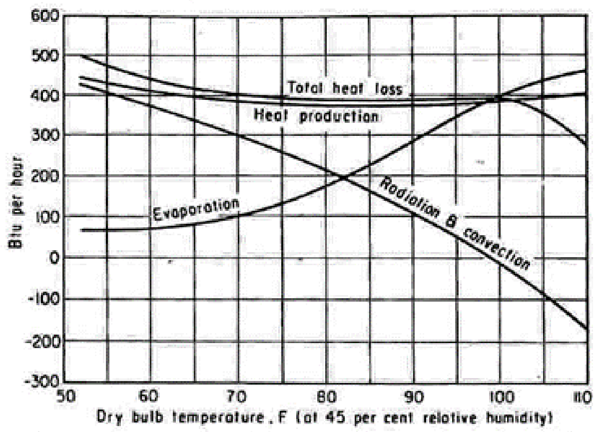

Figure 5: Body heat production and environmental heat exchanges for a healthy, young man seated at rest (Source: ASHRAE, 1938)

4. METHODS

The study used observation and instrumentation to record hourly data. Hourly surface temperature of top and bottom of the terrace slab with and without high albedo paint were measured using *Ambetronics* T-800D 8-channel calibrated data logger attached to K-type thermocouple sensors; Hourly indoor air temperature /dry bulb temperature (DBT) and relative humidity (RH) were measured using EBRO BI 20TH1 temperature and humidity logger; Hourly radiant temperatures were manually recorded using JRN 76mm black globe thermometer. The measurements and observation were carried out over a period of 25hours in May 2017 (peak summer). Hourly DBT and RH data for Nashik was obtained from the Indian Meteorological Department (IMD). Hourly Wet bulb temperatures were interpolated. Average wind speed for the two days was considered at 1.6m/s based on IMD data. Monthly electricity bills were obtained from the office to determine Energy Performance Index (EPI) and compared with prevailing benchmarks provided by the Bureau of Energy Efficiency.

5. THERMAL COMFORT STANDARDS

Since the office building under consideration is naturally ventilated day-time use building, the ASHRAE standard 55, 2013 and National Building Code (NBC) of India, 2016, were reviewed. The ASHRAE standard 55 defines thermal comfort as

That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation�到, while the National Building Code defines it as 'Thermal comfort is that condition of thermal environment under which a person can maintain a body heat balance at normal body temperature and without perceptible sweating'.

The 2013 version of ASHRAE standard 55 incorporates the model of 'Adaptive Thermal Comfort' especially in naturally ventilated spaces based on operative temperature range [2]. However, this standard is approved for a outdoor mean temperature range between 10^0C and 30^0C.

The National Building Code (NBC) 2016 India [3] refers to 3 thermal comfort indices that find applications for Indian climate viz. a) Effective temperature (ET), b) Tropical summer index (TSI), and c) Adaptive thermal comfort. Since Effective temperature or ET "appears to have an inherent error if used as an index of physiological strain, the error increasing with the severity of the environmental conditions" as per NBC, it was not considered. For IMAC standards, running mean outdoor temperature for 30 days is required. Hence Tropical Summer Index or TSI was used as a benchmark. Operative temperature was calculated using the formula below [4]:

$$\theta c = \frac{\theta ai\, \sqrt{(10v)} + \theta r}{1 + \sqrt{(10v)}} \qquad (1)$$

TSI is defined as the temperature of calm air at 50% relative humidity that imparts the same thermal sensations as the given environment. Mathematically, TSI (°C) is expressed as:

$$TSI = 0.745tg + 0.308\, tw - 2.06\sqrt{(v+0.841)} \qquad (2)$$

Where tw = wet bulb temperature, in °C;
tg = globe temperature, in °C;
and V = air speed, in m/s.

The thermal comfort of a person lies between TSI values of 25°C and 30°C with optimum condition at 27.5°C. As per the index, the warmth of the environment was found tolerable between 30°C and 34°C (TSI), and too hot above this limit. On the lower side, the coolness of the environment was found tolerable between 19°C and 25°C (TSI) and below 19°C (TSI), it was found too cold.

6. RESULTS AND DISCUSSION

6.1 Diurnal range of temperature

Outdoor diurnal range of Dry Bulb Temperature (DBT) was 14.7^{0}C as compared to indoor DBT range of 3^0C. Outdoor diurnal range of Relative Humidity (RH) was 71% in contrast to indoor RH range of 27.6%. The indoor RH is governed by the moisture content of the outside air that is drawn in by the toilet exhaust system. As dry outside air is drawn in by the ventilation system, it mixes with the room air, making it drier – reaching up to 30.4%. However, towards the evening, the outside RH increases resulting in increased room RH – up to 57% (Figure 6).

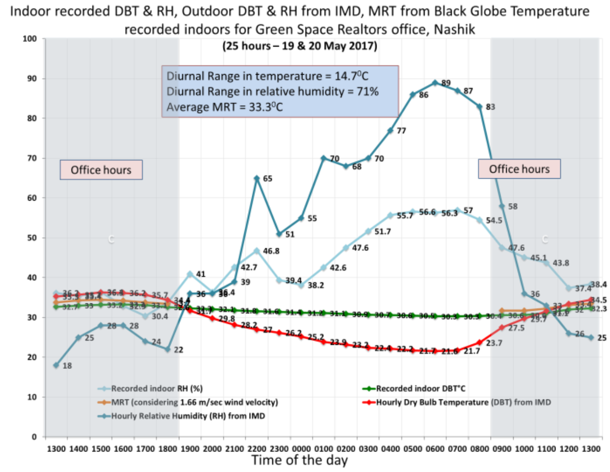

Figure 6: Diurnal range of temperature indoors is a mere 3⁰C as compared to diurnal range of temperature outdoors, which his nearly 15⁰C

6.2 Surface temperature of Terrace RCC slab

Surface Temperature of top of Terrace RCC slab with TOD system and high-albedo paint is found to be 3^0C lower than the bottom of the slab for the 24 hour period. It is noted that slab bottom temperature is higher than slab top during day-time (office hours) by an average 1.3^{0}C while slab bottom is lower than slab top by average 6^0C during night-time (Figure 7).

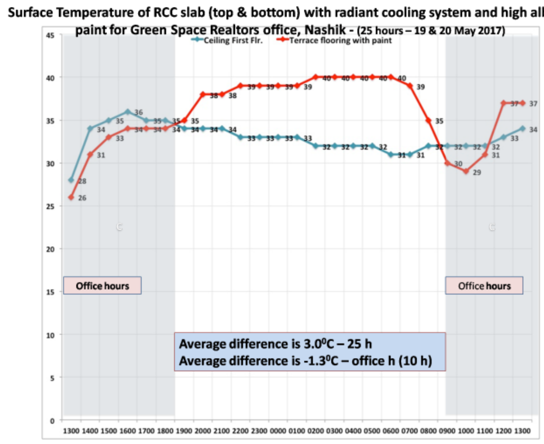

Figure 7: Comparison of top and bottom surface temperature of terrace slab with TOD system and high albedo paint

In the absence of high albedo paint, the slab bottom temperature is lower than slab top by an average 4.28^{0}C during 24-hour period and an average 1.09^{0}C **during night-time.**

Surface Temperature of top of Terrace RCC slab without high albedo paint is higher than the surface with paint by an average 1.280C throughout the day and an average and 2.10C during office hours (Figure 8).

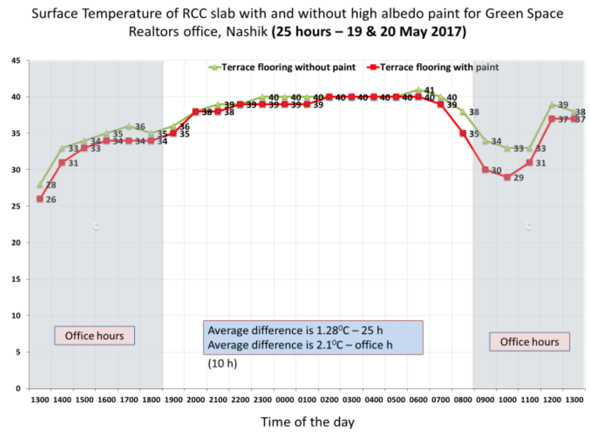

Figure 8: Surface temperature of Roof Slab without high albedo paint is higher than Roof slab with paint by an average 1.28⁰C

6.3 Tropical Summer Index

Comparison of indoor operative temperature with Tropical Summer Index: Indoor operative temperature of Green Space Realtors in May 2017 at outdoor max.DBT of 36.3⁰C was found to be **27.4⁰C**, which is within the range of acceptable TSI values of 25°C and 30°C and close to optimum value of 27.5⁰C.

6.4 Energy Performance Index (EPI)

The EPI, an outcome-based metric for building energy performance, was calculated based on electricity bills obtained from the office administration from June 2016 to May 2017. The EPI for the office building in Nashik was calculated to be **26.5 kwh/m2/year**, which can be categorized under the BEE's voluntary 5-star benchmark for energy efficient buildings (less than 50% air-conditioned) for composite climate of <40 kwh/m2/year, and way below the national benchmark of 86 kwh/m2/year for commercial buildings in this climate zone [6]. Monthly electricity bills for the office building are shown in Figure 9.

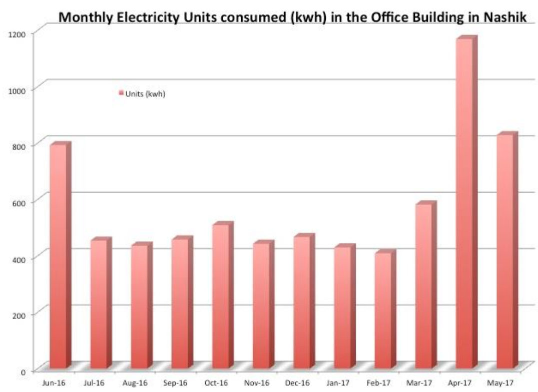

Figure 9: Average monthly electricity consumption in the office building in Nashik is 581.5 kwh

6.5 Envelope Thermal Transmittance

Thermal transmittance is a measure of the thermal effectiveness of the building envelope. It is an amalgamation of the thermal conductance of each material that is used in the building envelope. It is, however, calculated indirectly by finding out the thermal resistance of each layer including the air layer inside and outside. Cavity spaces or air gaps are also taken into consideration in the thermal transmittance calculations.

For the office building in Nashik, the U-value of roof and wall were calculated based on the cross section (Figure 10a and b) and available data on thermal conductivity from ECBC 2007 and CARBSE, Ahmedabad, India. The U-value of roof was calculated as 0.965 W/m^{2}K and the U-value of wall was calculated as 1.85 W/m^{2}K. Both of these do not meet the ECBC 2007 benchmarks of 0.409 and 0.44 W/m^{2}K for roof and wall in composite climate.

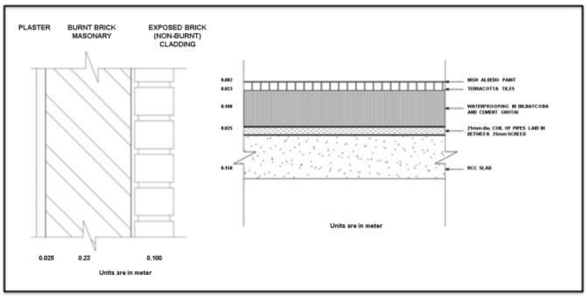

Figure 10: a. Cross section of Wall and b. Roof for calculation of Thermal Transmittance

7. CONCLUSIONS

The study shows that structural cooling system drastically reduced the diurnal range of temperature and relative humidity within the structure. With an average 4.28⁰C difference between slab top and bottom, the TOD system drains out radiant heat from the building that remains cools even when naturally ventilated. The indoor operative temperature in the peak of summer with outdoor temperature of 36.3⁰C, were found to be close **to the neutral temperature of 27.5⁰C (**Figure11) even though the thermal transmittance of roof and wall are much higher than prescribed national standards.

The system prevents the solar heat re-radiation from roof and floors by absorbing it before it adds to the sensible heat load and cause thermal discomfort to the occupants. Even in the hottest day of summer, the TOD system is able to maintain the floor temperature below human skin temperature, allowing a person to feel thermally comfortable sitting and walking on such floor with bare feet [5].

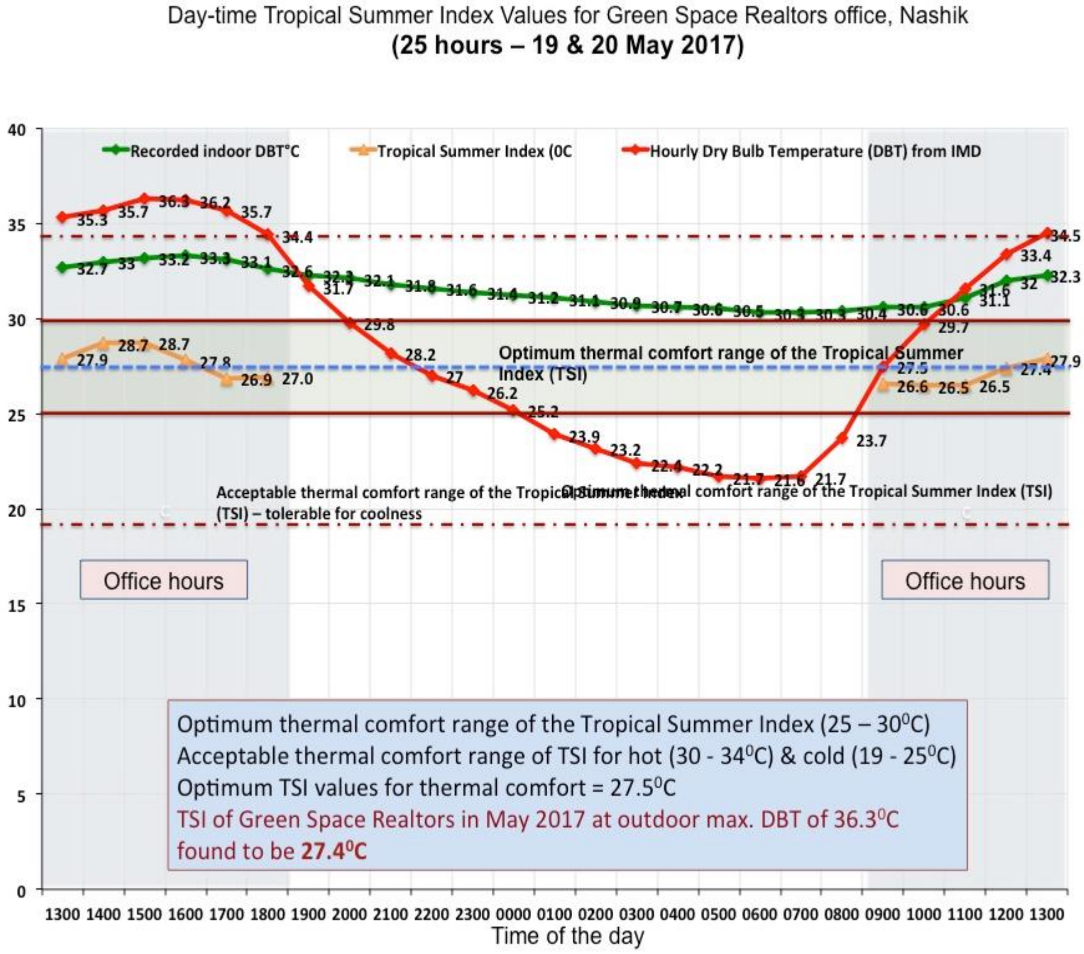

Figure 11: Indoor operative temperature within acceptable range of Tropical Summer Index (TSI)

In terms of capital cost, the structural cooling system is 50% less costly than a conventional HVAC system and the recurring energy cost is a mere 8.7% of a conventional system. The total life cycle costing (capital and running cost) of the TODsystemfor a period of 10 years amounts toRs. 6/ sq. ft./ year (US $ 1 per sq. m) as compared to Rs. 30/sq. ft./yearfora conventional HVAC system.

The system is passive except for 3 elements – Pump for the pipes grid, Fan for Radiator and Pump for Overhead Tank. The total energy consumption of these amount to 3000 kwh/ year as compared to 34,560 kwh/ year required for 12 Tr of conventional HVAC system(at 1.2kw/ Ton of refrigeration) required for the building. The difference in energy consumption is more than 10 times. The active components of the system are supplied energy primarily from solar PV panels.

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation extended to us by the owner of the Greenspace Realtors, Nashik, Mr. Kiran Chavan, Architect Sanjay Patil and structural cooling expert, Mr. Surendra Shah. We acknowledge the assistance of Dr. Ashok Joshi in validating the empirical set up for the research.

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