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Perceived Thermal Environment of Naturally-Ventilated Classrooms in India

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Abstract A field study of thermal environment in naturally ventilated classrooms was conducted in the Department of Architecture at the National Institute of Technology, Tiruchirappalli, India. The study included 176 architecture students and was conducted over five days during the comparatively cool months of December and January. The results show that 82% of participants voted for 'comfortable' on the thermal sensation scale. Cross tabulation of thermal sensation and thermal preference shows that 50% of those who voted within the 'neutral' thermal sensation range preferred cooler temperatures and 43% wanted no change. Classroom temperature was acceptable to 85% of students and unacceptable to 15% of students. Perceived thermal sensation tends toward the cool side (mean -0.26). Regression analysis yielded a comfort zone (voting within -1 and +1) of 26.9–30.8 °C, with neutral temperature of 29.0 °C. Standard adaptive comfort models yielded lower temperature than field findings.

Keywords: Thermal environment, Adaptive thermal comfort, Classrooms, Adaptive opportunities, Field Study.

1. INTRODUCTION

Higher education institutions are expected to provide high-quality education, which demands learning environments that have well-integrated information and communication technologies (ICT). Contemporary trends in pedagogy focus on, among other things, learner-centred environments. Institutions that are keen to promote ICT-enhanced education and to facilitate blended learning, wherein e-learning practices are integrated with traditional classrooms practices, face infrastructure challenges. There is a considerable and growing literature on the thermal environment of classrooms in several other countries

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[14,20,22,28,32,36,37]. However, field studies of thermal environment of classrooms in institutes of higher education in India are rarely reported in literature. A few field studies were recently conducted on thermal comfort in naturally ventilated laboratories and classrooms in Kharagpur, India, by Mishra & Ramgopal [24-27]. An earlier study in India by Pelligrnio et alinvestigated thermal comfort in classrooms in two universities in Kolkata[31].

Institutions that are in the process of upgrading and refurbishing naturally ventilated classrooms to meet the current and future pedagogy requirements consider providing air-conditioned environments, which has potentially serious implications for energy consumption. Considering the energy scenario in India, such decisions need to be revisited. There are increasing numbers of higher education establishments in both the public and private sectors. This phenomenal growth, coupled with increased number of air-conditioned learning spaces can adversely affect energy demand. During power-cuts, the diesel generators often installed in higher educational institutions in India are incapable of operating the air conditioners.

To reduce the energy consumption of educational buildings, it will be appropriate to use adaptive thermal comfort standards during the design phase. Currently in India, there are no such adaptive thermal comfort standards. This calls for increased number of field studies in various types of buildings, including educational buildings in different climatic zones of the country, so as to arrive at such standards. Apart from the serious energy implications, what does the indoor environmental quality mean to students, who are the primary or key stakeholders in such institutions? How do students perceive the thermal environment of their classrooms? There is a strong need to study such perceptions. The present study, therefore, investigates how architecture students at an institute of national importance in India perceive their classroom thermal environment.

In the context of air-conditioned spaces, the National Building Code (NBC) of India 2005[3] specifies conditions for classrooms during summer months as: 23–26 °C, with 50–60% relative humidity, and 23–24 °C with not less than 40% relative humidity during winter. The relevance of these specifications was questioned by Indraganti and Rao [15] and Pellegrino et al.[31]. For naturally ventilated spaces, the NBC specifies Tropical Summer Index within the range 25.0–30.0°C as comfortable (optimum 27.5 °C). However, the code does not refer to adaptive thermal comfort. The objective of this study was to assess students' perceptions of thermal environment, in terms of thermal sensation, satisfaction with classroom temperature; freedom to open or close window shutters, and to control the speed or switch on/off ceiling fans; the acceptability of: temperature and air movement and, thermal / air movement preferences

2. METHODOLOGY

2.1 Location

Tiruchirappalli (10°46 N, 78°43 E, 88 m AMSL) is located in the state of Tamilnadu, India. The study area is classified as a warm and humid climatic zone by the National Building Code of India 2005 [3]. The months of April–June are hot, that of May being the hottest with a maximum monthly mean temperature of 38.1°C. The period December–February is comparatively cool, and the mean monthly minimum temperature of 20.3°C occurs in the month of January. The North-East monsoon occurs during September to November.

2.2 The Case Study Building

This study was conducted in classrooms within the Department of Architecture of the National Institute of Technology at Tiruchirappalli (NITT). The study was conducted in two different classrooms. Objective and subjective surveys included students from all classes, from the first year to final year. The studies were conducted on five different days, one in December 2014, and four in January 2015. Except for the computer laboratory, all the learning spaces are naturally ventilated. The classrooms are located on the first floor of the two-storey building and studios are located on the ground floor. The building is a framed structure, with reinforced concrete columns and beams. All brick walls are 230 mm thick and plastered on both the sides with 12 mm cement plaster.

Physical and Spatial Characteristics of Classrooms: Each of the classrooms (L1 and L2) measures 12 m in length, 9 m in width and 4.2 m in height. The floor area and volume are $108m^2$ and $453.6m^3$ respectively. The area of openings (windows-cum-ventilators) is 29.37 m^2, which constitutes 27% of the floor area. During the study, it was observed that the window shutters were closed for better viewing of multi-media projection, affecting the natural air flow. The maximum seating capacity of each classroom is 60 and the floor space per student is 1.8 m^2. The characteristics of each classroom are shown in Figures 1 & 2.

Subjects were students of the five-year undergraduate programme in architecture. Of the 176 participants, 58% were male and 42% were female. Students' ages ranged from 18 to 23 years. The students originate from different states in India. Students of the second semester were admitted to the first year in July 2014 and thus were acclimatised for more than five months prior to this study in December 2014. All NITT students experience air-conditioned environments, including frequent use of departmental computer laboratories, the central computing facility, main auditorium, and various seminar halls.

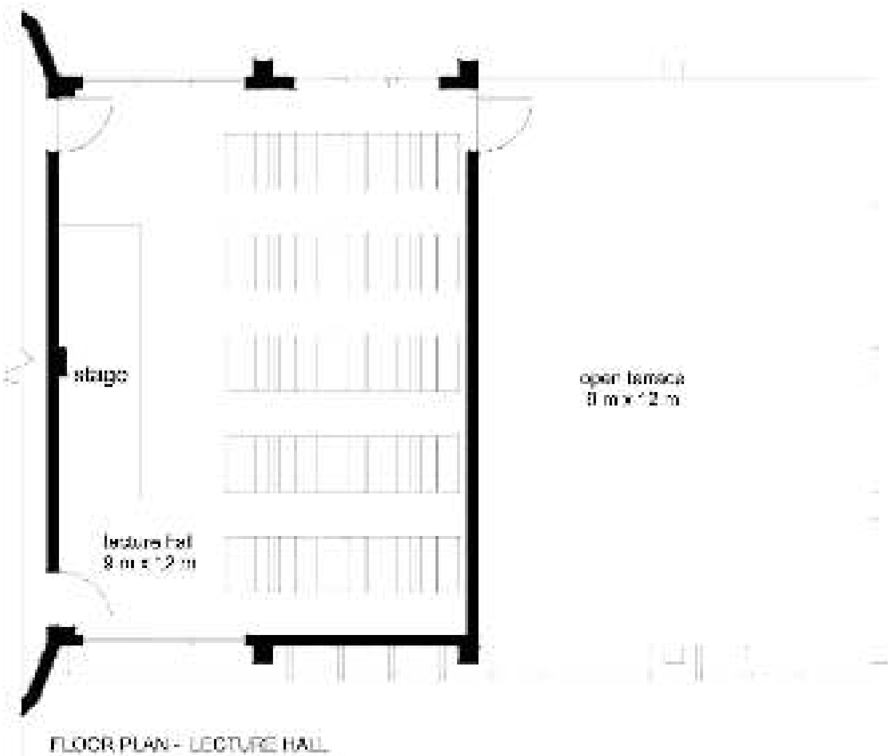

Figure 1: Floor plan of the typical classroom.

Figure 2: Wall-mounted pull-down screen, chalk board, and formal furniture layout.

Assessing Metabolic Rates and Estimating Clothing Levels: Student activities during lectures were limited to sitting and listening to the lecture, and occasionally taking down notes for their reference. A metabolic rate of 1.2 Met was assumed for this level of activity, akin to that given for "Sedentary activity (office, dwelling, school, laboratory)"in ISO 7730 [19]. The aim of the questionnaire survey was to capture students' perceptions of the thermal environment of the classrooms, during the end of lecture sessions, and with minimal disruption to their regular learning. Questions regarding the clothing worn by the students were included in the questionnaire. They revealed the clothing combinations used by students such as half-sleeve shirt and trousers / full-sleeve shirt and trousers / full-sleeve shirt with sleeves folded back and trousers, T-shirt and trousers; and similar combinations of shirts with jeans. Female students used the salwar-kameez, a traditional ensemble. Kameez were often half-sleeve / short sleeve, full sleeve, and occasionally sleeveless. Insulation of innerwear and footwear were added to the clothing insulation (clo) values. Calculated clo values ranged from 0.41 to 0.68 (mean 0.53; standard deviation 0.085). The traditional Indian sari ensemble worn by women was not used by any of the female students during the survey period. Social and cultural norms mean that students do not attend classes in other style of clothing such as short trousers or short skirts.

2.3 Objective and Subjective Data Collection

Typically, lecture sessions are scheduled for the morning hours, from 8.30 a.m. to 12.10 p.m. with a twenty-minute break from 10.10 to 10.30 a.m. Each lecture session lasts 50 min. Lunch break is from 12.20 to 1.30 p.m. Afternoon sessions are from 1.30 to 4.50 p.m. A few lectures are scheduled in the afternoon, but most sessions are for studios. This study conducted objective measurements and subjective assessment during the lecture sessions. Parameters such as air temperature, wet-bulb temperature, relative humidity, air speed, and globe temperature were recorded within each classroom throughout a 50 min lecture, using a data logger and relevant sensors (Table 1). A tripod containing the data logger and sensors was placed 1.1 m above the floor in the centre of the classroom. Towards the end of the lecture, the class professor distributed and collected the questionnaires and this process took less than six minutes.

The questionnaires for subjective assessment of perceived thermal environment are shown in Table 2.

Table 1: Instruments used for Indoor Environmental Measurement.

Parameter measured	Description	Trade name	Range	Accuracy
LSI Lastem R-Log data logger ELR 510M with the following sensors:				
Air temperature	Psychrometer sensor	Thermo hygrometric sensor ESU102LSI Lastem, Italy	-50 to 125 °C	±0.05 °C
Relative humidity			0 to 100%	±5%
Globe temperature	Black globe radiant temperature sensor (Radio)	ESR205 LSI Lastem, Italy	-20 to 60°C	±0.05 °C
Air speed	Omni-directional hot wire anemometer	ESV107 LSI Lastem, Italy	0.01 to 20 m/s	0 to 0.5 m/s = ±0.05 m/s 0.5 to 1.5 m/s = ±0.1 m/s and >1.5 m/s = 4%
Wet bulb temperature	Wet natural ventilation temperature sensor	Thermometric Sensor ESU121LSI Lastem, Italy	-50 to 125 °C	±0.05 °C

3. RESULTS AND DISCUSSION

Table 2: Thermal dimension of the Indoor Environment.

Measures	Scales Adopted
1.Thermal Sensation Votes (TSV)	Scale: TSV: -3 = cold, 3 = hot.
2. Satisfaction with temperature in classroom 3. Satisfaction with freedom to open or close window shutters 4. Satisfaction with freedom to control the speed of ceiling fans 5. Satisfaction with freedom to switch on/off ceiling fans 6. Satisfaction with air movement	Satisfaction: 1 = very dissatisfied, 5 = very satisfied.
7. Acceptability of temperature 8. Acceptability of air movement	Acceptability: 1 = acceptable2 = not acceptable.
9. Thermal preference 10. Air movement preference	Thermal preference - McIntyre scale: 1 = warmer, 2 = no change, 3 = cooler. Air movement preference: 1= More air movement, 2 = No change, 3 = Less air movement.

3.1 Study of the Thermal Environment

Indoor Thermal Environmental Conditions: Table 3 summarises indoor environmental parameters and calculated indices.

Table 3: Indoor Environmental Data and Calculated Indices.

	Mean	Std. dev.	Minimum	Maximum
Air temperature (°C) (T_a)	28.64	0.938	27.24	29.84
Globe temperature (°C) (T_g)	28.51	0.819	27.19	29.60
Wet bulb temperature (°C) (T_{wb})	22.09	1.453	20.66	24.41
Mean radian temperature (°C) (T_{mrt})	28.53	0.695	27.47	29.50
Relative humidity (%) (RH)	55.34	9.164	44.77	66.97
Air speed (m/s) (V_a)	0.07	0.045	0.01	0.12
Operative temperature T_{op} (°C)	28.62	0.752	27.48	29.68
Predicted mean vote (PMV)	1.24	0.211	1.02	1.64
Predicted percentage dissatisfied (PPD) (%)	37.89	10.717	27.00	58.50
Tropical Summer Index (°C)	28.02	1.104	26.56	29.89

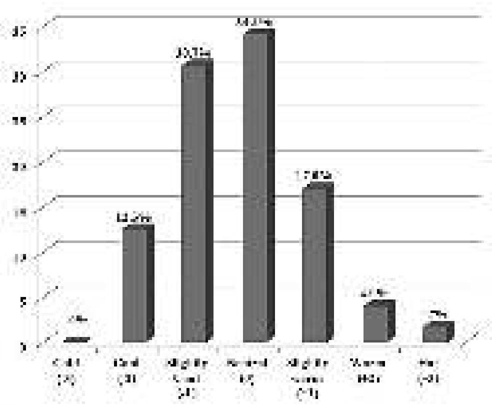

Figure 3: Frequency distribution of thermal sensation votes.

Thermal Sensation and Thermal Satisfaction: The ASHRAE seven-point scale was adopted for thermal sensation votes (TSV) (range -3 to +3: cold to hot). Thermal comfort is assumed to correspond with the neutral region of the scale (-1 to +1), which is also considered to be the point of maximum acceptability and optimum temperature. As per ASHRAE 55, an acceptable thermal environment is one that satisfies at least 80% of occupants[1]. The questionnaire responses show that 82% of the 176 respondents voted within the three central categories of the ASHRAE scale and are, therefore, thermally comfortable. A skew towards the cool side is observed for TSV (Figure 3).

Table 4: Cross Tabulation of Thermal Sensation and Thermal Preference Scale.

	Thermal preference			Row totals
TSV	**Warmer**	**No Change**	**Cooler**	
-3, -2	22.7% (5)	68.2% (15)	9.1% (2)	(22)
+1, 0, -1	7% (10)	43% (62)	50% (72)	(144)
+3, +2	10% (1)	0% (0)	90% (9)	(10)
Column totals	16	77	83	176

Cross tabulation of the thermal sensation and thermal preference scale (Table 4) shows that 50% voters within the 'neutral' thermal sensation range preferred cooler temperatures and 43% wanted no change. Similar findings were reported by Wong and Khoo [36] from a study of naturally ventilated classrooms in Singapore, wherein 72.4% of respondents in the neutral category preferred cooler temperatures. Kwok and Chun [21] studied thermal comfort in Japanese schools, and reported that in naturally ventilated classrooms, 54.9% of occupants in the neutral category preferred cooler conditions whereas 41.9% preferred no change. In the context of naturally ventilated offices in Thailand, 64% of users preferred cooler temperatures even though they had voted within the neutral category of thermal sensation [5,6]. Zhang et al [38] found that, in naturally ventilated classrooms in a subtropical Chinese region voters within the central three categories, 50.9% did not want change while only 22.7% preferred cooler conditions and 26.5% preferred warmer temperature.

A direct question on the acceptability of classroom temperature revealed that it was acceptable to 85.2% of students and unacceptable to 14.8%. To determine what percentage of participants who expressed neutral thermal sensation actually found the thermal environment acceptable, the responses to that direct question were cross-tabulated with TSV. Although 82% of participants voted for the three neutral categories of the ASHRAE thermal sensation scale, only 70% responded "acceptable" to the direct question. It is observed that students who expressed thermal sensation outside the three neutral categories also found the thermal conditions acceptable.

3.2 Assessment of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)

The concepts of PMV and PPD by Fanger [9] have been incorporated within international standard ISO 7730 [9] and ASHRAE Standard 55[1]. PMV index

Table 5: Assessment of Tropical Summer Index in Different Classrooms.

Class room	Date and time	Wet-bulb temperature (°C) (T_{wb})	Air speed (m/s) (v_a)	Globe temperature (°C) (T_g)	Tropical Summer Index (TSI) (°C)	Thermal Sensation[a]
L2	Dec 05, 2014 9.20 - 10.10 am	22.46	0.01	27.19	27.8	Comfortable
L2	Jan 23, 2015 11.20 am - 12.10 pm	23.25	0.10	28.45	28.5	
L2	Jan 06, 2015 3.10 - 4.00 pm	20.89	0.12	29.09	28.2	
L1	Jan 12, 2015 10.30 - 11.20 am	20.66	0.03	28.20	27.9	
L1	Jan 09, 2015 10.30 - 11.20 am	24.41	0.08	29.60	29.8	

[a] Comfortable Range = TSI 25.0 to 30.0 °C

predicts the subjective ratings of users of a given environment. PPD index predicts how many people are dissatisfied with their thermal environment. People who vote outside the three central categories of the seven-point scale are regarded as thermally dissatisfied. PPD is expressed as a percentage and is calculated from PMV value [9]. PMV and PPD were calculated using the CBE Thermal Comfort Tool [11]. PMV calculated for the classrooms ranged from 1.02 to 1.64 (mean 1.24), corresponding to a thermal sensation of slightly warm to warm. The mean TSV obtained in this study is -0.26. The finding that PMV clearly overestimates thermal sensation supports the findings of other researchers[8,13,16,18,30]. Only 18% of participants indicated that the thermal environment was unacceptable, whereas PPD estimated thermal dissatisfaction as 38%. Since PMV significantly overestimated thermal sensation, PPD is also observed to be much higher.

Assessment of Tropical Summer Index (TSI)

Sharma and Ali [34] conducted field studies of thermal comfort in Indian subjects, from which they derived Tropical Summer Index (TSI):

$TSI = 0.308\ T_{wb} + 0.745\ T_g - 2.06\ V_a^{1/2} + 0.841$ (1) where T_{wb} = wet-bulb air temperature (°C), T_g = globe temperature (°C), V_a = velocity of air (m/s) (1)

Sharma and Ali (1986) define TSI as the air/globe temperature of still air at 50% relative humidity that produces the same overall thermal sensation as the environment under investigation. A TSI of 27.5°C was found to make subjects most comfortable; TSI of 19.0–25.0°C (optimum value 22.0°C) will give rise to slightly cool thermal sensation; TSI of 25.0–30.0°C (optimum 27.5°C) will be perceived as comfortable; TSI of 30.0–34.0°C (optimum 32.0°C) will be perceived as slightly warm [34]. The measured data were used to calculate TSI for each of the classrooms (Table 5). The calculated TSIs indicate that thermal sensation in this study was "comfortable". This finding is in accordance with students' votes on thermal sensation, wherein 82% voted in the central three categories, indicating that thermal comfort and temperature of the classroom was acceptable to students. TSI complies with the specifications in the National Building Code of India 2005[3].

3.3 Regression Analysis for Neutral Temperature (T_n)

Regression of Mean PMV on Operative Temperature: Regression analysis of mean PMV on operative temperature (Fig. 4) yielded equation (2):

$$PMV = 0.256T_{op} - 6.081 \tag{2}$$

$(R^2 = 0.834, R = 0.913, p<0.001)$

Using equation (2), the PMV comfort range (-1 to +1) was determined as 19.9–27.7°C; neutral temperature (T_n) was 23.8°C, which is approximately 5°C lower than T_n obtained from TSV.

Regression of Observed TSV on Operative Temperature: Regression analysis of observed thermal sensation votes (TSV) on operative temperature (Equation 3) yielded a neutral temperature (T_n) of 29.0°C with thermal comfort zone from 27.4 °C to 30.7°C of operative temperature (Figure 5).

$$TS = 0.602T_{op} - 17.471 \tag{3}$$

$(R^2 = 0.166, R = 0.408, p<0.001)$.

The T_n of 29.0°C obtained in the present study is comparable to 29.2°C, reported by Indraganti [16] in a study of naturally ventilated apartments in Hyderabad. Interestingly, in the study of naturally ventilated classrooms in Kharagpur, India, Mishra & Ramgopal obtained regression neutral of 29.0°C [27]. Wong and Khooreported T_n of 28.8°C in a study of thermal comfort in classrooms in the tropics[36]. A T_n of 30.2°C was reported in naturally ventilated classrooms in Dhaka[35]. However, the regression obtained shows that only 17% of the variance is explained and is, therefore, far from significant. It indicates that in naturally-ventilated classrooms, students' thermal sensation is significantly influenced by other factors.

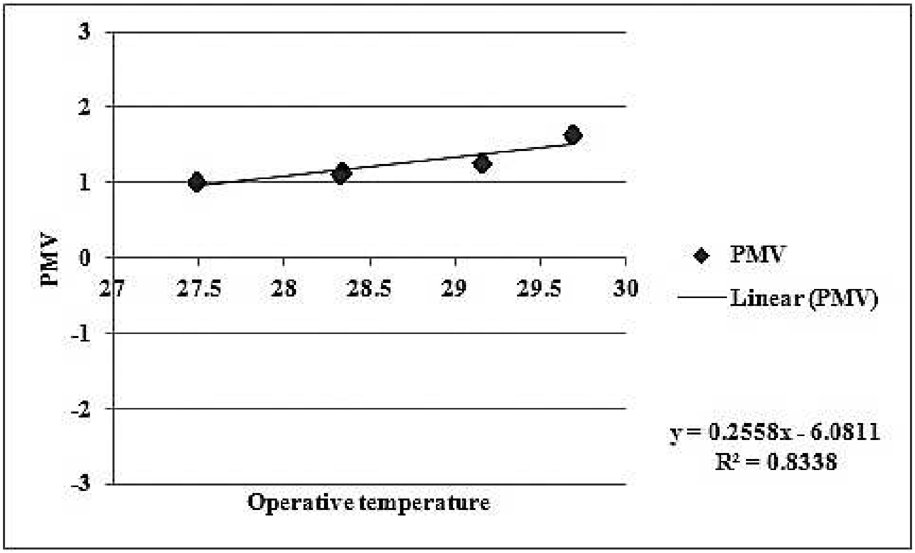

Figure 4: Regression of PMV on operative temperature.

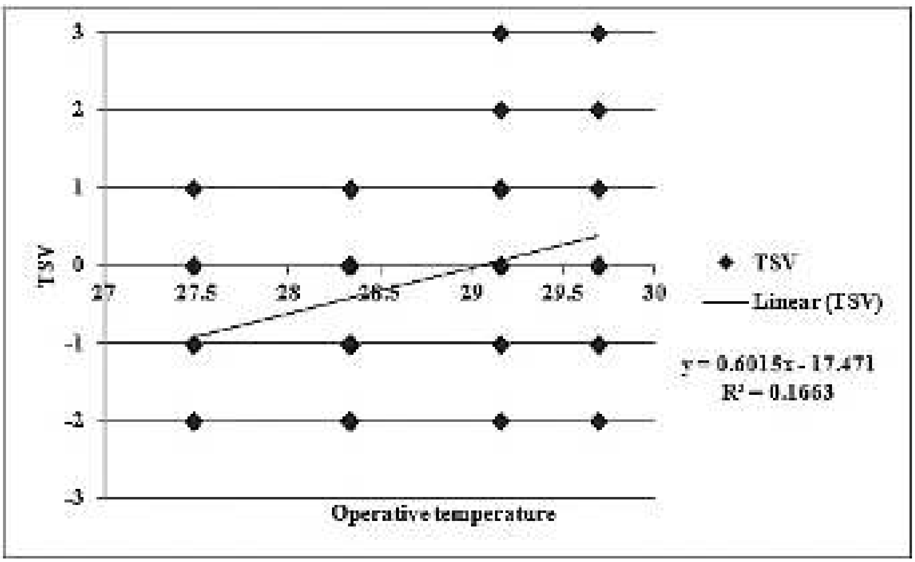

Figure 5: Regression of observed TSV on operative temperature.

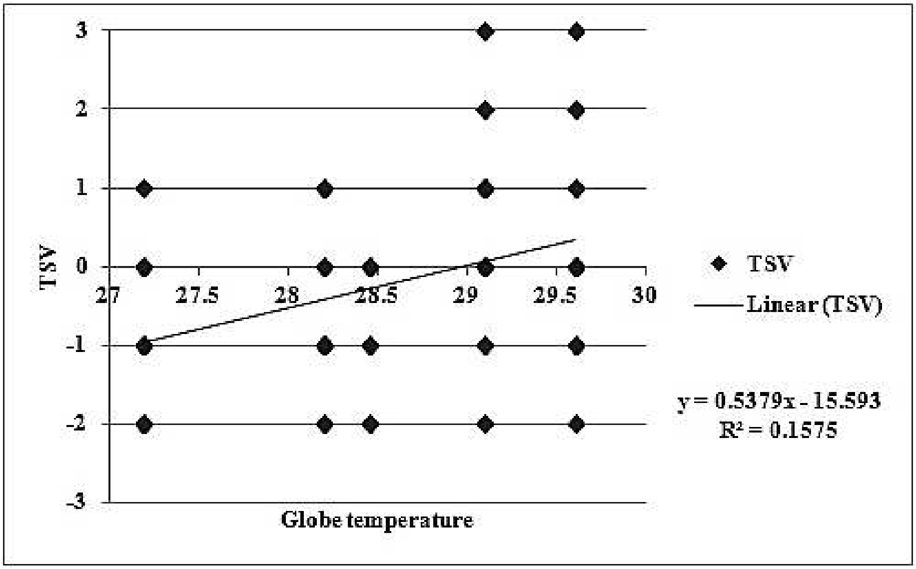

Figure 6: Regression of observed TSV on globe temperature.

Regression of Thermal Sensation and Globe Temperature: One method of evaluating neutral temperature in a field study is to use linear regression of thermal sensation and indoor globe temperature[18].The data obtained in the present study (Figure 6) gives equation (4):

$$TS = 0.538T_g - 15.593 \tag{4}$$

(R^2=0.158, R=0.397, p<0.001).

The regression neutral temperature (T_n) estimated from equation (4) is 29.0°C and the comfort zone is 26.9 to 30.8°C (sensation votes -1 to +1). These results are comparable to those reported for naturally ventilated apartments (T_n of 29.2°C, comfort zone 26.0–32.4°C) in Hyderabad, India[15] and T_n of 29.0°C reported for naturally ventilated classrooms in Kharagpur[27]. The regression presents a value of R^2 = 0.158 which is a very small correlation and the relationship indicated in Figure 6 is not strong.

Comfortable Temperature Predicted by Griffiths' method

The Griffiths comfort equation[10] is given by $T_{comf} = T_g$ - TSV/G_{cons}, where, T_{comf} is the Griffiths comfort temperature (°C), T_g is the indoor globe temperature (°C), TSV is thermal sensation vote, and G_{cons} is the Griffiths constant. T_{comf}

Table 6: Comfort Temperature calculated using different Griffiths Constants.

Regression coefficient		Griffiths comfort temperature T_{comf} (°C)	Regression neutral temperature (°C) (in this study)
(a)	0.54 (from this study)	29.0	29.0
(b)	0.50 Humphreys et al. [13]	29.0	
(c)	0.33 Nicol et al. [30]& McCartney and Nicol [23]	29.3	
(d)	0.25 Nicol et al. [30]	29.5	

is calculated by using four different regression coefficients: (a) 0.54, obtained in this study and those from the literature: (b) 0.50, (c) 0.33, and (d) 0.25, as presented in Table 6.

Griffiths comfort temperatures with G_{cons} of 0.54 and 0.50 show close agreement with the neutral temperature obtained in the present study. Mishra and Ramgopal [27] obtained comfort temperature of 29.5 °C using Griffiths equation with regression coefficient of 0.50 and that is comparable with this study.

4. ADAPTIVE OPPORTUNITIES AND ADAPTIVE THERMAL COMFORT

4.1 Satisfaction with Adaptive Opportunities

The freedom to adjust window shutters and therefore air movement is important for modifying thermal comfort. The results show that 35% of students were dissatisfied with the present arrangement, whereas the remainder were either neutral or satisfied. The key reason for dissatisfaction being that the windows were small in height and either had top-hung shutters or centrally pivoted shutters, unlike the normal windows with side-hung shutters installed in other buildings on the NITT campus. Each of the classrooms has 8 four-speed ceiling fans with controls provided inside the classrooms. Throughout the study period, it was observed that the ceiling fans in all classrooms were operating at speed 3 (mean wind speed of 1.4 m/s) or, a maximum speed of 4 (mean wind speed of 2.0 m/s). When the ceiling fans were operating at speed

Table 7: Comfort Temperatures calculated using Standard Adaptive Comfort Models.

Comfort Equations	Humphreys et al. [13]	EN15251 [7]	ASHRAE (2013) [2]
	$T_{comf} = 0.53T_o + 13.8$	$T_{comf} = 0.33\ T_{rmt} + 18.8$	$T_{comf} = 0.31\ T_m + 17.8$
Inputs used (°C)	Running mean temperature (T_{rmt}) was calculated as per the procedure detailed by Nicol and Humphreys [29].		Last seven-day average of daily mean temperature (T_m) was taken on the survey day [27].
T_{comf} (°C)	24.0	25.1	25.4

3 and 4, the mean background noise from the fans were 54.5 decibels (dB) and 61.5 dB respectively, exceeding the maximum acceptable noise level of 45-50 dB specified for classrooms by NBC [3]. Only 20% of students were dissatisfied with their freedom to adjust the speed of the ceiling fans and 17% were dissatisfied with the freedom to switch the ceiling fans on or off. Freedom to choose where to sit in the classroom is important, as it allows individuals to sit below the ceiling fan, closer to windows, or to obtain better visibility of the chalk-board or screen. Only 11% of the students were dissatisfied with this freedom, while more than 70% were satisfied.

4.2 Adaptive Thermal Comfort

Running mean temperature (T_{rmt}) and seven-day average of daily mean temperature (T_m) were calculated from outdoor climatic data obtained from NITT campus weather station monitored by National Institute of Wind Energy (NIWE), Chennai, India. Comfort temperatures (T_{comf}), calculated using the standard adaptive comfort models, are 24.0°C, 25.1°C and 25.4°C respectively (Table 7). However, the neutral temperature and Griffiths comfort temperature are higher, indicating that the participants in this study are acclimatised and tolerant of a wider range of temperature.

5. CONCLUSIONS

The subjects of this study are the students of architecture who are aware of the issues regarding the various dimensions of the indoor environment, including thermal comfort. TSI indicates thermal sensation as "comfortable" and this complies with the specifications in the National Building Code of India 2005.

A skew toward the cool side is observed in TSV and the mean thermal sensation was -0.26. Standard adaptive comfort models yield lower temperature than field findings, indicating that the students are well adapted and tolerant of a wide range of temperatures. Further field studies are needed in various types of buildings and in different climatic zones of the country in order to develop an adaptive thermal comfort standard relevant for India.

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